GLOBAL HEALTH

FOOD SECURITY & AGRICULTURE

HUMAN RIGHTS

EDUCATION

DIGITAL INCLUSION

50 BREAKTHROUGHS

CRITICAL SCIENTIFIC AND TECHNOLOGICAL ADVANCES NEEDED FOR SUSTAINABLE GLOBAL DEVELOPMENT

WATER SECURITY

ACCESS TO ENERGY

RESILIENCE TO GLOBAL CHANGE

GENDER EQUITY

EMERGING TECHNOLOGIES

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INTRODUCTION

"This is the beginning of a conversation."

So began the 2015 introduction to the 50 Breakthroughs study, when it was first published as the technology backbone for the Sustainable Development Goals (SDGs). Since then, the central role of breakthrough technologies in achieving the SDGs has become increasingly recognized—in part because of a number of the 50 Breakthroughs have come to life in very impactful ways, and in part because a few unexpected breakthroughs are promising to fundamentally upend conventional pathways to technology-enabled progress.

We believe that the overall trajectory of technologies in service of the SDGs is positive, albeit somewhat slower than required to fully meet the 2030 targets. Out of the 50 breakthroughs identified as essential to achieving the SDGs, 10 have been developed (for example, a low-cost smartphone, point-of-care diagnostic devices for primary healthcare, and a low-cost solar mini-grid system), and a number of them appear to be on the way to reaching meaningful scale within the next three to five years.

Judging by the current trajectory and the emphasis on technology innovations, we project that at least 40 of the 50 breakthroughs will be developed by the year 2030. However, fewer than 20 of them are likely to reach the hundreds of millions (let alone billions) of people needed to fully impact the SDGs. Still, 2030 is a somewhat artificial deadline, and overall it does appear that a new generation of critical technologies will come into service within the next decade or so.

As our chapter on Emerging Technologies discusses, we believe that the gene-editing tool CRISPR has the potential to be a game-changer in the 2030 timeline. Aerial imagery via drones and low-cost satellites is another frontier technology that is beginning to rapidly increase transparency into issues like deforestation, mass atrocities and similar events. It is now possible to have reasonably affordable images of every point on Earth once a day; over time, the spatial and temporal resolution of such imagery will only increase, making it an essential tool for many development tasks.

On the other hand, we believe AI and blockchain are likely to have marginal impact in the foreseeable future. AI will not live up to the hype—at least in the 2030 timeline—because there simply isn't enough robust data about issues affecting low-income communities to utilize advanced AI.

Perhaps the most promising sign that technological advancement is going hand-in-hand with human development, is the investment that many emerging economies are making in their local technology and innovation ecosystems—from fostering research capabilities in their universities, to promoting partnerships between local companies and global technology corporations.

When we first published the 50 Breakthroughs in 2015, we hoped it would serve as a helpful guidepost to institutions and individuals seeking to make a difference in human development through the power of technology. We are grateful that it has become a pillar of the technology-for-good ecosystem. We are particularly grateful for the UN Commission on Science and Technology for Development for recognizing the study as a cornerstone of the global effort to achieve the SDGs.

WHAT IS A BREAKTHROUGH?

Breakthrough technologies refer to those innovations that will help solve the most critical human development challenges, and are dramatically different from existing technologies in industrialized settings.

Compared to current technologies, they are available at a fraction of the cost, requiring only a fraction of the energy, significantly less reliant on technical skills to operate, not needing elaborate infrastructure, and being generally robust and low-maintenance.

Such breakthrough technologies do not currently exist (at least not in the right configuration of cost and usability), or have recently entered the market in small scale. They will require serious science, robust engineering and inventive business models to enable distribution, scale and sustainability.

Through the post-WWII history of efforts to alleviate global poverty, a small number of breakthrough technologies have had transformative impact.

For example, the polio vaccine has all but eradicated a disease that was leading to life-long paralysis of millions of people around the world. Another example is high-yielding crop seed varieties that launched the Green Revolution, which led to agricultural self-sufficiency through much of Asia and Latin America.

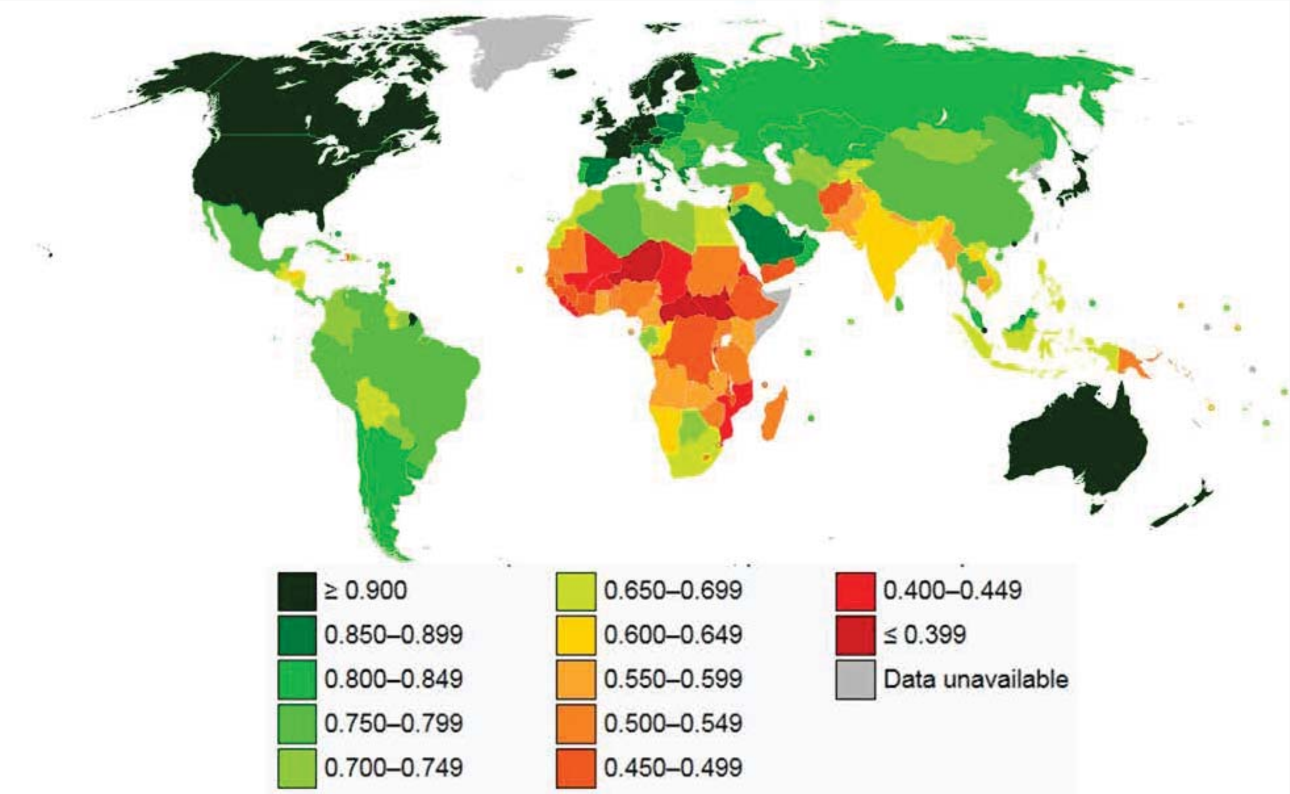
The 50 Breakthroughs study seeks to identify the next generation of technologies that are needed to continue human development advances for a growing global population.

GEOGRAPHIC FOCUS

The geographic focus of this study is sub-Saharan Africa and South Asia, primarily because poverty is concentrated in these regions. The map below shows the various countries of the world, ranked in terms of the United Nations' Human Development Index (HDI), and grouped into population deciles. The HDI is a composite metric that combines wealth, health and education, and serves as a general measure of human development.

According to HDI data, the worst-off countries are in sub-Saharan Africa and South Asia. While our focus throughout this study is on these two poorest regions, poverty persists in other parts of the world as well. Many of the technology solutions identified in this study are equally applicable outside of South Asia and sub-Saharan Africa.

Human Development Index of countries, 2017



Source: https://en.wikipedia.org/wiki/List_of_countries_by_Human_Development_Index

NOTES ON METHODOLOGY AND LAYOUT

Studies focused on future-facing topics have traditionally relied on surveys of experts, using approaches like the Delphi Method,[1] a structured iterative process of interviews and reviews. Early in our study, we discovered two challenges with such a process. First, the absence of a broad, credible evidence base about what does and does not work has led to entrenched opinions. Second, such an approach would likely have led to a laundry list of technologies or devices, rather than a robust problem analysis that logically leads to the breakthroughs required—agnostic to specific technologies.

Hence, this study employs a six-part approach to reach its conclusions:

1. Describe and analyze the five to 10 most important contextual facts about the specific problem.

2. Identify the key challenges that have kept effective solutions from becoming a reality.

3. Identify, based on input from recognized topic-specific experts, the most promising interventions to overcome those hurdles.

4. Determine the dependence of each of these interventions on: policy reforms, infrastructure development, education and human capital development, behavior change, access to user finance, innovative business models, and finally, the development of new breakthrough technologies.

4. Focus on interventions with a significant dependence on a breakthrough technology, and identify the important parameters the technology needs to fulfill. Based on the underlying technical challenges, estimate the time-to-market by when these breakthroughs may become deployable products.

5. Finally, identify the most important hurdles to sustainable, large-scale deployment, based on many of the factors listed above (such as policy reform and infrastructure), and score the difficulty of deployment on a five-point scale: simple, feasible, complex, challenging, and extremely challenging. The purpose of this final analysis is to encourage technologists and funders to understand these deployment challenges before making major investments in their work.

Each chapter is divided into three parts: Core Facts and Analysis, Key Challenges, and Scientific and Technological Breakthroughs.

The five-point scale and the complexity we ascribe to each of the factors and constraints relevant to the deployment of a particular technology are illustrated in **Table A**. The lowest score (simple) is reserved for cases when the particular constraint is not relevant to deployment; the constraint is given the highest score (extremely challenging) if it can be a serious bottleneck to deployment. The aggregate score reflects the overall degree of difficulty, considering the collective weight of the individual constraints. The methodology is clearly subjective. **Exhibit A** is a sample of how we have illustrated the deployment difficulty of each breakthrough across the study. This particular sample highlights a challenging breakthrough.

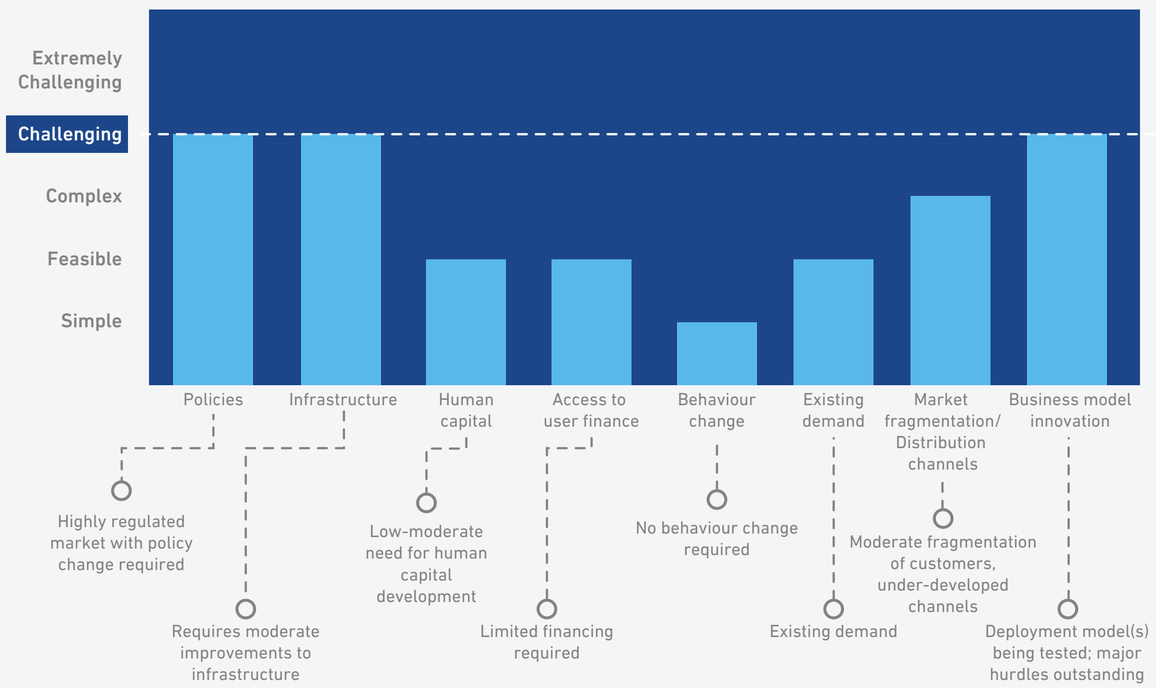
[1]The Delphi method is a structured communication technique, originally developed as a systematic, interactive forecasting method that relies on a panel of experts who anonymously reply to questionnaires and subsequently receive feedback in the form of a statistical representation of the 'group response', after which the process repeats itself. The Delphi method is based on the assumption that group judgments are more valid than individual judgments. It was originally developed by the RAND Corporation in the 1950s to forecast the impact of technology on warfare.

Table A

	Simple	Feasible	Complex	Challenging	Extremely Challenging
Policies	Minimal role of policy/regulation	Low role of policy/regulation	Regulated market with supportive policies	Highly regulated market with policy changes required	Highly regulated and controversial changes required
Infrastructure	Minimal need for infrastructure	Dependent on existing infrastructure	Requires some improvements to existing infrastructure	Requires moderate improvements to infrastructure	Requires major improvements to infrastructure
Human capital	Minimal need for human capital development	Low/moderate need for human capital development	Moderate need to train a limited number of people	Requires high level of training for large numbers of people	Requires national scale training programs
Access to user finance	Financing not required	Limited financing required	Moderate financing needed, viable mechanism available	Significant financing required, limited mechanisms available	Significant financing required, no identified mechanism
Behaviour change	No behaviour change required	Minimal behaviour change required	Moderate behaviour change required with evidence of behaviour change being viable	Major behaviour change required, limited mechanisms available	Significant behaviour change needed on daily basis, changes contrary to cultural norms
Existing demand	Strong existing demand	Existing demand	Moderate demand	Low demand, needs to be built	Extremely low demand or not a percieved need
Market fragmentation/ Distribution channels	Highly concentrated market or well defined channels	Fairly concentrated market and/or well defined channels	Moderate fragmentation of customers, under-developed channels	Fragmented market, weak distribution channels	Highly fragmented, challenging to reach customers
Business model innovation	Clear deployment models existing at scale	Deployment model in process of scaling	Deployment model(s) being tested	Deployment model(s) being tested, major hurdles outstanding	No identified deployment model, major hurdles identified

Exhibit A

Breakthrough: Difficulty of deployment



THE 50 BREAKTHROUGHS

Across the different topic areas covered in this study, we have identified 50 scientific and technological breakthroughs that can substantially improve the lives of the poor, especially those living in South Asia and sub-Saharan Africa. The 50 breakthroughs are numbered and listed in the order they appear in the report, and we have not ranked the breakthroughs in order of importance.

1 A low-cost system for precision application of agricultural inputs, ideally combining water and fertilizer

In some regions like South Asia, the Green Revolution has brought unfortunate consequences including over-exploitation of groundwater resources and over-application of synthetic fertilizers. In other regions like sub-Saharan Africa, such transformation has not occured and there is under-utilization of groundwater resources and ongoing nutrient mining of soils. There is need for a low cost, robust, scalable technology to precisely meter and distribute irrigation water and fertilizer to field crops. This would allow farmers to apply the right amounts of water and nutrients (not too much or too little) at the right time to maximize economic returns and reduce nutrient loss. If made affordable, precision application systems for irrigation and fertilizers, calibrated to local crop type and soil conditions, could be a very effective way to increase agricultural yields, while also reducing negative impacts on the environment.

2 A very low-cost scalable technique for desalinating brackish water

Desalination is increasingly used to provide household and industrial water in regions with scarce freshwater but abundant salt water. Most current desalination facilities use seawater as feedwater and are powered by fossil fuels. Seawater desalination technologies based on membranes, such as reverse osmosis, are approaching the thermodynamic limits of efficiency and have limited opportunity for further improvement. In contrast, there are large potential efficiency gains by using brackish water as feed. There are major opportunities for significant reductions in brackish water desalination cost and energy use through innovative electrochemical or other emerging techniques. Beyond households and industries, the introduction of very low-cost, high-efficiency desalination of brackish water resources could enable sustainable irrigation in vast regions of the world, and enhance resilience in areas facing aquifer salinization.

3 Network of low-cost distributed monitoring sensors to measure and map air and water quality

Detection of environmental pollutants currently requires costly equipment and elaborate sampling protocols, and provides only isolated snapshots of individual places, times and contaminants. To fully understand and solve the problem of environmental pollution of air and water, a more fine-grained knowledge of exposure is required. There is an urgent need for the development and widespread deployment of sensors that detect the levels of the most significant pollutants affecting the air and water, and transmit that information to a platform where it is validated and publicly displayed. Sensors will need to identify and measure a broad range of pollutants. Key air contaminants to be measured include particulate matter, ozone and carbon monoxide, while essential water contaminants include *E. coli*, salinity and arsenic. Though challenging, there is an important and growing need to measure diverse chemical toxins from sources including industry, vehicles and agriculture.

4 Sustainable, affordable, household-level fecal waste management system

A large share of the population in rural and peri-urban areas of many low-income countries lacks access to household toilets, and many others use substandard toilets. This poses serious health risks in the form of diarrheal and other diseases. An effective household sanitation system must provide an initial hygienic separation of the fecal waste, as well as prevent opportunities for secondary exposure to the fecal pathogens such as surface and groundwater contamination. Ultimately, the fecal waste must be made harmless and definitively disposed of. A wide range of on-site sanitation technologies have been developed, including pit latrines, pour-flush pit toilets with septic tanks and leach pits, vermicomposting toilets, dry composting toilets, and anaerobic reactor toilets. However, existing on-site sanitation methods fall short of completely containing and processing the wastes. Despite our long experience accumulated with sanitation practices, there is a large gap for a sustainable, affordable, decentralized, on-site sanitation solution for low-income households.

5 Medium- to large-scale sewage treatment process with recovery of water (and ideally nutrients and energy)

Raw sewage discharged into water bodies is causing enormous health problems for downstream populations, and the organic and nutrient loading has adverse environmental impacts. The quantities of wastewater generated in major cities are enormous, thus reusing this water for other purposes is a major lever for enhancing water security. Reusing wastewater brings two important benefits: less pollution entering water bodies, and less need for freshwater withdrawals. To enable massive scale-up, novel sewage treatment technologies should be net sources of resources, rather than sinks. Integrated sewage treatment allows the harvest of renewable sources of water, energy or nutrients while disposing of a waste product. There is a great need for a low-cost, sustainable and scalable sewage management process for deployment in fast-growing cities in developing regions. The most appropriate method of treatment for wastewater will depend largely on the intended use of the recycled wastewater and the scale of the treatment facility.

6 Low cost drilling technologies for shallow groundwater, which reduce the cost to less than $100 per farmer

Less than 5 percent of farmland in sub-Saharan Africa is irrigated, despite the presence of extensive, renewable, shallow groundwater. An important reason for this lack of irrigation is the relatively high cost of well drilling in the region. Current well drilling technologies suffer from high cost, limited portability, slow drilling rate or limited geologic suitability. To expand irrigation opportunities to rural populations facing economic water scarcity, a drilling technology is needed that combines the speed and capability of powered equipment with the portability and low cost of manual techniques. It should be comprised of lightweight, easily transportable components, yet powered by a portable mechanized source. An affordable method to reach shallow groundwater will enable widespread irrigation in sub-Saharan Africa, providing smallholder farmers with increased crop yields, the possibility of cultivating during dry seasons and droughts, and the opportunity to grow high-value nutritious crops. As with other irrigation solutions, it will be important to ensure that groundwater is used sustainably.

7 Affordable (less than $50), lightweight, energy-efficient, solar-powered irrigation pumps

Currently available manual irrigation pumps are expensive and strenuous to use, especially for women farmers. Motorized pumps available on the market are even more expensive, and the cost hurdle is compounded by the recurring cost of diesel fuel. A solar powered pump that costs under $50, and pumps enough water for a typical smallholder farm, could dramatically increase access to irrigation. Direct-drive photovoltaic solar pumping can be quite efficient, as all harvested power is used for pumping and there is no need for batteries and associated losses. Nevertheless, a significant barrier to the scale-up of PV-powered irrigation pumps is the high upfront cost of PV systems, which are typically 10 times that of conventional pumps. Despite the very low operating costs of solar irrigation pumps, the high capital cost leads to untenably-long economic payback times. Strongly reducing cost, while ensuring reliable service, is thus essential. It will be important to ensure that groundwater is used sustainably, since there is zero marginal cost for additional water pumping.

8 New processes of nitrogen fixation that are less capital intensive than current (Haber-Bosch) processes

Fertilizer factories that use the Haber-Bosch process, the only known scalable process for synthetic nitrogen fixation, cost hundreds of millions of dollars to build, and must be located near a source of natural gas. As a result, there are no fertilizer manufacturing plants in sub-Saharan Africa (outside of South Africa), and this creates a cost burden for African farmers who must buy fertilizer from international sources. An ideal alternative for nitrogen fixation will be significantly less capital-intensive, less energy-intensive, and will not require close proximity to sources of natural gas or other extractive resources. The technology solution may be biological or electrochemical or some yet-undiscovered method. Enabling nitrogen fixation closer to farms, or even on farms, will reduce or eliminate fertilizer transport costs and enable widespread sustainable intensification of agriculture in sub-Saharan Africa.

9 A low-cost, point-of-use device to evaluate soil nutrient content and recommend tailored use of fertilizers for specific crops

Understanding exactly which type of fertilizer is needed, how much should be applied and at what stage of the plant's lifecycle, is critical for optimizing crop yields and maximizing returns on the farmers' investment. A low-cost device, with a simple user interface, for rapid chemical analysis of the soil—tailored to the crop, underlying soil type, season and plant lifecycle—can prove extremely helpful in improving nutrient uptake, yield, and eventually demand for fertilizer. Importantly, more precise knowledge of soil nutrient status would help avoid the problem of over-application of fertilizers. This would improve the economics of farming, and would also greatly reduce nutrient runoff which would protect watersheds and populations downstream from farm fields.

10 New generation of affordable herbicides that are specific to most destructive weeds and are safe for humans

Weeds are a major cause of low farm productivity in both sub-Saharan Africa and South Asia. By aggressively competing with crops for soil nutrients and water, weeds can cause losses of up to 30 percent. Herbicides are the most widely used method of dealing with weeds in industrialized markets, but currently are too expensive for smallholder farmers in developing countries, and usually make economic sense only for high-value cash crops. Furthermore, most herbicides are non-specific, in that they can damage the crops in addition to the weeds. Novel herbicides are needed that specifically attack the most destructive weeds in smallholder fields, but are harmless to the crops. Such herbicides must be more environmentally friendly than herbicides currently available in most markets, and be safe for human health.

11 Novel, low-cost, environmentally friendly pest control mechanisms (chemical or spatial), specifically targeting the most destructive insectst

Insects and other pests reduce yields by up to 15 percent for smallholder farmers in Africa. While crop damage is caused by numerous pests, a small number—borers, mealybugs, mites—cause a disproportionate share of these losses. A new type of pest control method is needed, specific to the most destructive pests and without negative effects on humans and the broader environment. A low-cost spatial repellent that irritates pests (for example, based on particular sound frequencies) could be an effective and sustainable mechanism to protect crops. Alternatively, a chemical-based pesticide would ideally be made from locally (or regionally) available agro-ingredients, to help catalyze the development of a large number of less capital-intensive production facilities closer to the market.

12 Affordable (less than $50) off-grid refrigeration for smallholder farmers and small agribusinesses

The absence of affordable refrigeration and electricity severely limits the ability of smallholder farmers to produce, preserve and sell perishable commodities like vegetables, fruits, meat and dairy. While there are some inexpensive refrigerators available in emerging markets, they still cost more than $100, need reliable electricity and are difficult to repair once damaged. To serve the needs of rural, low-income farmers, refrigerators need to be operable off-grid (like solar-powered), considerably less expensive than the current versions, and easy to repair. Such technologies appear to be on the horizon, as a new generation of refrigerators using thermoelectric technology is on the market, supplementing existing vapor-compression models. Nevertheless, current costs are too high for mass adoption in low-income countries. A new kind of refrigerator that costs less than $50 and can run on solar power will help smallholder farmers provide better nutrition for their families, and take high-value commodities to market, thereby increasing their incomes.

13 Commercial scale, affordable and energy efficient refrigeration/cold-chain systems for agribusinesses and transport of food

The ability to transport food to markets while preserving its freshness will help farmers increase their incomes from higher-value produce like vegetables, fruit, meat, and dairy products. Currently, the absence of refrigerated cold-chain infrastructure, including storage and transportation, is one of the factors contributing to the lack of a market for such commodities. Refrigerated trucks and cold rooms available on the market today are unaffordable for small agribusiness entrepreneurs, and are generally inappropriate for conditions of unpaved roads and erratic electricity supply found in low-income countries. In order to be useful in sub-Saharan Africa, refrigerated cold chain equipment must be built for unpaved, remote terrain, and cost less than $5,000.

14 An affordable and portable toolkit for extension workers, which includes a core set of devices for testing crop health, livestock health and quality of produce

Extension agents can provide valuable training for farmers, helping them optimize yield and improve product quality. However, most extension agents do not have the tools to perform many of the services farmers need. An ideal extension worker toolkit should help them test soil and produce quality, identify pests and pathogens, advise on irrigation and other on-farm equipment, and show videos or other instructional material to farmers. A similar toolkit for veterinarians and livestock extension agents, including point-of-care diagnostics for major diseases, a vaccine cooler, and other tools to provide on-farm care for animals, could significantly improve the health and productivity of livestock.

15 A low-cost mechanism to preserve animal semen (including new methods to produce liquid nitrogen or alternatives to liquid nitrogen)

Artificial insemination is an effective mechanism for breeding cattle and other animals, leading to significant improvements in livestock health and productivity. Preservation and transport of animal semen requires extremely low (sub 100 degree Celsius) temperatures, currently achieved only with liquid nitrogen. Nitrogen liquefaction is very energy-intensive and expensive, yet there is no other proven mechanism to preserve a particularly thermosensitive substance like animal semen. A new mechanism to preserve and transport animal semen that avoids the costs associated with producing liquid nitrogen could lead to a greater adoption of artificial insemination in Africa. This, in turn, can lead to major improvements in livestock health and farmer incomes.

16 Alternative meat production system that is affordable, desirable and environmentally sustainable

Large scale meat production is resulting in deforestation, polluted waterways and a host of other adverse environmental effects. Alternative meat products are potentially healthier and more efficient alternative to conventional meat, with lower use of land, water and agricultural inputs. One production approach, often called substitute meat or meat analog, involves the conversion of non-animal biomass to have the characteristics of actual meat. Another approach, often called cultured meat, cellular meat or in-vitro meat, involves the managed growth of actual animal cells. An affordable, sustainable alternative meat production system could satisfy our population's growing meat demand with reduced environmental impacts and potentially increased nutritional value.

17 New seed varieties that are tolerant to drought, heat, salinity and/or other emerging environmental stresses (ideally using cis-genetic modification)

Agriculture will face numerous stressors during the coming decades, such as droughts due to climate change, salinization of farmland and groundwater, and basin-level limits to water supply. Conventional plant breeding techniques are hard-pressed to develop crop varieties to accommodate such rapid changes. Genome editing techniques such as CRISPR/Cas9 have the potential to create a new generation of crop varieties with tolerance to worsening conditions of drought, heat and salinity. This type of cisgenic editing is proving to be less controversial than transgenic modification, because the edited organisms could, in principle, have been created through conventional breeding. Just as new seed varieties were critical to the Green Revolution in Asia and Latin America, new varieties of seeds for essential crops (like maize, rice and wheat) that are tolerant to drought, heat, salinity and other emerging environmental stresses will be necessary for agricultural development and food security in the near future.

18 Smart electronic textbooks that dynamically adapt content for different skill levels, languages and other user specific needs

Education for low-income students is fundamentally constrained by the absence of qualified teachers and adequate instructional tools. Smart electronic textbooks with well-designed applications can be a powerful way to compensate for systemic gaps in infrastructure, human capital and policy. As smartphones and tablets become increasingly affordable and feature-rich, and as more of the world gets connected to the Internet, there is a tremendous opportunity to leapfrog current education methods, and create new models of content development, content delivery and instruction. Grade-specific smart electronic textbooks will require curated and up-to-date content, 'wiki' interfaces for vernacular and other locally relevant and gender-inclusive material, visual and dynamic learning tools for students, interfaces and tools for teachers, student-teacher interaction and peer-to-peer collaboration.

19 Affordable healthy homes that are resilient to extreme weather events

The majority of the poor—particularly in urban areas—live in densely packed shacks made with found material, which have very limited light or ventilation, and no running water or sanitation. The increased frequency and intensity of extreme weather events is putting vulnerable communities at greater risk of losing their homes. A breakthrough is needed to develop a functional and very low-cost housing system accessible to the global poor that is resilient to extreme weather events. Improved materials together with improved architectural design are required for robust, affordable, healthy housing that is environmentally and culturally compatible, and can scale-up to meet global demand. Improving living conditions by reinventing the home for the poor can significantly improve quality of life in low-income countries.

20 A simple point-of-use, low-cost DNA-based rape kit capable of delivering rapid results

One key hurdle in holding accountable the perpetrators of sexual violence is a lack of physical evidence, which enables societal and interpersonal power dynamics to rule. Rape kits are becoming increasingly common in higher income countries, that conduct DNA analysis of biological samples to match against potential perpetrators. However, they require skilled technicians and a sophisticated, expensive laboratory. To be useful in low resource or conflict settings, a rape kit is needed that is very low cost, usable off-grid and does not require much clinical training to use. In addition, the analysis should be rapid, with the ability to digitize and transmit relevant data for secure (presumably cloud-based) storage. While such a device can greatly support progressive legal efforts, its actual utility would depend critically on actions of the broader judicial systems.

21 Low cost (less than $50) wearable, or otherwise easily concealable, cameras with automatic geocoding and timestamps, capable of SOS data preservation (such as via satellite)

The rapid proliferation and falling cost of digital cameras, especially those integrated into mobile phones, has dramatically increased the number of human rights violations that are documented. This unprecedented level of transparency has made perpetrators more likely to face justice, and would-be perpetrators more wary. Cameras that are more inconspicuous and affordable, and equipped with geocoding and timestamp metadata on the time and place where the images are captured, will likely lead to greater levels of documentation of human rights violations. A particularly valuable feature for a wearable miniature camera would be the capability to preserve data (for example, via one-time SOS satellite uplink), especially in a situation where the data may otherwise be destroyed. Note that such technologies will cause legitimate privacy concerns.

22 Low-cost aerial vehicles to capture high-resolution imagery for use by civil society groups, to document large-scale human rights violationst

Many large-scale human rights violations occur in the open, partly because perpetrators have no fear of accountability. In recent years, satellites are being increasingly used to document large-scale destruction of habitats such as villages and forests. However, continuous coverage of at-risk locations requires satellite data that is currently not accessible to civil society groups; and neither is the imagery of high enough resolution to be actionable. Low cost (under $100,000) satellites are now being developed, and may make focused monitoring and documenting of violations more feasible. In addition, very inexpensive drones—increasingly available today—can be a valuable tool for collecting detailed imagery. However, drones are typically deployable over a specific location only after an incidence has taken place, and therefore more likely to be useful in contexts where there are recurring violations.

23 Vaccines that can effectively control and eventually help eradicate the major infectious diseases of our time—HIV/AIDS, malaria, tuberculosis and pneumococcus

Collectively, HIV/AIDS, malaria, tuberculosis and pneumonia kill more than five million people a year, and represent a significant disease burden for low income populations in sub-Saharan Africa and South Asia. Effective and affordable vaccines for these diseases do not exist yet due to the intrinsic complexity of the pathogens causing them, and a lack of understanding of the specific mechanisms through which our immune systems protect against these diseases. The process of vaccine development—basic research on disease etiology, vaccine construction, pre-clinical and clinical testing—is technically challenging, expensive and time consuming.

24 Microbicides to provide a method of protection for those who are otherwise vulnerable to HIV/AIDS infection by their partner

Women are often limited in their ability to ensure that their sexual partners use condoms, particularly in places with high rates of sexual violence and prevalence of polygamy. Specific high-risk populations, like sex workers and transgender people, also find themselves restricted in their ability to use protection during sexual contact. Vaginal or rectal microbicides, if effective, can be a viable alternative to condoms for controlling the spread of HIV/AIDS and other sexually transmitted diseases. Ideally, microbicides would be discreet, easy to use, long-lasting and easy to distribute.

25 PrEP (pre-exposure prophylaxis) to reduce the risk of HIV infection

PrEP involves the use of antiretroviral therapy (ART) by those at a high risk for HIV infection to reduce the possibility of contracting the disease. Although it is included as a preventive strategy in WHO HIV prevention guidelines for high-risk populations, access and adherence to PrEP is challenging for certain populations. Newer formulations and different delivery methods, such as a long-acting injectable PrEP or implants, can improve adherence. In addition to the currently available Truvada, a large number of antiretroviral-based preventive products are now in the pipeline, mostly in the pre-clinical stage. Next-generation strategies will use longer-acting drugs, focusing on delivery methods that are not widely used for HIV treatment. However, despite early encouraging signs, gaps remain in understanding the safety, effectiveness, and long-term implications of the emerging suite of PrEP drugs.

26 Improved, longer-lasting antiretroviral therapy (ART) formulations to control HIV viral replication and increase patient adherence

While access to antiretroviral therapy (ART) is improving globally, children and those living in rural areas with poor infrastructure are still particularly disadvantaged due to the demands of the treatment and associated costs and constraints. Reformulation of current ART drugs can improve ease of use, and in turn access, especially for neglected populations. Improved and more effective drugs with simplified treatment regimens (like single fixed-dose pill or easy to administer pediatric formulations) and reduced toxicity can help prevent treatment interruption and increase patient adherence. Long-acting ARTs can go a step further by helping reduce overall treatment costs. These improved treatments should be low cost, remain stable in high heat and humidity, require few supportive technologies to deliver the treatment, and offer improved safety profiles to allow use with minimal medical supervision.

27 Shorter course treatments for both drug-sensitive TB and MDR-TB

Many challenges related to controlling TB are a function of long and demanding treatment regimens. Currently, treating drug-sensitive TB with the typical cocktail of antibiotics takes more than 6 months. Drug regimens for drug-resistant TB sometimes exceeds two years. In addition, some current drugs are not easily co-administered with antiretrovirals for patients with TB-HIV co-infection. These drug challenges lead to high rates of non-compliance, expensive delivery systems to provide treatment responsibly, and the growth of drug-resistant TB. New drugs that can treat drug-sensitive TB over the course of weeks as opposed to months and years, will dramatically alleviate many of the challenges of controlling TB. A short course drug can significantly increase treatment adherence, and therefore also reduce the spread of drug-resistant TB.

28 New generation of antibiotics capable of treating fast-mutating bacteria like MTB and MSRA

Antibiotic resistance is reaching dangerously high levels in all parts of the world, with some of the most common infections now becoming difficult to treat. This occurs when bacteria develop the ability to defeat the drugs that are designed to kill them, making the drugs ineffective. Each year, hundreds of thousands of people die from drug-resistant strains of common bacterial infections, and the number is increasing steadily. Antibiotic resistance is a complex problem that is driven by many interconnected factors, and coordinated effort is required to minimize its emergence and spread. Action on numerous fronts is needed, though there is a critical need for a new generation of antibiotics that are effective against the bacteria that are resistant to current drugs. While there are some new antibiotics in development, none of them are expected to be effective against the most dangerous forms of resistant bacteria.

29 A single-dose complete cure for malaria

The majority of safe medications for malaria target the blood stage of the parasite, but not other stages of the parasite lifecycle such as the gametocyte stage. The persistence of the gametocytes following treatment creates a human reservoir of parasites, which remain viable for years in an otherwise asymptomatic and healthy person. While this does not cause disease directly, it does pose challenges for malaria control and elimination. A single-dose complete cure to eliminate all malaria parasites in the human body—both blood stage and liver stage and both sexual and asexual—would represent a significant breakthrough in malaria control.

30 New long-lasting spatial mosquito repellents or attractants (chemical and non-chemical) for vector control

There are great opportunities for novel spatial mosquito repellents or attractants for vector control and improved health. Breakthroughs may be chemical-based or non-chemical, such as sound-based. It is unlikely that existing chemicals will provide sustained control while limiting the development of resistance. New classes of long-lasting chemical repellents are required and need to be delivered through novel mechanisms that are easy to use and adopt. Delivery strategies must provide community-level protection. Control methods should be optimized for the most lethal African vectors—*Anopheles gambiae*, *A. arabiensis* and *A. funestus*—but will ideally be effective across all primary and secondary vector species. To be effective, the control method will need to be considered in the broader context of the community and ecosystem, not just the individual household.

31 Integrated suite of digitally enabled primary care devices including point-of-care diagnostics, therapeutic devices and clinical operations

Currently, equipping a clinic to provide basic primary healthcare would cost in excess of $100,000, which is clearly too expensive for low-income populations in the absence of adequate public funding. In addition, essential medical devices are often difficult to install, complicated to use, and expensive to maintain. A digitally-integrated suite of devices for primary care is needed, that includes point of care diagnostic devices for basic blood, urine and vitals tests. It would also include therapeutic devices for common conditions, for example, warming, phototherapy and oxygen concentration devices. It would also support clinical operations, such as sterilization devices and refrigeration for thermo-sensitive pharmaceuticals. A power management system would be integrated, including renewable energy supply where appropriate. A patient and clinic management platform is at the core, and needs to be built using a provider and patient-centered design approach.

32 Low cost, novel diagnostics for pneumonia

While the gold standard for diagnosis is through a chest X-ray, it is too costly for low- and middle-income countries, thus pneumonia is currently diagnosed by a clinic consultation of symptoms. This makes it difficult for care providers to identify whether a patient has viral or bacterial pneumonia or quickly determine the infecting pathogen, which could help indicate the potential severity of the illness. While a urine-based diagnostic for pneumococcus bacteria is now available, a diagnostic that can discriminate between bacterial and viral pneumonia, and severe and non-severe pneumonia, is more technologically complex. Accurate diagnostics will lead to improved patient outcomes, reduced medicine wastage, and lower risk of antimicrobial resistance.

33 Low cost, off-grid oxygen concentrators

Oxygen therapy is a valuable intervention for treating patients with severe pneumonia, but is seldom used in developing countries, especially in rural areas. While various types of oxygen concentrators are available in industrialized countries, these are expensive (over $1,000), require reliable power, regular maintenance, and significant training for users. The oxygen concentrator needs to be redesigned to be less expensive, robust, easy to maintain, and not dependent on grid power. An ideal system should include oximetry as part of the system.

34 Automated multiplex immunoassays that can test for a broader range of diseases (compared to the current state) and are compatible with easily collected sample types

Currently, a patient presenting a particular symptom, for example fever, needs to be tested for the range of conditions that could cause the symptom—each with its own diagnostic—until a positive result is achieved. Most rural clinics serving low income patients do not have the necessary diagnostics available to test the full range of conditions linked to specific symptoms. As a result, some conditions are misdiagnosed, often resulting in inappropriate treatment. One common problem is presumptive treatment, which happens often in the case of malaria where the disease is endemic. Instead of being tested for the actual febrile illnesses they have, patients are simply treated for malaria. Point-of-care immunoassays that can use different types of samples (like saliva, whole blood, urine), and test for multiple biomarkers from a single patient sample, represent a major breakthrough in diagnosis and patient care.

35 Point-of-care nucleic acid test (NAT) that is simple, robust, and compatible with easily collected sample types

Nucleic acid tests (NATs) are a highly reliable method of detecting the presence of pathogens in a patient, by detecting the presence of the pathogen's genetic material (DNA or RNA). This method can be used to accurately quantify the level of infection, identify pathogen strains, and determine drug resistance profiles, which is essential for diagnosing and treating diseases like TB and HIV. Currently, NATs are expensive and complex, and require trained laboratory technicians. They are mainly used in hospitals and centralized laboratories. Low cost point-of-care NATs represent a major breakthrough in disease detection. These tests should be compatible with simple sample types (such as whole blood), rapid, user-friendly for minimally trained technicians, robust (despite high heat and humidity), and not reliant on refrigeration, running water or stable electricity.

36 Affordable, home-use point-of-care diagnostics suite (blood, urine, vitals) for the common NCDs

Point-of-care testing is essential in low- and middle-income-countries given the paucity of trained care-providers and lack of access to quality healthcare services. Lately, there has been a move towards integrating tests with mobile applications due to ease of data capture, better user experience and wider adoption of smartphones. These include both standalone mobile health applications and more integrated testing applications. Many of these technologies have already been developed and commercialized in developed economies but are yet to find adoption and successful commercial models for widespread adoption in developing economies. Low-cost point-of-care devices for the common NCDs that take advantage of recent developments in biosensors, lateral flow tests, and integrated or lab-on-a-chip technologies will be a crucial link to ensuring essential healthcare services for all.

37 Affordable wearable technology with broader functionality for patient adherence and monitoring of health status

Wearable devices (including implantable devices) can be worn by a consumer to capture and track basic health and fitness data. Today most common wearables (like Fitbit and goqii) track heart rate, blood pressure, breathing patterns, physical activity and sleep levels. However, the next set of devices currently at prototype stage aim to be able to collect data on blood glucose, cardiovascular disease risk and even cancer. The data collected can be used to analyze the risk of specific non-communicable diseases by either providers or other healthcare ecosystem players, monitoring at-risk patients and those diagnosed as well as track and improve patient adherence.

38 Low cost off-grid refrigerators for preserving vaccines (and other temperature sensitive pharmaceuticals) in remote settings

Vaccines and some other lifesaving pharmaceuticals are highly temperature sensitive, making it very difficult to administer them in remote, low resource settings. Currently, most rural clinics have neither electricity nor refrigerators, and cannot routinely provide vaccinations. The equipment used for vaccination outreach campaigns in remote areas—insulated boxes with freezer packs—is highly ineffective; many vaccines freeze, others get too warm, and outreach trips are limited to 1 or 2 days. A solar-powered vaccine refrigerator in the $500-$1,000 range will significantly improve the ability of remote clinics to immunize rural populations. A reliable, portable 'passive' cooling mechanism that is considerably less expensive (under $100) and can keep vaccines from either freezing or getting too warm for several days, will also be very helpful.

39 A thermo-stabilizing mechanism for vaccines and other temperature sensitive pharmaceuticals

Many vaccines are thermosensitive, and need to stay between 2 and 8 degrees Celsius continuously, from the point of manufacture to the point of administration. While a new generation of low-cost refrigeration technologies can make progress on vaccine preservation, the long-term solution is to obviate the need for refrigeration altogether. This can be done by making the pharmaceuticals thermostable, through stabilizing additives, novel molecular formulations, or other means. While a number of promising technologies are in the early stages of development, none has been extensively field tested, or proven applicable to the full set of essential vaccines.

40 A new generation of wireless broadband network technologies that radically cut the cost of expanding coverage to rural areas

Even as the penetration of mobile phones, tablets and other computing devices increases, their usefulness depends on the availability of broadband connections. Expanding access to rural areas is challenging—populations are less dense, further from main networks, and have lower purchasing power. Instead of the traditional network infrastructure used for broadband connectivity (meaning, blanket coverage with many adjacent cells each supported by a base station), a new set of network technologies is required. This could include low/medium altitude satellites, other aerial devices, and innovative use of unused portions of the radio frequency spectrum.

41 Affordable (less than $50) smartphones that support full-fledged internet services and need limited electricity to charge

The recent penetration of mobile phones across the broader developing world has been nothing short of dramatic. However, there remains a pronounced discrepancy in access to, and use of, communications technology between industrialized and developing countries. Most low-income people, if they have a phone at all, use basic phones which do not offer advanced functionality beyond voice and SMS text. For true digital inclusion, we believe that smartphones—with their ability to exchange information via a range of modalities (like touchpad, voice-driven control and various ports), and their ability to support a wide array of Internet-based services—are essential. Unfortunately, today's smartphones are too expensive for low-income users.

42 Productized biometric ID systems, linking birth registry, land title registry, financial services, education history, medical history, and other information critical for ICT enabled services

Individuals born in industrialized countries have formal IDs, which are linked to a range of services vital to their wellbeing and empowerment, and are an intrinsic part of their day-to-day lives. ID systems are inadequate in most developing countries, in part due to the absence of the institutional framework necessary for issuing and using IDs for individuals. This is one of the reasons why a majority of citizens in many low-income countries operate in informal economies, cannot assert all the rights they are entitled to, and cannot hold their governments accountable for services. Biometric technologies can enable developing countries to bootstrap ID systems, empowering individuals to assert ownership of land and other assets, have accurate medical, educational and financial histories available to service providers, and truly become part of formal economic structures. Stringent safeguards are required to ensure privacy, and to protect individuals from being targeted by repressive regimes.

43 A standardized, solar mini-grid system that makes it simpler, cheaper and faster to set up and operate mini-grids

Currently, setting up mini-grids in rural areas is time consuming, complex and costly, due to weak and fragmented supply chains, poor roads, a lack of skilled workers, and the absence of integrated components. The solution is a standardized 'utility-in-a-box', a bundled package of mini-grid components that can be easily integrated and installed, and whose parts work seamlessly, making operations simpler. Such a system should include all the essential components of a decentralized renewable energy mini-grid for generation, storage and grid management. Standardization and self-help tools for installation, O&M and troubleshooting will be key. This would make mini-grids much more attractive to both service providers and investors, and significantly reduce barriers to expansion. In short, it would make the business of running rural mini-grids more profitable and less risky.

44 Appliances for household use and income generation that are significantly more affordable and energy-efficient than those on the market

For electricity to have an impact on development and quality of life, users need a range of amenities and services. This requires electrical appliances for reducing manual workloads, physical discomfort and health hazards, and increasing the productivity of income generating activities and enabling digital inclusion. There has been a proliferation of devices such as portable solar powered lights and mobile phone charging kits, but a suite of larger appliances like refrigerators, televisions, fans and irrigation pumps are required to contribute substantially to human development. Nevertheless, even if such appliances were currently affordable, the cost of powering them would exceed the energy budget of low-income users, hence the energy efficiency of the appliances also must be increased significantly. While affordability may be achieved by mass production, energy efficiency will likely be driven by technological advancements.

45 New electricity storage technologies that can be used for decentralized mini-grids, which provide improved performance at a cost approaching that of lead-acid batteries

Bulk storage for backup power and load balancing is crucial for reliable electricity in decentralized mini- grids, especially renewable energy ones, where supply (sun, wind) is intermittent. However, storage technologies that can be applied at mini-grid scale are not commercially available at the desired cost and performance. The current standard—lead acid batteries—is the most affordable, but faces serious performance limitations causing early degradation of battery capacity, especially at high ambient temperatures. Lithium ion batteries present a promising alternative, but even with rapidly declining costs, they are still too expensive for mass adoption in mini-grids. Alternative and emerging battery technologies, like sodium sulfur and flow batteries, are still pre-commercial and need significant cost and performance improvements.

46 Advanced biomass cookstoves that are desirable, affordable, robust and very clean

Household air pollution caused by cooking with fuels like wood, straw and dung causes millions of deaths each year due to respiratory and cardio-vascular diseases. Today, more households currently use solid fuels for cooking than at any time in human history, due to growing population size. A number of cookstove improvements have been made. However, due to the non-linear exposure-response function, substantial reduction in emissions from current improved stoves brings only a modest decrease in health risk. To effectively eliminate associated health risks, emissions must be reduced much further than is possible with current biomass stove designs. In addition to having low pollutant emissions, an effective advanced biomass cookstove must be durable, low-cost and low maintenance. Critically, it must be compatible with traditional foods and cooking styles, and be desired by the users.

47 Novel ways of converting household or village waste products into clean cooking fuel or electricity

Although gas and electricity are clean cooking fuels, their usage remains low in rural due to the high infrastructure cost and logistical challenges. Decentralized production of biogas by means of anaerobic digestion of organic materials such as manure and crop waste is an established practice, but is used by only a small fraction of households. While clean cooking fuel is lacking in rural regions, many areas have abundant organic waste materials such as human waste, animal waste, crop residue or household garbage. A breakthrough is needed in the form of an affordable, robust process to convert diverse organic waste products into clean and reliable gas or electricity for cooking. In principle, this could be achieved by various conversion routes, such as biochemical, thermochemical or electrical. Such a process would not only provide clean cooking fuel, but would safely dispose of waste products and result in cleaner surroundings.

48 A mechanism to remove particulate emission from old trucks and other heavy-duty vehicles

Particulate emission from old heavy-duty vehicles like trucks and buses are a major source of outdoor air pollution in low-income countries. This is due to the large number of operating older vehicles coupled with poor vehicle maintenance, inadequate infrastructure and low fuel quality. Existing heavy-duty fleets are likely to continue operating for many years, due to the inherently slow turnover of vehicle fleets and the limited economic means to obtain cleaner replacements. There is a need for a robust, low-cost device that can be retrofitted onto old heavy-duty diesel vehicles to reduce particulate matter exhaust. This engineered solution must be inexpensively produced—less than $1,000—with simple retrofitting onto existing fleets of trucks and buses.

49 Small-scale waste incinerators with efficient combustion and clean emissions

The challenge of urban waste management remains unmet in many cities in low- and middle-income countries. Mounds of household rubbish often accumulate uncollected, spreading disease vectors and increasing health risks. Facing the lack of centralized waste management, households typically burn their garbage in uncontrolled open-air fires, leading to emission of particulate matter, volatile organic compounds and other toxins, with serious adverse health impacts on residents. An important lever to solve the solid waste problem in low-income cities is well-engineered, appropriately-sized incineration plants that safely combust household waste. Breakthrough designs will be needed to ensure consistently safe air emission levels, even with diverse input materials. Siting of multiple small-scale incineration plants will facilitate collection of waste at local disposal centers. Mobile incinerators moved between collection points may allow higher capacity utilization and improved economics.

50 Low cost (under $500) electric vehicle for family transport

Affordable personal and family transport has been a critical component of improving productivity and quality-of-life for large portions of the global population. Yet, for most of the rural poor, especially women, walking long distances and carrying heavy loads remains a daily reality. While global scaleup of conventional fossil-fueled vehicles is untenable due to climate and air pollution concerns, mass adoption of electric vehicles powered by distributed renewable energy would be a transformative example of sustainable development. Several promising low-cost vehicles (like three-wheeled solar and electric rickshaws) are becoming available in the $500-$1,000 range, although the full system including power charging is currently more expensive.

BREAKTHROUGH HEATMAPS

Beyond the list of breakthroughs, there are a number of important questions that warrant discussion: Are there any quick wins? Which breakthroughs have the most difficult path to impact? Which of these are commercially attractive for profit-seeking businesses, and which are important public goods without commercial prospects? What are the most appropriate funding mechanisms for these breakthroughs? How can various governments, funders and other institutions shape their agendas to enable the realization of these breakthroughs?

Some of these issues are discussed below and others will need to be part of the ongoing conversation this study hopes to spur. To that end, the following groupings—matrices—of the breakthroughs may be helpful.

Matrix A: 50 Breakthroughs funding model assessment

Matrix A analyzes the funding models appropriate to each of the breakthroughs, based on their commercial attractiveness. The vertical axis shows the projected time to market, as a proxy for the breakthrough's technical difficulty and the amount of funds required. Along the horizontal axis, it groups them into four categories.

- Some technologies (left column, red color) can have significant social impact, but will not (and should not) earn profits. The only mechanism for these technologies to materialize is through grant funding.

- In many cases, technologies and products will (and should) be commercially sustainable in the long run, but the seed R&D capital may not be recouped. These are ideal for early-stage grants to lay the platform. These are identified in the second column from the left, in orange color.

- Some of the identified technologies will have an attractive market in developing countries (third column, yellow color). However, the profits will not be attractive enough for investors motivated to maximize commercial returns. These represent very promising investments for funders focused on profitable ventures in emerging markets. Philanthropic grant capital may not be appropriate for these technologies, because such funding often does not require adequate rigor on sustainable deployment models.

- Technologies that have attractive commercial prospects in industrialized markets, as well as in developing country markets (right column, green color). In all likelihood, there are ongoing investments to take advantage of these commercial opportunities. This space represents fertile territory for funders seeking to invest in a true 'double-bottom-line'.

Matrix A: 50 Breakthroughs funding model assessment

Likely time to market (years) as proxy for technical difficulty and required funding × Commercial potential

Likely time to market (years)	Non-commercial (unprofitable)	Potentially attractive for emerging markets, but requires derisking (sustainable)	Attractive for emerging markets (lower profits)	Attractive for industrialized markets (high profits)
>10	**20.** Rapid and simple DNA-based rape kit	**8.** New nitrogen fixation process **15.** Animal semen preservation method **23.** Vaccines for major infectious diseases **27.** Shorter course treatments for TB **29.** Single-dose complete malaria cure		
7-10	**3.** Sensors for air and water quality	**1.** Precision irrigation and fertilization **2.** Brackish water desalination **11.** Insect pest control method **19.** Affordable and resilient homes **24.** Microbicides against HIV/AIDS **30.** Mosquito repellents or attractants **33.** Off-grid oxygen concentrators **34.** Automated multiplex immunoassays **35.** Point-of-care nucleic acid test **46.** Advanced biomass cookstoves **47.** Converting waste to clean cooking fuel **49.** Small scale waste incinerators	**13.** Cold-chain system for agribusiness **48.** Particulate removal from old trucks	**26.** Improved antiretroviral therapy **28.** New generation of anitbacterials **39.** Thermo-stabilization for vaccines
4-6		**9.** Soil nutrient analysis kit **10.** Safe and effective herbicides **14.** Agriculture extension toolkit **17.** Stress tolerant seed varieties **32.** Low cost diagnostics for pneumonia **38.** Off-grid vaccine refridgerator	**7.** Solar-powered irrigation pump **12.** Small off-grid refridgerator **50.** Low cost electric transport vehicle	**36.** Home-use diagnostics for NCDs **37.** Wearable health technology
0-3	**42.** Productized biometric ID systems		**40.** Expanded wireless broadband network	**18.** Smart electronic textbooks **21.** Cameras with data preservation
In market		**4.** On-site household sanitation solution **5.** Sewage treatment and water reuse **31.** Digitally-enabled primary care devices	**6.** Shallow groundwater drilling **41.** Affordable full-featured smartphones **43.** Standardized solar mini-grid system **44.** Affordable and efficient appliances	**16.** Alternative meat production **22.** Low-cost aerial platform for imagery **25.** PrEP (pre-exposure prophylaxis) **45.** Electricity storage technologies

Commercial potential

Matrix B: 50 Breakthroughs technical and deployment challenges

Matrix B assesses the challenge landscape of the breakthroughs, comparing their technical and deployment difficulties. The vertical axis again shows the projected time to market, as a proxy for the breakthrough's technical difficulty and the amount of funds required. The horizontal axis shows the difficulty of deployment of the breakthroughs once they are market ready. Based on this analysis, there are four categories.

- The relative quick wins (bottom-left of the matrix, in green color), which are market-ready or appear to be on the horizon from a technical point-of-view, with relatively achievable deployment models. It is important to note that categorizing a breakthrough as a quick win does not mean that it is guaranteed to happen. It simply suggests that anyone wishing to invest effort or funds into a problem with a likelihood of relatively quick results should consider this set of issues.

- Problems that have significant technical hurdles (top left of the matrix, in yellow color), but with seemingly surmountable deployment challenges. In such cases, once the technology problems are solved, there is a good chance that they will lead to impact.

- Problems with market-ready or seemingly imminent technical solutions (bottom right of the matrix, in orange color), but with significant barriers to deployment. The biggest risk facing current projects attempting to address these issues, is that there will be excessive focus on the technical solution without an appreciation of the deployment challenges.

- Issues that face major hurdles on both the technological and deployment fronts (top-right of the matrix, in red color). These represent the most difficult challenges in the technology-for-development space. For those investing in technologies to address these issues, it is important to be equally demanding of solutions to deployment hurdles.

Matrix B: 50 Breakthroughs technical and deployment challenges

Likely time to market (years) as proxy for technical difficulty and required funding / **Difficulty of deployment**

Likely time to market (years)	Feasible	Complex	Challenging	Extremely Challenging
>10	**23.** Vaccines for major infectious diseases **27.** Shorter course treatments for TB **29.** Single-dose complete malaria cure			**8.** New nitrogen fixation process **15.** Animal semen preservation method **20.** Rapid and simple DNA based rape kit
7-10	**26.** Improved antiretorviral therapy **28.** New generation of anitbacterials **39.** Thermo-stabilization for vaccines	**2.** Brackish water desalination **3.** Sensors for air and water quality **19.** Affordable and resilient homes	**1.** Precision irrigation and fertilization **24.** Microbicides against HIV/AIDS **30.** Mosquito repellents or attractants **33.** Off-grid oxygen concentrators **46.** Advanced biomass cookstoves **47.** Converting waste to clean cooking fuel **48.** Particulate removal from old trucks **49.** Small scale waste incinerators	**11.** Insect pest control method **13.** Cold-chain system for agribusiness **34.** Automated multiplex immunoassays **35.** Point-of-care nucleic acid test
4-6		**7.** Solar-powered irrigation pump **14.** Agriculture extension toolkit **36.** Home-use diagnostics for NCDs **37.** Wearable health technology **50.** Low cost electric transport vehicle	**9.** Soil nutrient analysis kit **12.** Small off-grid refridgerator **17.** Stress tolerant seed varieties **32.** Low cost diagnostics for pneumonia **38.** Off-grid vaccine refridgerator	**10.** Safe and effective herbicides
0-3		**21.** Cameras with data preservation	**18.** Smart electronic textbooks **40.** Expanded wireless broadband network **42.** Productized biometric ID systems	
In market	**41.** Affordable full featured smartphones	**25.** PrEP (pre-exposure prophylaxis) **43.** Standardized solar mini-grid system **44.** Affordable and efficient appliances **45.** Electricity storage technologies	**4.** On-site household sanitation solution **5.** Sewage treatment and water reuse **6.** Shallow groundwater drilling **16.** Alternative meat production **22.** Low-cost aerial platform for imagery	**31.** Digitally-enabled primary care devices

- Green: Potential quick wins
- Yellow: Primarily technology challenges
- Orange: Breakthroughs appear imminent; innovative business models need to be developed
- Red: The most difficult challenges; very complex technologies and daunting deployment hurdles

Matrix C: Development Stage of the 50 Breakthroughs

Matrix C shows the current development stage of each breakthrough. Some of the breakthroughs are at the initial research and development stage, where foundational work is still required. Other breakthroughs are at the engineering and prototype stage, building on earlier discoveries and developing viable products.

Some breakthrough technologies are now market ready, but with small production levels and tenuous presence. Few of the breakthroughs have achieved large-scale presence in the market.

Matrix C: Development Stage of the 50 Breakthroughs

Matrix D: 50 Breakthroughs and the Sustainable Development Goals

Matrix D maps the 50 breakthroughs to the 17 Sustainable Development Goals, showing the most relevant associations.

Breakthrough	1. No poverty	2. No hunger	3. Good health	4. Education	5. Gender equality	6. Water and sanitation	7. Energy	8. Jobs and growth	9. Industry and infrastructure	10. Reduce inequality	11. Sustainable cities	12. Responsible consumption	13. Climate action	14. Life below water	15. Life on land	16. Peace and justice	17. Partnerships
1. Precision irrigation and fertilization		■						■									
2. Brackish water desalination		■				■											
3. Sensors for air and water quality			■			■											
4. On-site household sanitation solution			■		■	■											
5. Sewage treatment and water reuse			■			■								■			
6. Shallow groundwater drilling		■				■											
7. Solar-powered irrigation pump		■				■											
8. New nitrogen fixation process		■										■					
9. Soil nutrient analysis kit		■										■					
10. Safe and effective herbicides		■										■					
11. Insect pest control method		■										■					
12. Small off-grid refrigerator		■						■									
13. Cold-chain system for agribusiness		■						■									
14. Agriculture extension toolkit		■						■									
15. Animal semen preservation method		■							■								
16. Alternative meat production		■										■					
17. Stress tolerant seed varieties		■											■				
18. Smart electronic textbooks				■						■							
19. Affordable and resilient homes			■								■						
20. Rapid and simple DNA-based rape kit			■		■												
21. Cameras with data preservation					■											■	
22. Low-cost aerial platform for imagery																■	
23. Vaccines for major infectious diseases			■														
24. Microbicides against HIV/AIDS			■		■												

Matrix D: 50 Breakthroughs and the Sustainable Development Goals

Breakthrough	1. No poverty	2. No hunger	3. Good health	4. Education	5. Gender equality	6. Water and sanitation	7. Energy	8. Jobs and growth	9. Industry and infrastructure	10. Reduce inequality	11. Sustainable cities	12. Responsible consumption	13. Climate action	14. Life below water	15. Life on land	16. Peace and justice	17. Partnerships
25. PrEP (pre-exposure prophylaxis)			■														
26. Improved antiretroviral therapy			■														
27. Shorter course treatments for TB			■														
28. New generation of antibacterials			■														
29. Single-dose complete malaria cure			■														
30. Mosquito repellents or attractants			■														
31. Digitally-enabled primary care devices			■														
32. Low cost diagnostics for pneumonia			■														
33. Off-grid oxygen concentrators			■							■							
34. Automated multiplex immunoassays			■														
35. Point-of-care nucleic acid test			■														
36. Home-use diagnostics for NCDs			■														
37. Wearable health technology			■														
38. Off-grid vaccine refrigerator			■						■								
39. Thermo-stabilization for vaccines			■							■							
40. Expanded wireless broadband network									■	■							
41. Affordable full-featured smartphones				■				■									
42. Productized biometric ID systems		■							■	■							
43. Standardized solar mini-grid system		■					■										
44. Affordable and efficient appliances							■		■								
45. Electricity storage technologies							■		■								
46. Advanced biomass cookstoves			■				■										
47. Converting waste to clean cooking fuel			■				■										
48. Particulate removal from old trucks			■								■						
49. Small scale waste incinerators			■								■						
50. Low cost electric transport vehicle									■								

WATER SECURITY

Water is one of the world's most critical natural resources. Essential for every form of life on the planet, it is also a key input for agriculture, industry and household livelihoods.

By all accounts, the world is facing a multi-faceted water crisis: depletion of groundwater stocks, shrinking bodies of surface freshwater, pollution of sources of drinking and household water, rising sea levels and acidification of ocean water, among others.

While there are many specific issues constituting this global water crisis, our study focuses narrowly on the issues impacting the health, lives and livelihoods of the global poor in developing countries. As such, this study does not discuss other important water-related challenges, such as damage to ecosystems and water scarcity in industrialized countries.

Exhibit 1 shows a time series estimate of global human water use by sector since 1900. Total global water withdrawals have increased steadily during the past century. Around the world, humans withdraw a total of about 4,000 cubic kilometers of water from surface and groundwater sources each year (Wada, et al., 2016). This amount is roughly equal to the volume of Lake Michigan, one of the Great Lakes.

Irrigation is the dominant water use sector, with current global withdrawals of over 2,800 cubic kilometers per year, having more than doubled in the last 50 years. Water withdrawals for industrial use has more than tripled in the last 50 years, now accounting for 950 cubic kilometers per year. Domestic water withdrawals have increased more than fourfold, now standing at 450 cubic kilometers per year. Water use by livestock has also increased, but is a relatively minor 20 cubic kilometers per year.

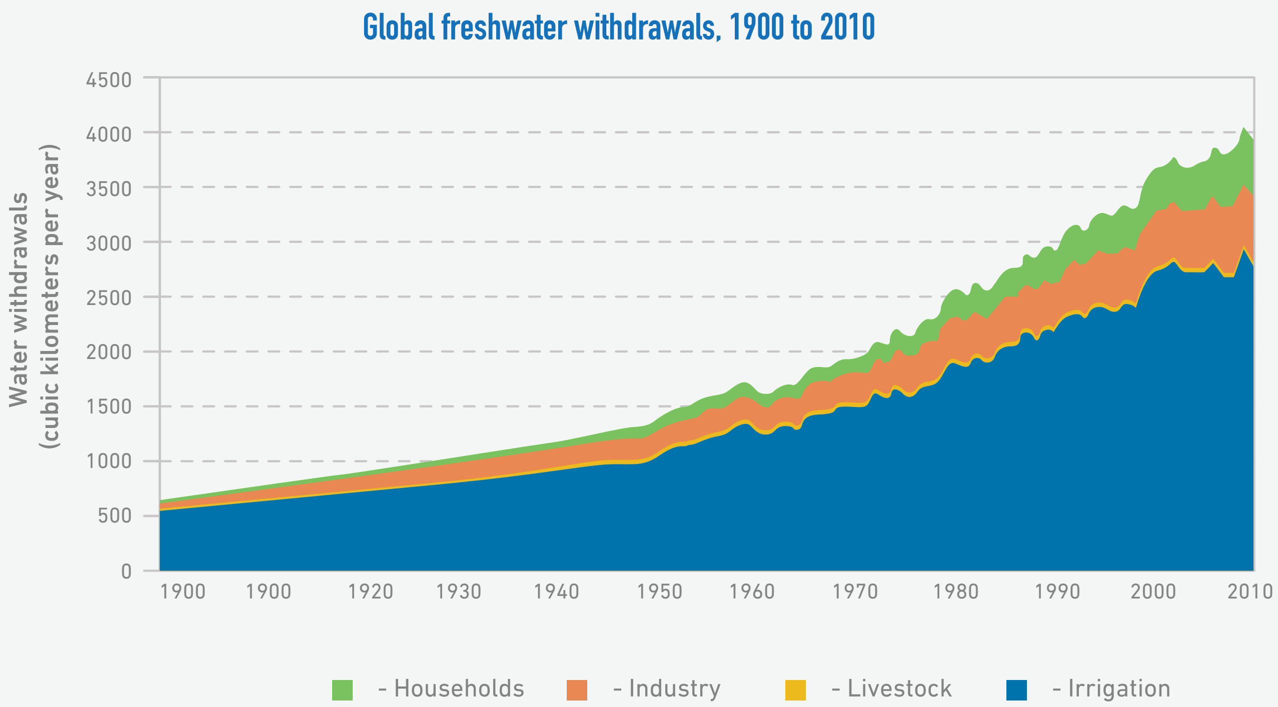


Exhibit 1: Total global water withdrawals have increased steadily during the past century. Irrigation is by far the largest single use of water, followed by industrial and household uses. (Source: Wada, et al., 2016)

1. Usage of water varies significantly between industrialized and developing countries and also between different developing regions of the world

Many of the challenges related to water for developing countries are different from those facing industrialized countries. Not surprisingly, there are also some significant differences between the challenges in South Asia and those in sub-Saharan Africa, due to population density, the relative differences in development and the impact of intensified agriculture launched by the Green Revolution in South Asia (Spielman & Pandya-Lorch, 2009).

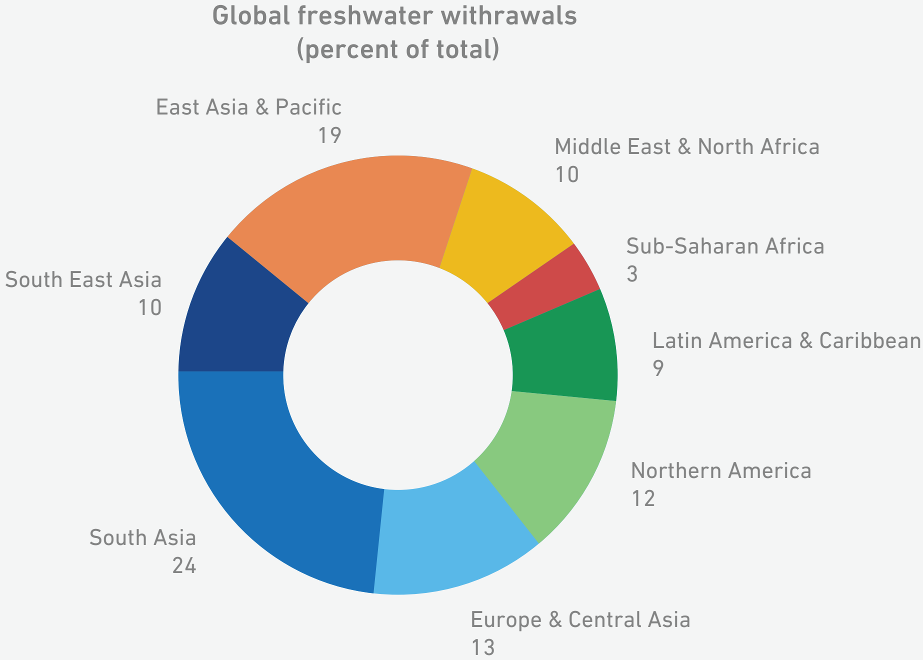
There is an important distinction between water withdrawal and water consumption: Water withdrawal (often simply called "water use") is the total volume of water that is removed from a source such as a lake, river or aquifer, while water consumption is the volume of withdrawn water that is not eventually returned to the original water source. Water that is consumed is no longer available because it has evaporated, been transpired by plants, incorporated into products or crops or otherwise removed from the immediate water environment.

The difference between water withdrawal and consumption is water return flow, which is water that is withdrawn and used and is then returned to its original source. Return flows—examples of which include domestic sewage water contaminated by fecal matter and irrigation runoff water that is contaminated by fertilizer and pesticide residues—are often of lower quality than the originally withdrawn water.

Of the total global water withdrawal of 4,000 cubic kilometers per year, about 48 percent, or 1,900 cubic kilometers, is consumed (Wada, et al., 2016). Of the irrigation water withdrawal of 2,800 cubic kilometers per year about 50 percent, or 1,400 cubic kilometers, is consumed. Of the industrial water withdrawal of 950 cubic kilometers per year only 32 percent, or 300 cubic kilometers, is consumed. Of the household water withdrawal of 450 cubic kilometers per year, 44 percent, or 200 cubic kilometers, is consumed.

Exhibit 2 shows the amount of water withdrawn in different regions of the world (FAO 2018). South Asia withdraws the most water (24 percent), followed by East Asia and the Pacific (19 percent) and Northern America (12 percent).[1] However, on a per capita basis, Northern America is the largest user of water, withdrawing almost 1,300 cubic meters per person per year. South Asia uses one-third of that and sub-Saharan Africa uses less than 10 percent of Northern American per capita withdrawals. Global average freshwater withdrawal is 512 cubic meters per capita per year.

Freshwater withdrawals by region



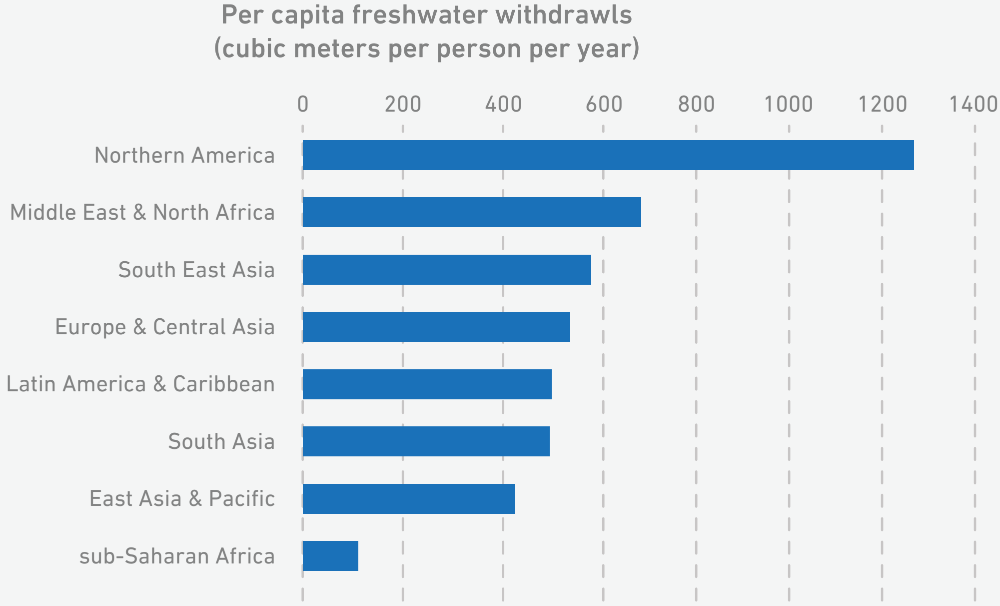


Exhibit 2: On a per capita basis, citizens of Northern America withdraw the most water in the world, people in sub-Saharan Africa use less than 10 percent of that, and usage in South Asia and other regions falls in between. In aggregate, however, South Asia withdraws the most water, followed by East Asia and the Pacific and North America. Sub-Saharan Africa withdraws only 3 percent of the global water supply. (Source: FAO, 2018)

[1]Note that different agencies collect and report statistical data in different geographic aggregations. In this chapter, the term "Northern America" refers to Canada and the United States, and in this context Mexico is included in "Latin America & Caribbean". When the term "North America" is used, it refers to Canada, United States and Mexico, and Mexico is then not included in "Latin America & Caribbean".

Exhibit 3 shows the purposes for which water is withdrawn in different regions of the world (World Bank, 2017). In high-income regions (e.g., Europe and North America), about half of water withdrawals is used for industrial purposes, particularly energy production.

In Africa and Asia, on the other hand, agricultural irrigation accounts for the largest use of water.

Freshwater withdrawals for agricultural, industrial and household use

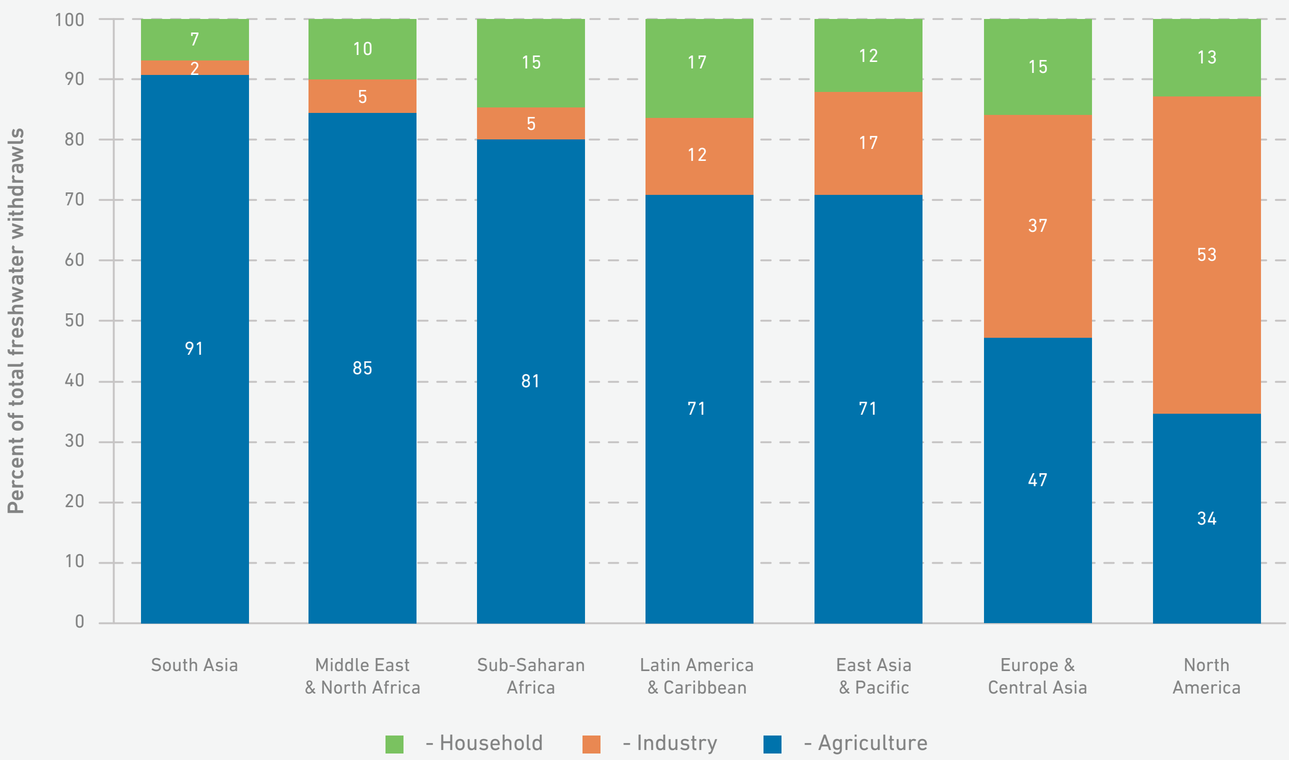


Exhibit 3: Globally, about 70 percent of water is withdrawn for agriculture, driven heavily by developing countries. In developed countries, a smaller fraction is withdrawn for agriculture and more is for household and industrial applications. (Source: World Bank, 2017)

2. The primary sources of water vary between regions, based on both geophysical and economic constraints

Populations draw water from sources that are most easily accessible to them. The two main sources for freshwater are underground aquifers (known as groundwater) or lakes, rivers and other reservoirs, known as surface water. Typically, the easiest way to access water is from nearby surface sources. As a result, 75 percent of water used around the world is from lakes, rivers and other surface water bodies (**Exhibit 4**).

The rest comes mostly from underground aquifer, and a negligible amount (0.2 percent) is drawn from desalination of brackish water or seawater. Industrialized countries rely on surface sources for 70 to 80 percent of their water, largely with extensive infrastructure involving dams, reservoirs, canals and pipes for distribution.

In South Asia, the Green Revolution (Spielman & Pandya-Lorch, 2009) and the subsequent intensified agricultural practices have led to a heavy reliance on groundwater, with mechanized pumps being used to draw the water to farms.

In sub-Saharan Africa, on the other hand, the absence of comprehensive agricultural development programs has limited construction of wells and access to irrigation systems, thereby restricting local groundwater use. As a result, more than 90 percent of what little water is withdrawn in sub-Saharan Africa is from surface sources (FAO, 2018).

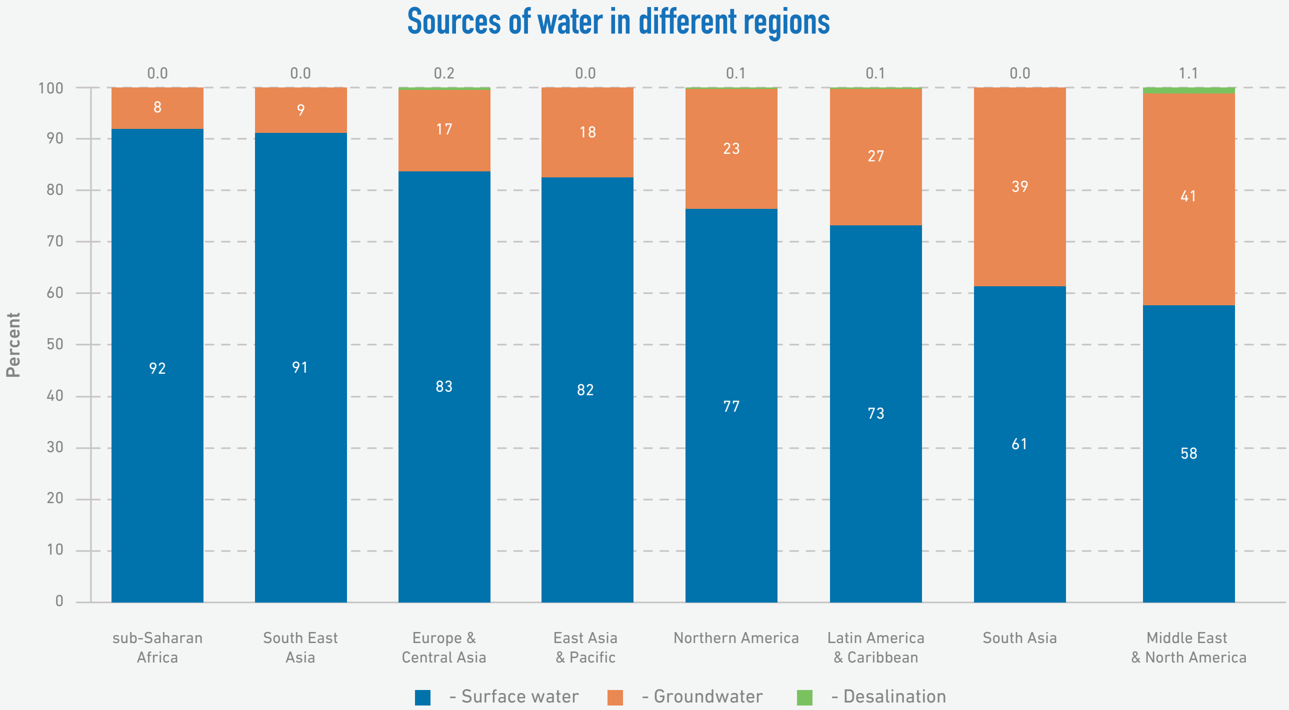


Exhibit 4: Globally, 75 percent of water used for various human activities is withdrawn from surface sources (rivers, lakes and reservoirs). Surface sources account for 92 percent of all water used in sub-Saharan Africa and 61 percent, a relatively lower share, in South Asia. (Source: FAO, 2018)

3. Various regions of the world face different combinations of three water-related stresses: physical scarcity, economic scarcity and quality

Over the past few decades, population growth, agricultural development and broader economic development have led to a significant increase in water use. Consequently, this has placed stress on available renewable water sources. South Asia is facing a particularly dire shortfall. The per capita renewable water supply in the region is a fraction that of other areas that depend primarily on agriculture **(Exhibit 5**).

Only the Middle East and North Africa region—largely desert—has less water per capita. Exhibit 6 shows the reduction in per capita freshwater between 1962 and 2017 (FAO, 2018). Globally, there has been a 57 percent reduction in per capita renewable water over the past five decades. A number of large countries in sub-Saharan Africa and South Asia have witnessed greater declines than the global average, including Pakistan (75 percent), India (64 percent), Nigeria (74 percent), Kenya (81 percent) and Uganda (81 percent). It is important to note that due to its large population, South Asia began with an already low base of per capita supply.

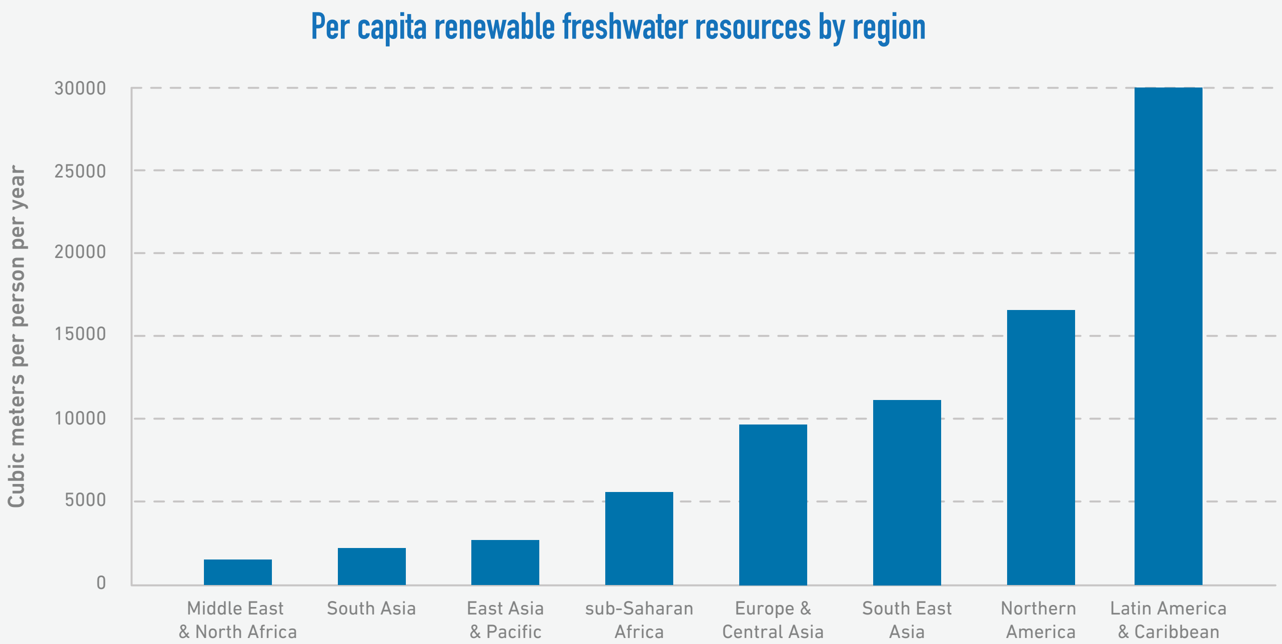


Exhibit 5: South Asia, Middle East and North Africa regions have the lowest per capita renewable water resources. (Source: FAO, 2018)

Per capita water resources are decreasing

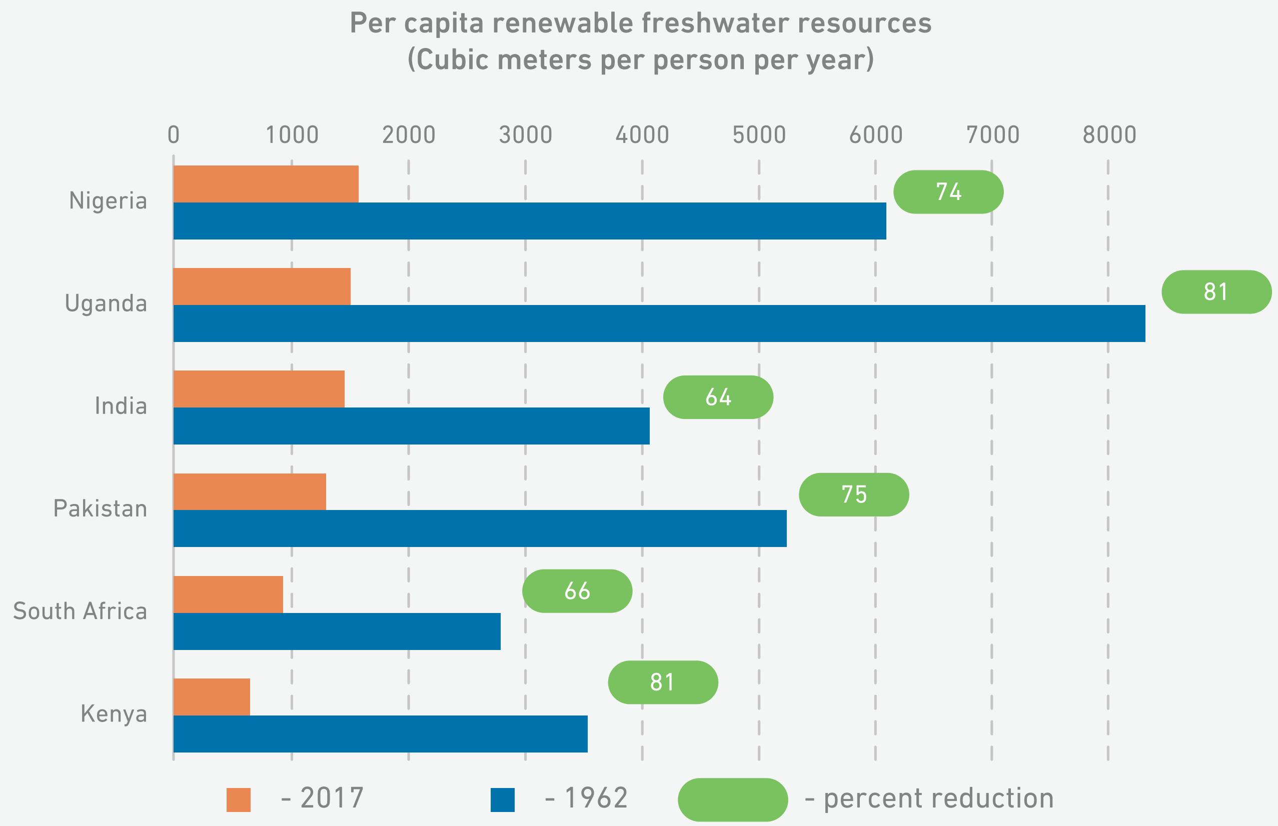


Exhibit 6: A number of large countries (with population over 20 million) are facing dramatic reductions in water supply on a per capita basis due to population growth. In Kenya, for example, per capita renewable water has shrunk by 81 percent over the past 55 years. In Pakistan, it has shrunk by 75 percent during the same period, while India has witnessed a 64 percent reduction (from an already low base). By comparison, the global average reduction between 1962 and 2017 is about 57 percent. (Source: FAO, 2018)

Exhibit 7 shows the parts of the world that are experiencing physical water scarcity due to intrinsic geographic constraints (such as desert countries in the MENA region), or as a consequence of heavy consumption (like India and Pakistan).

A number of analyses have concluded that the situation is grave enough that even within the next decade water scarcity in these regions may destabilize countries, threaten food security and lead to water being used as a weapon in cross-border negotiations (US Intelligence Community Assessment, 2012; Goldenberg, 2014).

In addition, there appears to be a continued increase in the frequency and severity of 'water wars' between pastoral communities in the Horn of Africa (Pavanello, 2009; Yale University, 2010).

Exhibit 7 also shows regions facing economic scarcity. These are areas where the population cannot access water, which may be available in abundance, due to the lack of infrastructure (dams, canals, large-scale pumps and piping systems) and because most households are too poor to invest in small-scale boreholes and pumps.

As a result of economic water scarcity in sub-Saharan Africa, the vast majority of smallholder farmers do not have access to adequate irrigation. Not surprisingly then, agricultural yields in the region are a fraction of that in other food producing parts of the world and food insecurity has been an ongoing crisis on the African continent for decades.

Only 3.4 percent of farmland in Sub-Saharan Africa is irrigated (FAO, 2016). By comparison, 46 percent of farmland in South Asia and 56 percent in East Asia is irrigated. Importantly, of the total irrigated land in Africa, more than two-thirds is concentrated in five countries—Egypt, Madagascar, Morocco, South Africa and Sudan (IFPRI, 2010). Only two of these countries are in sub-Saharan Africa.

Global map of water scarcity

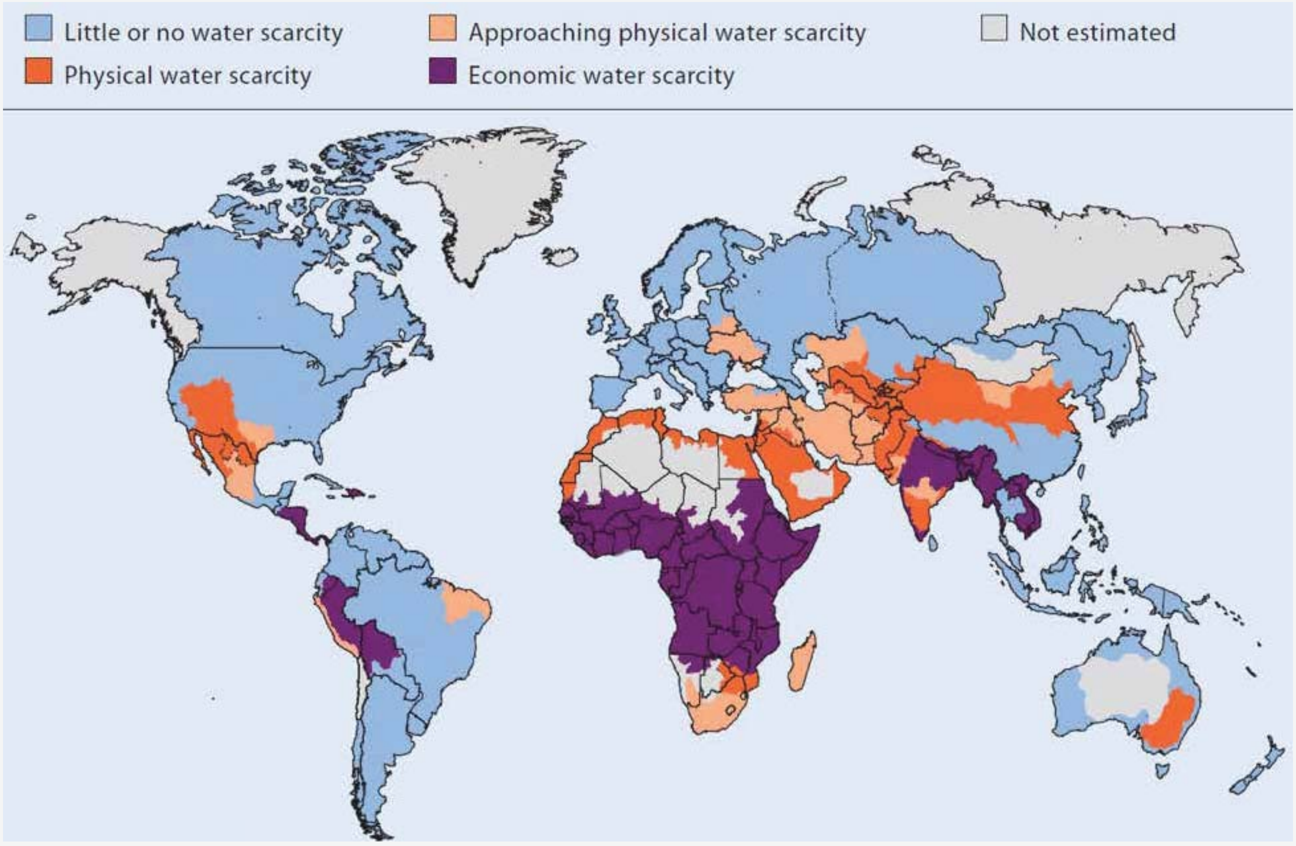


Exhibit 7: Water scarcity can be due to physical reasons (i.e., there is insufficient water in the area), or economic reasons (i.e., the water is physically present, but people cannot access it). Most of sub-Saharan Africa faces economic scarcity. South Asia faces a combination of both types of scarcity. (Source: UNEP/ GRID-Arendal, 2008)

Another type of water problem has to do with the quality of water, especially for drinking and household use. Many people in developing countries lack access to adequate sanitation facilities, especially in rural areas. In urban areas, where sanitation facilities like toilets are available, sewage treatment facilities are often lacking.

As a result, there is a high prevalence of open defecation and discharge of untreated sewage into rivers and other waterways. Human fecal matter carries a range of bacteria, viruses, parasites and helminths, which can enter drinking water sources that are not adequately protected. Using water drawn from sources that are not protected from such contamination can lead to illness.

As **Exhibit 8** shows, 42 percent of the population in sub-Saharan Africa lacks access to an improved water source. South Asia is somewhat better off, with 12 percent lacking access. Exposure to fecal pathogens causes widespread diarrheal disease, which is among the leading causes of mortality among children under 5 in South Asia and sub-Saharan Africa (**Exhibit 9**).

Other water quality problems may be caused by naturally occurring contaminants such as arsenic or fluoride, or may be caused by agricultural runoff of fertilizers and pesticides, or effluent from industrial facilities.

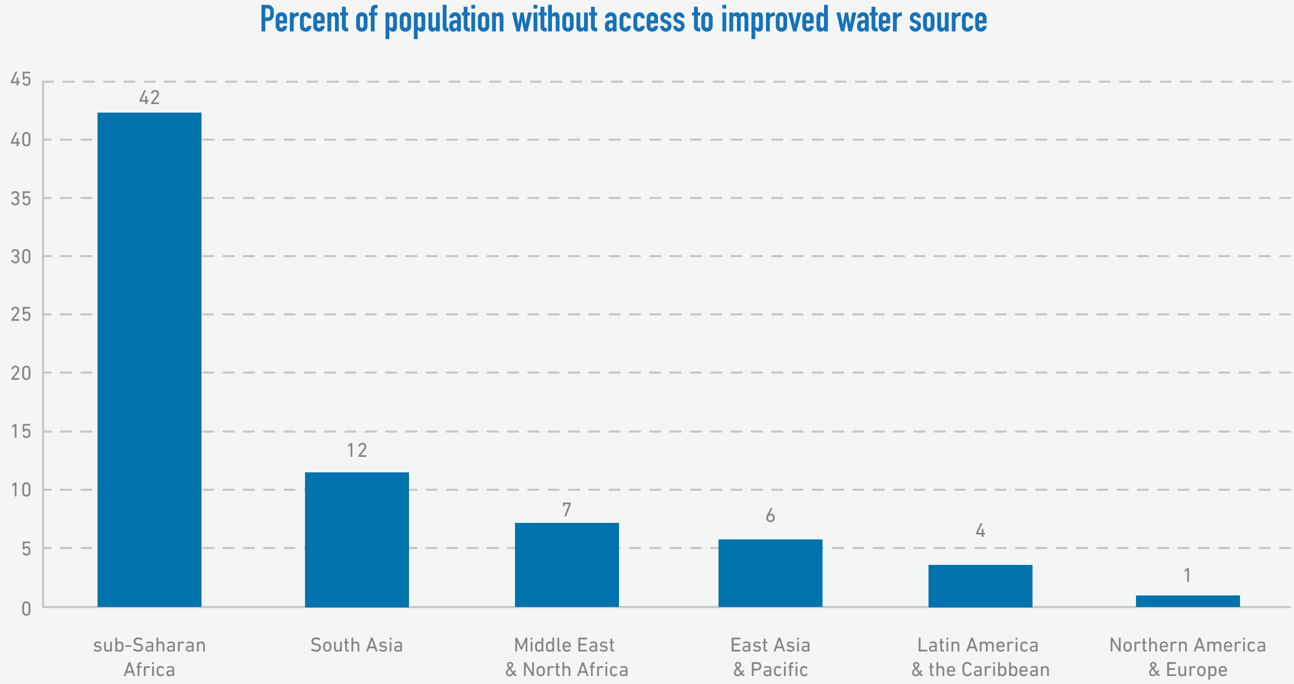


Exhibit 8: About 42 percent of the sub-Saharan African population lacks access to improved water sources[2] that are safe from contamination. Many people in South Asia also lacks access to such sources. (Source: JMP, 2018)

[2]Access to household water includes aspects of water availability, quality and delivery. The WHO/UNICEF Joint Monitoring Program (JMP) has developed "service ladders" to categorize household water services around the world in an effort to monitor and improve access. JMP defines five categories of water access, Safely Managed, Basic, Limited, Unimproved and Surface Water, which are briefly defined below.

- Safely Managed: Household water from an improved water source, which is located on premises, available when needed and free from fecal and priority chemical contamination.
- Basic: Household water from an improved source, provided collection time is not more than 30 minutes for a roundtrip including queuing.
- Limited: Household water from an improved source for which collection time exceeds 30 minutes for a roundtrip including queuing.
- Unimproved: Household water from an unprotected dug well or unprotected spring.
- Surface Water: Household water directly from a river, dam, lake, pond, stream, canal or irrigation canal.

Exhibit 8 shows the percent of populations with Limited, Unimproved and Surface Water categories.

Global deaths due to diarrhea, by region

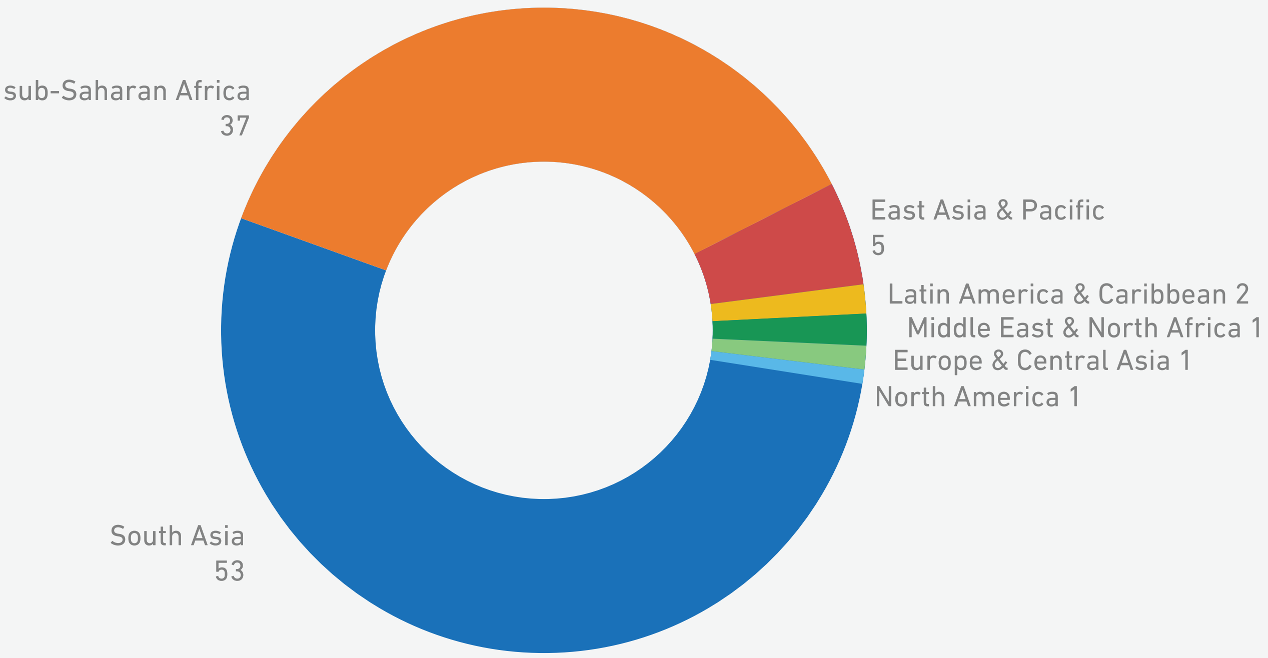


Exhibit 9: Of the 1.7 million deaths per year due to diarrheal disease, more than half occur in South Asia and more than a third are in sub-Saharan Africa. (Source: GHDX, 2018)

Water security is a multifaceted challenge involving physical water and economic water scarcity and poor water quality. **Exhibit 10** shows the percentage of the global population facing each of three types of water problems: physical scarcity, economic scarcity and poor quality. This is based on ITT's analysis combining definitions and data from multiple sources.[3]

We categorize a country as facing a water quality problem if the death and disease due to water-related diarrheal diseases exceed a threshold.[4] We categorize a country as facing physical water scarcity using WRI's rating of water stress by country, based on ratios of total withdrawals to total renewable supply (WRI, 2013).[5]

We base economic water scarcity on the mapping done by WWAP (2012) supplemented by country-specific analysis. While this broad-brush national-level analysis lacks many nuances of local water security, it gives strong directional indication of the types and scales of global water security problems.

Exhibit 11 provides details of the severity of various water security challenges in the 10 largest countries by population. Pakistan, India and China appear to have the most severe water security issues.

[3]Based on the 50 largest countries by population (year 2018 projection by UN, 2017), which collectively are home to 87 percent of the global population.
[4]Countries are considered to have water quality problems if the annual disability-adjusted life years (DALYs) lost to water-related diarrheal diseases exceed 500 per 100,000 people, based on 2015 DALY data (Troeger, et al., 2017) and 2015 population data (UN, 2017). DALYs are an indication of the severity of a disease's impacts on a population including morbidity and mortality effects.
[5]Countries are considered to have physical water scarcity if they have "medium to high" or greater average exposure of water users in each country to water stress, based on ratios of total withdrawals to total renewable supply (WRI, 2013).

Global occurrence of physical scarcity, economic scarcity and water quality problems

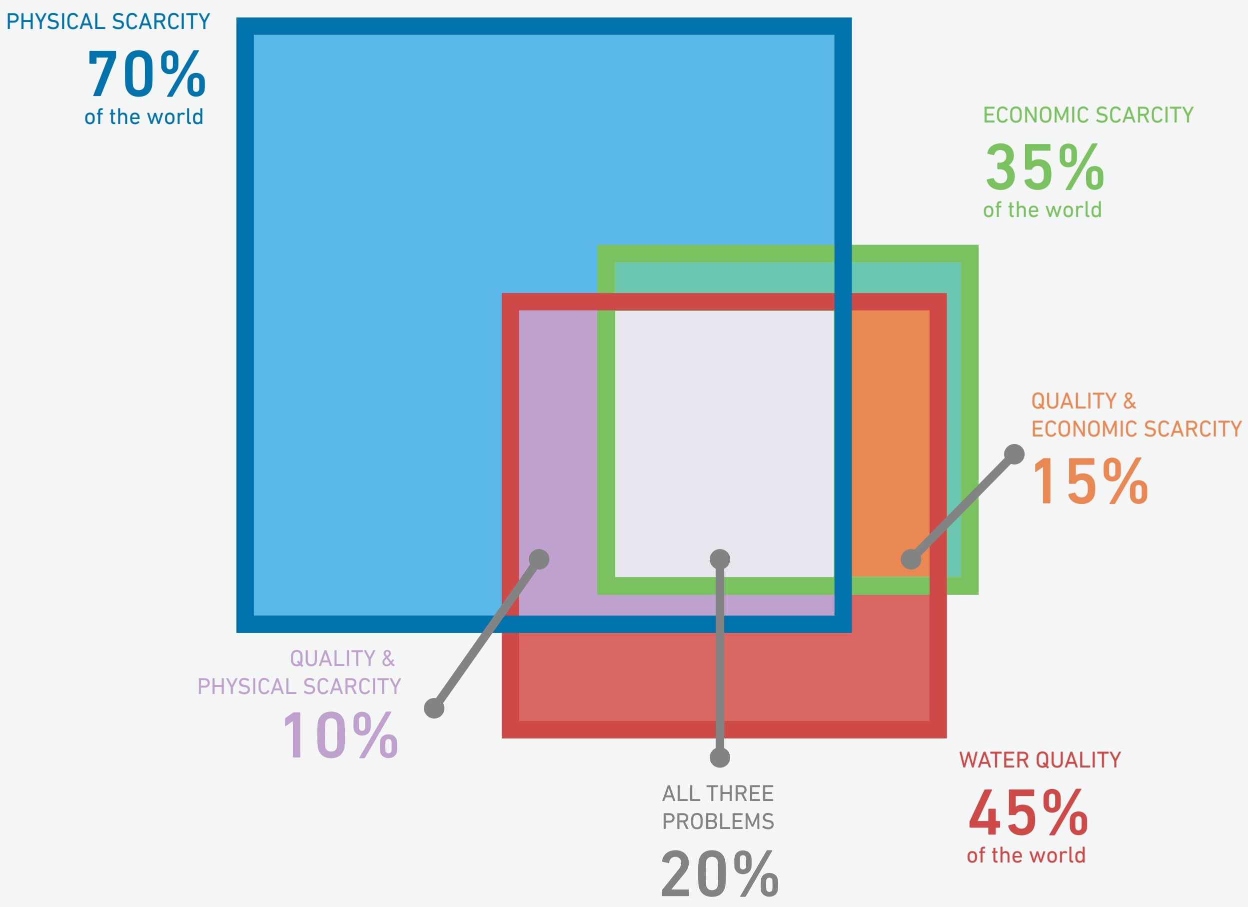


Exhibit 10: The world's water problem can be characterized as the intersection of three issues— physical scarcity (meaning, where consumed water is a major share of all renewably available water), economic scarcity (where water is present but cannot be accessed due to lack of economic means) and quality (due to contamination by biological or chemical impurities). Countries face different combinations of these problems based on their geography, population, level of industrialization, economic activity and management practices. According to our analysis, 85 percent of people live in countries that face at least one of these three problems; 45 percent live in countries facing at least two of the three challenges, and 20 percent are facing all three problems at the same time. (Source: ITT analysis)

Based on these definitions, only 15 percent of the world's population lives in countries without any major water-related problems; these countries include Brazil, Russia and Germany.[6] The remaining 85 percent of the world's population lives in countries that face at least one of the three problems.

- Sub-Saharan Africa and South Asia primarily bear the brunt of economic water scarcity. These regions are also dominated by agriculture and smallholder farming.
- 20 percent of the world's population faces all three problems simultaneously, primarily those living in India.
- 15 percent of the world's population face poor water quality and economic water scarcity, including Bangladesh, Nigeria and Ethiopia.
- 40 percent of the total population primarily faces physical scarcity or unsustainable use of water, including China, the United States and Mexico.
- 10 percent of total population suffers from poor water quality and physical scarcity/unsustainable use, including Indonesia, Pakistan and South Africa.
- A very small number of countries face the challenges of water quality or economic scarcity in exclusion of the other problems.

Water security challenges of the 10 largest countries

Legend	Severe	High	Moderate	Fair	Low					
	China	India	USA	Indonesia	Brazil	Nigeria	Pakistan	Bangladesh	Russia	Mexico
Surface water supply in closed river basins is fully utilsed and cannot increase	Severe	Severe	High	Low	Fair	Fair	Severe	Low	Low	Moderate
Groundwater over-extraction in hard rock regions causes seasonal critical depletion	High	Severe	Fair	Fair	Low	Low	Moderate	Fair	Low	Moderate
Groundwater over-extraction in alluvial regions causes long-term decline of water table	Severe	Severe	Severe	Low	Low	Low	Severe	Low	Low	High
Faecal contamination of water bodies causes health and environmental impacts	Low	Severe	Low	Moderate	Fair	Severe	Severe	Moderate	Low	Fair
Arsenic and fluoride contamination of groundwater causes health impacts	Moderate	High	Fair	Low	Low	Low	Moderate	Severe	Low	Fair
Diverse industrial effluent and agricultural runoff cause health and environmental impacts	Severe	High	Fair	Low	Fair	Fair	Moderate	Fair	Moderate	Moderate
Urban water demand from growing cities exceeds local supplies	Severe	Severe	Severe	Fair	High	Moderate	Severe	Fair	Low	Severe
Available water supply becomes brackish or saline from groundwater salinization	Moderate	Moderate	Fair	Fair	Fair	Fair	Moderate	High	Low	Fair
Irrigated agricultural land becomes waterlogged and salinized over time	Moderate	Moderate	Moderate	Low	Low	Low	Severe	Low	Fair	Fair
Flooding during storms will become more frequent and intense	Moderate	Moderate	Moderate	Fair	Fair	Fair	Moderate	Moderate	Low	Fair
Glacial melting is permanently altering surface water flow	Fair	Fair	Low	Low	Low	Low	High	Fair	Low	Low
Lack of means to access local water sources causes economic water scarcity	Fair	High	Low	Moderate	Fair	Severe	Moderate	High	Low	Fair

Exhibit 11: People around the world face a diverse set of water problems of varying severity. Here, the severity of 12 major water security challenges are estimated for the 10 largest countries by population. (Source: ITT analysis)

The remainder of this chapter focuses on the three challenges of Physical water scarcity, Water quality, and Economic water scarcity.

[6] The coarseness of this national-scale analysis is evident, for example Brazil overall is very water abundant, though cities like São Paulo have faced severe deficit; Russia overall has low diarrheal rates but some locations suffer severe industrial water contamination.

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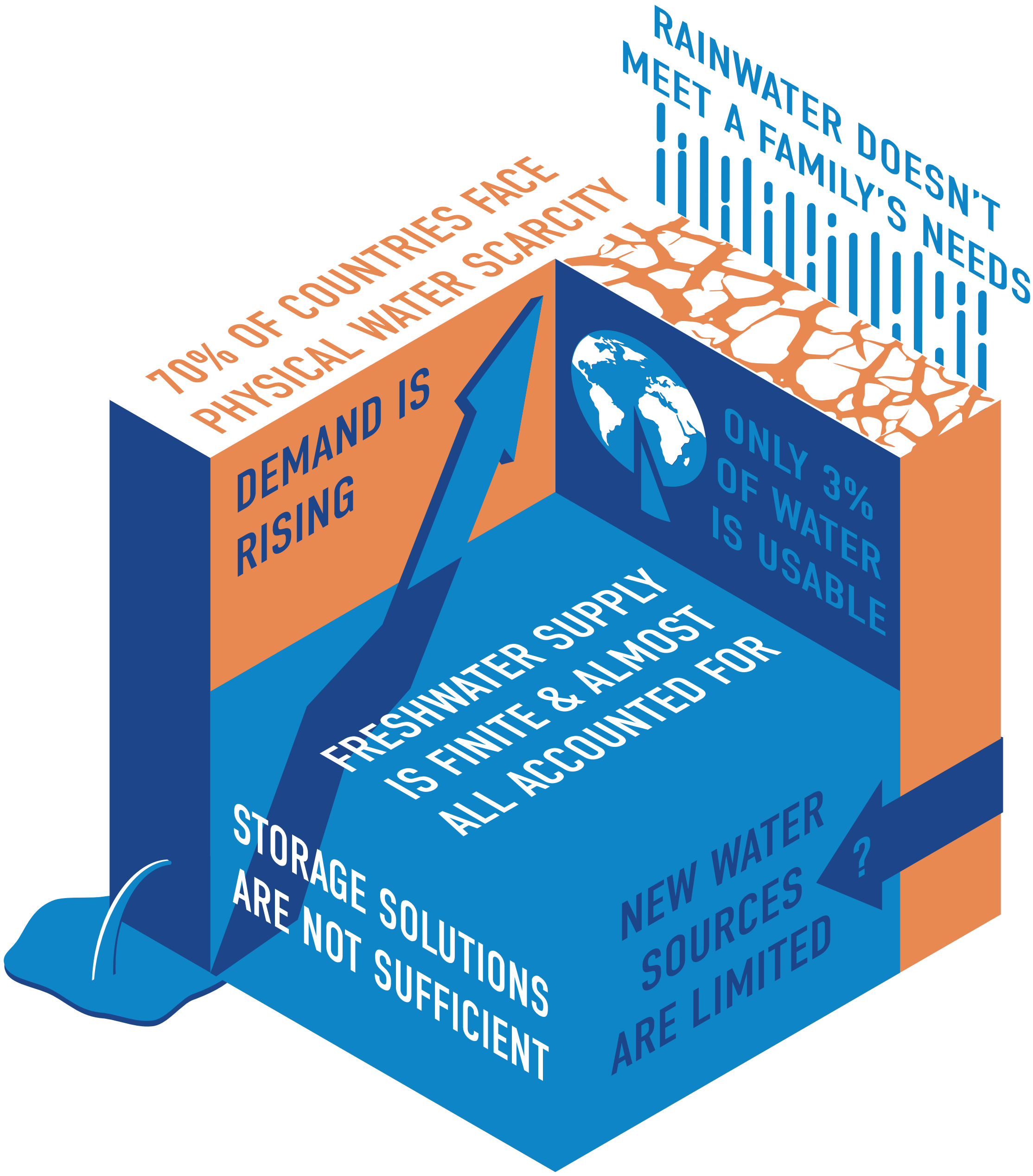


PHYSICAL WATER SCARCITY

INTRODUCTION

Physical water scarcity occurs when the amount of water physically present in a region is insufficient to satisfy the demand.

Most commonly, this happens when demand for water increases over time, eventually approaching or exceeding the available supply. The amount of available water, while previously adequate to meet the limited demand, eventually becomes insufficient to meet growing requirement for agriculture, industry and households.

Physical water scarcity may also occur due to reduction in water availability, which causes insufficient supply to meet previously-satisfied demand. Such reduction in water supply may be temporary and short term (seasonal to several years) owing to natural variability in weather patterns, though long-term reduction in water supply is an emerging threat in some regions due to global climate change.

In light of these challenges, three technology breakthroughs can substantially reduce the burden of physical water scarcity:

- Breakthrough 1. A low-cost system for precision application of agricultural inputs, ideally combining water and fertilizer
- Breakthrough 2. A very low-cost scalable technique for desalinating brackish water
- Breakthrough 5: Medium to large-scale sewage treatment process with recovery of water (and ideally nutrients and energy)

Because water is essential to life, human settlements have always been located with reliable access to the precious liquid. As water demand for households, farms and industries has grown rapidly in recent decades, many regions now face physical water scarcity, where there is simply not enough water available to meet all demands. This is exacerbated by global climate change, which affects the amount and reliability of precipitation.

CORE FACTS AND ANALYSIS

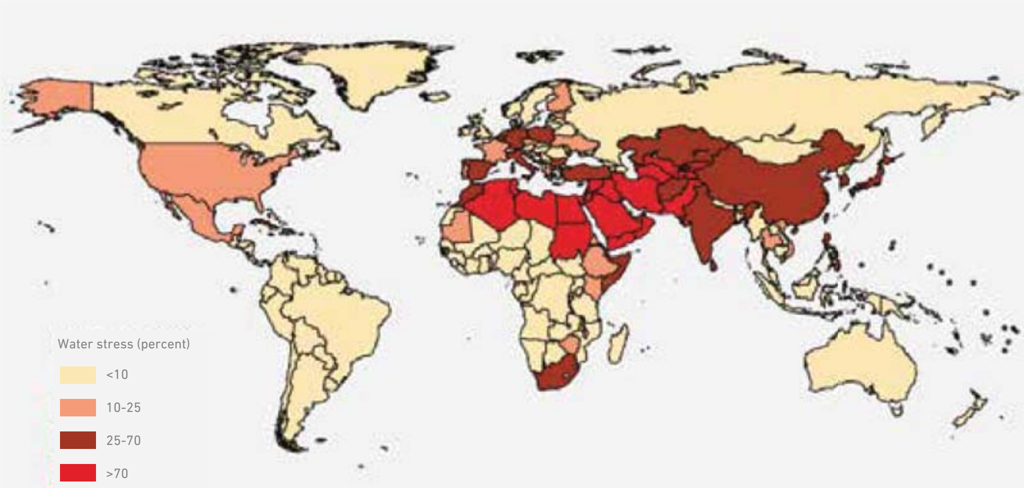
1. Physical water scarcity varies greatly by country and region

Exhibit 1 maps the world's physical water stress at a country-level, based on the definition used to track progress on Sustainable Development Goal 6.4.2 regarding water stress. This indicator tracks how much freshwater is being withdrawn for all activities, compared to the total renewable freshwater resources available. Specifically, physical water stress is calculated as the total freshwater withdrawal per year, divided by the total annual renewable freshwater resources minus the environmental flow requirements (FAO, 2018b).

The global regions most affected by physical water scarcity include Northern Africa and Southwestern Asia. Southern and Central Asia, and select countries in other global regions, are also affected. At a finer resolution, physical scarcity often varies widely within countries, as some areas can be water stressed while other areas have abundant water.

Physical water scarcity is manifest in the closure of river basins, the depletion of groundwater stocks, the challenge of supplying water to growing cities and the change in rainfall patterns in some regions. These topics are detailed in the following sections.

Physical water stress varies by country and region



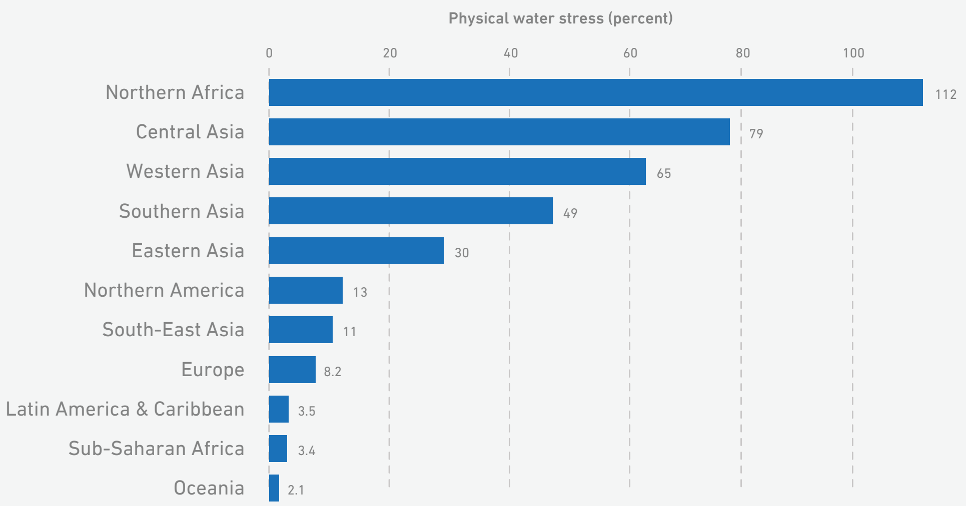


Exhibit 1: Physical water stress varies greatly between countries. Generally, the countries most affected are in Northern Africa and South and Central Asia. (Source: FAO, 2018b; map shows country averages from 2000 to 2015, chart shows regional stress in 2015)

2. There is great variability in water availability, which is exacerbated by global climate change

Globally, about 550,000 cubic kilometers of water falls as precipitation each year. Given the Earth's surface area, this corresponds to an average annual precipitation of about 1,050 millimeters (Legates & Willmott, 1990; Pidwirny, 2018). However, there are large differences between global regions in the timing and amount of precipitation (see **Exhibit 2**). About 80 percent of total precipitation falls over the oceans.

- The highest rainfall occurs in the tropical regions near the equator, where strong solar heating causes vertical uplift of air. As the air rises it expands and cools, and water vapor condenses and falls as rain. Global circulation patterns cause northern and southern air masses to converge in the tropics. Annual rainfall in tropic regions usually exceeds 2,500 millimeters.
- Subtropical regions are typically quite dry due to a global scale atmospheric circulation pattern (known as the Hadley cell) in which warm air rises near the equator and loses its moisture, then flows poleward at high elevation and descends in the subtropics, and finally returns near the surface toward the equator. Many of the world's deserts are located within the subtropics.
- The temperate mid latitude regions have moderate levels of precipitation, much of it associated with the development of cyclonic activity and frontal lifting when warm subtropical and cold polar air masses meet. The air masses in this region generally move from west to east, causing heavy precipitation on western facing coastlines and less precipitation in the interior regions of continents as the air dries and moves further away from the oceans.
- Polar regions are dry because the air is too cold to contain much water vapor. Some parts of Antarctica and the Arctic are as dry as the hot desert climates of the subtropics.

Mean annual precipitation, 1961 to 1990

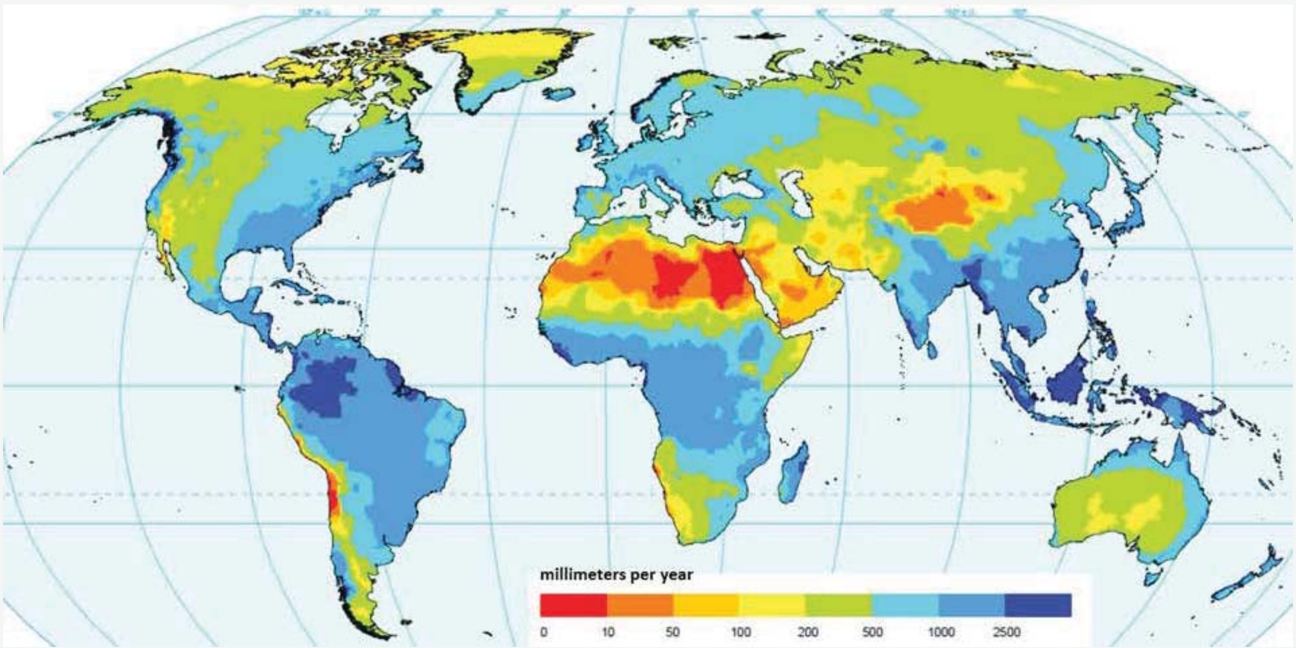


Exhibit 2: Global map of historical average annual precipitation from 1961 to 1990. (Source: GPCC, 2018)

The amount of precipitation that a region receives largely determines the potential for non-irrigated (rainfed) agriculture. Other important factors include the seasonal distribution of rainfall, the inter-annual variability in rainfall, the evapotranspiration rate, the soil water storage capacity and the types of crops grown (Droogers, et al., 2001).

Exhibit 3 shows the estimated potential for rainfed farming throughout the world.

Potential for rainfed agriculture

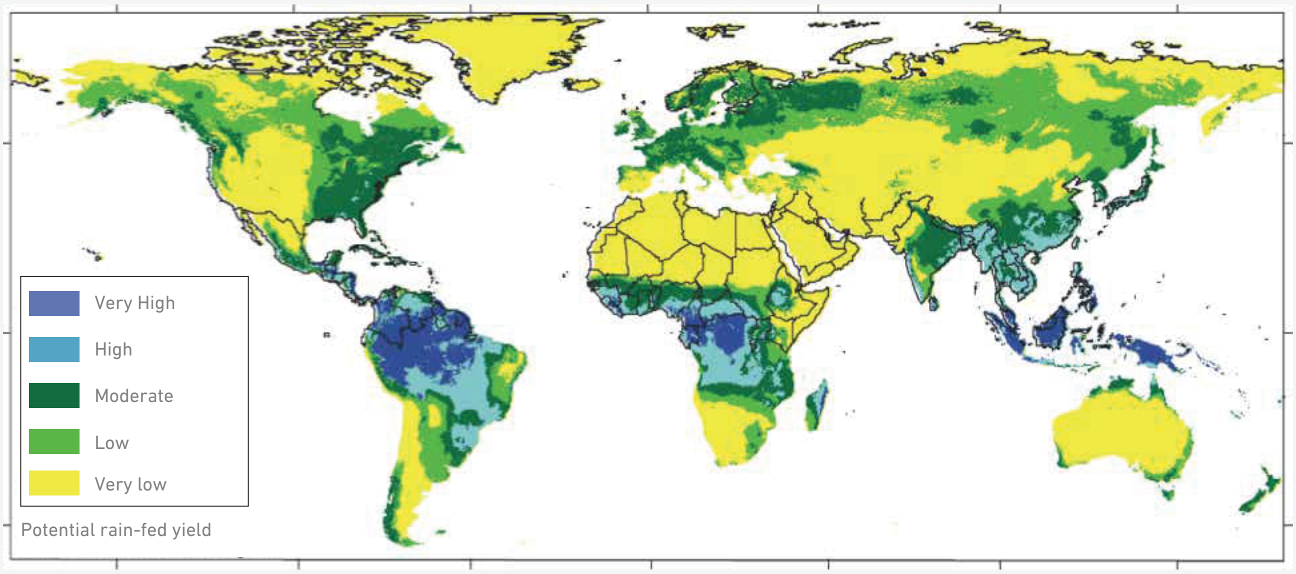


Exhibit 3: Global map of rainfed agriculture potential. (Source: Droogers, et al., 2001)

As the climate warms, changes in the global water cycle are projected to occur (IPCC, 2013). Average global precipitation is expected to gradually increase in the 21st century.

The global hydrological cycle will generally intensify due to global warming and mean water vapor, evaporation and precipitation are projected to increase on global average.

Changes of average precipitation in a much warmer world will not be uniform, with some regions experiencing increases while others face decreases or little change. Precipitation is expected to increase in many wet tropical areas and at high latitudes.

Many mid latitude and subtropical arid and semi-arid regions will likely experience less precipitation.

The Asian monsoon will likely increase in average total precipitation, but with greater variation from year to year.

The melting of snowpack and glaciers will affect the amount and timing of water flows in downstream areas, for example in the Indus River basin in Pakistan (Scott, et al., 2019).

Despite variability and uncertainty in climate change projections, there is now agreement from a number of different climate models that Africa is at the highest risk from climate change, given the magnitude of existing stresses in the continent (UNDP, 2009). It is highly likely that significant areas of African drylands will face changing rainfall patterns in the coming decades.

Exhibit 4 shows model projections of future changes in average rainfall during rainy seasons in Africa, under global temperature rises of 2 degrees Celsius and 3 degrees Celsius (Weber, et al., 2018). Average precipitation is expected to decrease in northern and southern Africa and increase in central and eastern Africa. Similar conclusions were reached by Nikulin, et al. (2018) and Maúre, et al. (2018).

Projected change in precipitation due to climate change

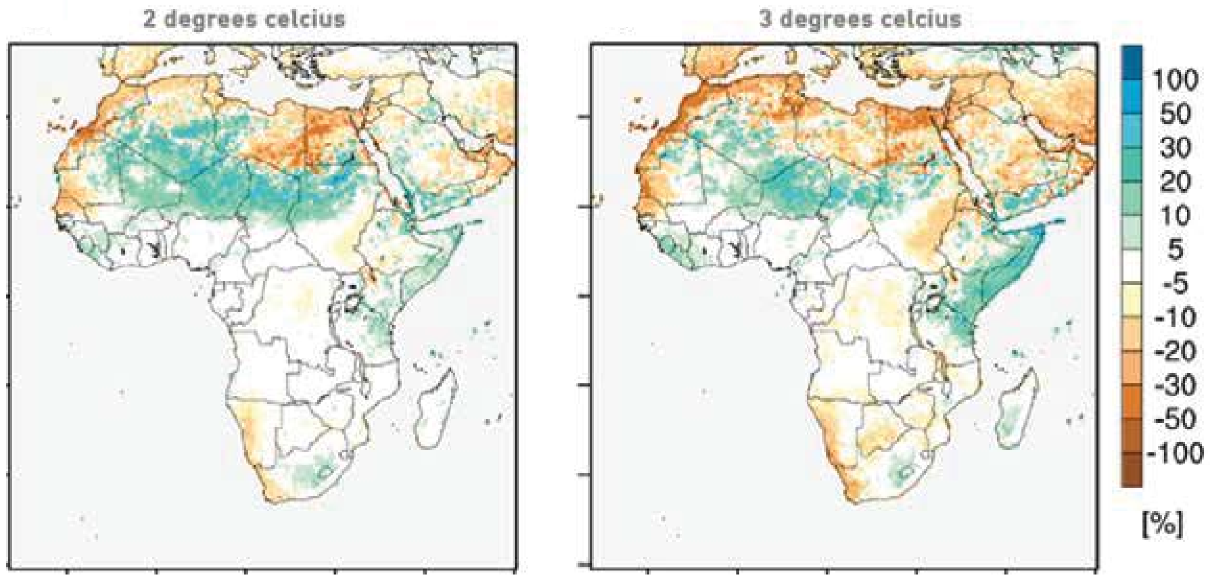


Exhibit 4: Results from climate models suggest that precipitation patterns in Africa will change as global temperature rises. Average rainfall during rainy seasons is expected to decrease in northern and southern Africa, and increase in central and eastern Africa. The effect is more pronounced under a 3 degrees Celsius temperature rise (right) than a 2 degrees Celsius rise (left). (Source: Weber, et al., 2018)

The most significant impact of extreme weather events on human development will likely be due to frequent and prolonged droughts in some regions. Many climate models project an increased likelihood of agricultural droughts in regions that are presently dry, with extended decreases in soil moisture (IPCC WG2, 2014).

Farmers and pastoralists in drylands with insufficient access to drinking and irrigation water risk a decrease in agricultural productivity.

This will affect the livelihoods of rural people, particularly those depending on water-intensive agriculture. There is a corresponding risk of food insecurity and conflict over available water and food resources (UNDP, 2009).

Droughts also affect urban populations with inadequate water services by worsening the available supply for domestic and industrial use, causing health and economic impacts. Droughts can significantly affect energy security because they reduce the energy supply from hydropower stations and can force water-cooled thermal power stations to shut down.

A major drought in 2001 in Brazil, a country which received 80 percent of its electricity from hydropower, caused a 20 percent reduction in electricity supplies in the country and led the government to introduce rationing (Lee, at al., 2012). Ethiopia is quite vulnerable to droughts because of its high dependence on agriculture as well as hydropower for electricity.

A delayed monsoon in India contributed to widespread sustained blackouts in 2012, by raising electricity demand for pumping groundwater for irrigation while reducing hydropower generation. Between 2013 and 2016, fourteen of India's largest thermal power utility companies experienced disruptions at least once due to water shortages (WRI, 2018a).

3. Several major river basins are closed, meaning that all available surface water is fully utilized and supply cannot increase to meet growing demand

A river basin is considered closed when all of the surface water available in an average year is fully allocated and little or no river water discharges into the ocean.[1]

Several major river basins in South Asia are now closed basins, including the Indus River in Pakistan, the Helmand River in Afghanistan and the Krishna, Kaveri, Penna, Vaigai, Sabarmati and Banas Rivers in India (World Bank, 2005; Venot, et al., 2007; Kumar, et al., 2008; Falkenmark & Molden, 2008).

Within southern Africa, the Orange, Limpopo and Incomati basins are also closed (Turton & Ashton, 2008). Other major closed river basins include the Yellow River in China, the Colorado River in the United States, the Murray-Darling basin in Australia and most rivers in the Middle-East and Central Asia (Molle, et al., 2007).

In these basins, the total annually available surface water supply is fully or nearly fully utilized. There is little or no opportunity to increase extraction of surface water in these regions to meet rising urban and agricultural demands (Venot, et al., 2007).

The Indus River basin, for example, is extensively developed to use surface water in the largest contiguous irrigation system in the world, the Indus Basin Irrigation System (IBIS) (see **Exhibit 5**).

Comprising three major storage reservoirs, 19 barrages, 12 inter-river link canals and 45 major canal commands irrigating about 15 million hectares, IBIS uses virtually all the water flowing in the Indus River (see **Exhibit 6**).

[1]Note that an alternative hydrological definition of the term 'closed river basin' is applied to an endorheic basin that terminates in an inland sea, lake or other sink and does not flow into an ocean.

Most water in the Indus River is withdrawn and used

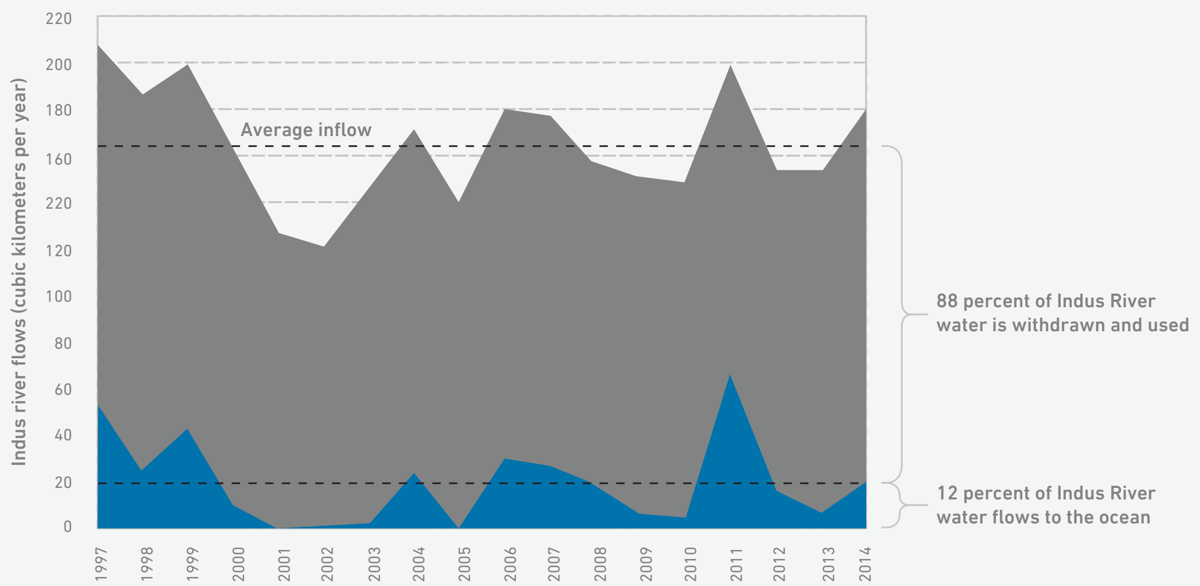


Exhibit 5: The Indus River basin is effectively closed, with little opportunity to increase surface water extractions. Most of the river water available in an average year is already allocated and used. No water flows from the Indus River to the ocean in years of below-average rainfall. (Source: ITT analysis based on data from Pakistan Bureau of Statistics (2007 and 2014); River inflow includes the Indus at Kalabagh, Chenab at Marala, Jhelum at Mangla, and minor inflows from Ravi and Sutleg Rivers; River outflow is discharge below Kotri barrage)

Exhibit 6: Kotri barrage in Sindh Province, Pakistan, is the last stop on the Indus River before it reaches the Arabian Sea. During years of normal precipitation, little water flows in the Indus River below Kotri Barrage. (Source: Google Maps, 2018)

In closed basins, while river water is fully used during normal and dryer-than-normal years, some flood water reaches the ocean during years of above-average precipitation. Attempting to capture and utilize this lost water leads to diminishing returns, requiring significant infrastructure that will only be used irregularly, making 100 percent utilization of river flow impractical.

During years of less-than-average precipitation, the surface water supply will not meet demand in closed basins. Such years are projected to become more frequent due to climate change. In the absence of a structured water allocation system, upstream water users will continue to extract river water, while downstream users will be left with inadequate supply.

The closure of river basins has been made possible by our significant alteration of the natural water cycle, allowing us to withdraw and use a greater proportion of available water.

We have changed the patterns of surface water flow by impounding river water behind dams, aiming to control floods, generate hydroelectricity, enable transportation and provide reliable water supply for farms and cities.

Exhibit 7 shows that artificial reservoirs now have the capacity to hold about as much water as contained in Lake Michigan, one of the Great Lakes (Vörösmarty & Sahagian, 2000; van der Leeden, et al., 1990).

Global water storage capacity in artifical reservoirs since 1900

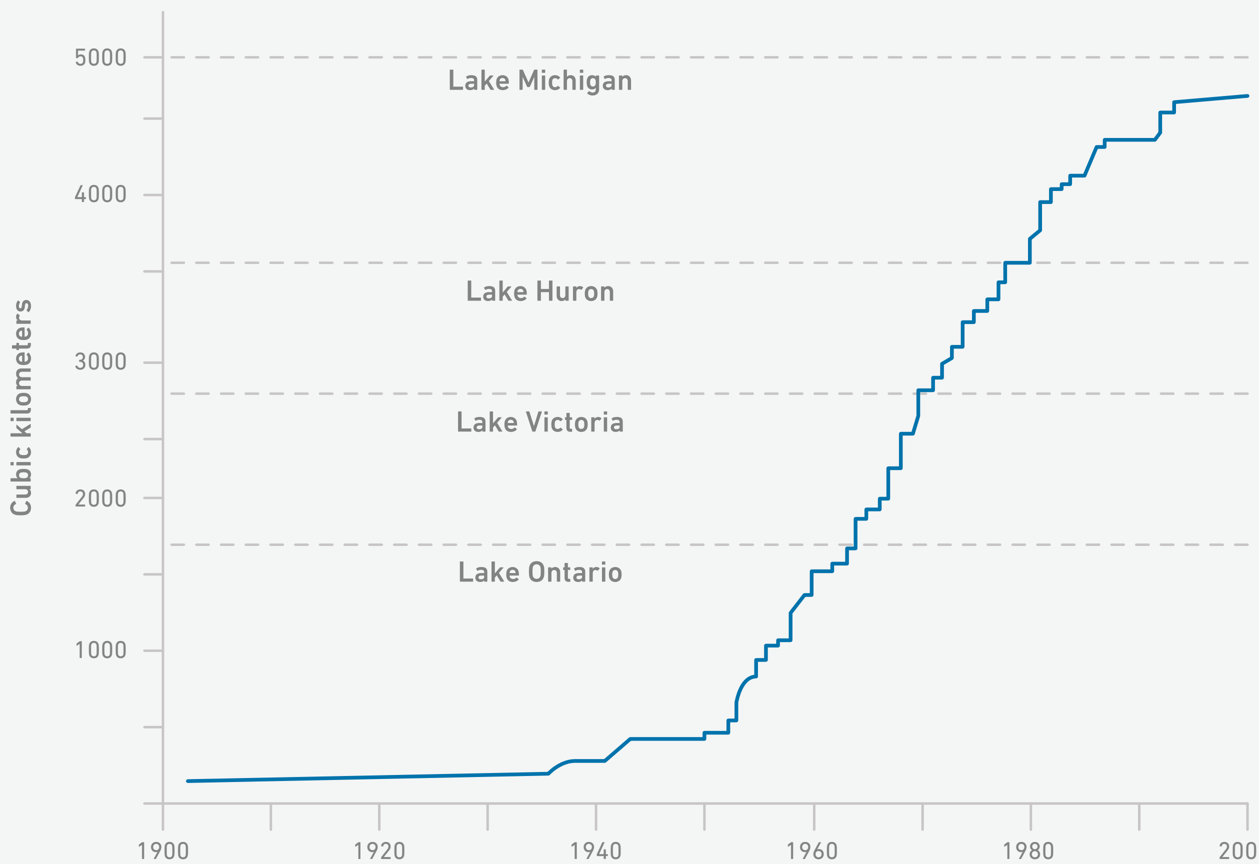


Exhibit 7: Construction of dams and reservoirs increased significantly after 1950. By 1960 the total water storage capacity within artificial reservoirs globally was equivalent to that of Lake Ontario; by 1980 it was equal to Lake Huron. Currently, human-created reservoirs have the capacity to hold about as much water as there is in Lake Michigan. (Source: storage capacity data from Vörösmarty & Sahagian, 2000; lake volume data from van der Leeden, et al., 1990)

An important, though often underappreciated, use of surface water is the maintenance of environmental flows, which are required to sustain riverine and estuarine ecosystems and to maintain other natural river processes.

In resource management best practices, a sufficient amount of river water is allotted to environmental flows, just as water is allotted to agriculture, industry and communities. Environmental flow requirements are complex and varied, involving quantity, quality and timing of the water flows.

Comprehensively defining and maintaining the required environmental flows is challenging, due to hydrological variability, the difficulty and expense of waste treatment scale-up, water resource disputes between countries/states/provinces and a lack of quantitative data on relationships between river flows and river ecology (Smakhtin and Anputhas, 2008).

As river basins approach closure, maintaining adequate environmental flows becomes more difficult since they reduce the amount of water available for other potential uses. Ensuring adequate environmental flows in rivers has not been a high priority in most countries.

Generally, little respect has been paid to the natural ecology of river basins and the biological, chemical and physical interactions within the watersheds (Smakhtin and Anputhas, 2008).

For example, environmental flow requirements of the Indus River in Pakistan are not met 11 months of the year, while the Ganges River in India faces environmental flow deficits eight months of the year (Jägermeyr, et al., 2017).

Pakistan's environmental flow deficits make up 31 percent of modelled global deficits, while India's make up 18 percent (Jägermeyr, et al., 2017). These deficits are largely due to surface water withdrawals for irrigation.

4. Groundwater over-extraction is causing long-term depletion of aquifers

Groundwater is an important and increasing source of water for farms, industry and cities. Groundwater occurs in porous underground formations, or aquifers, that are naturally recharged over time by rainwater infiltrating into the ground. Some aquifers are very porous and extensive, while other aquifers are less porous and of limited extent.

Groundwater recharge depends on the timing and amount of precipitation and on land surface characteristics and subsurface geology. Groundwater is removed from aquifers both by natural drainage and by extraction from wells and boreholes.

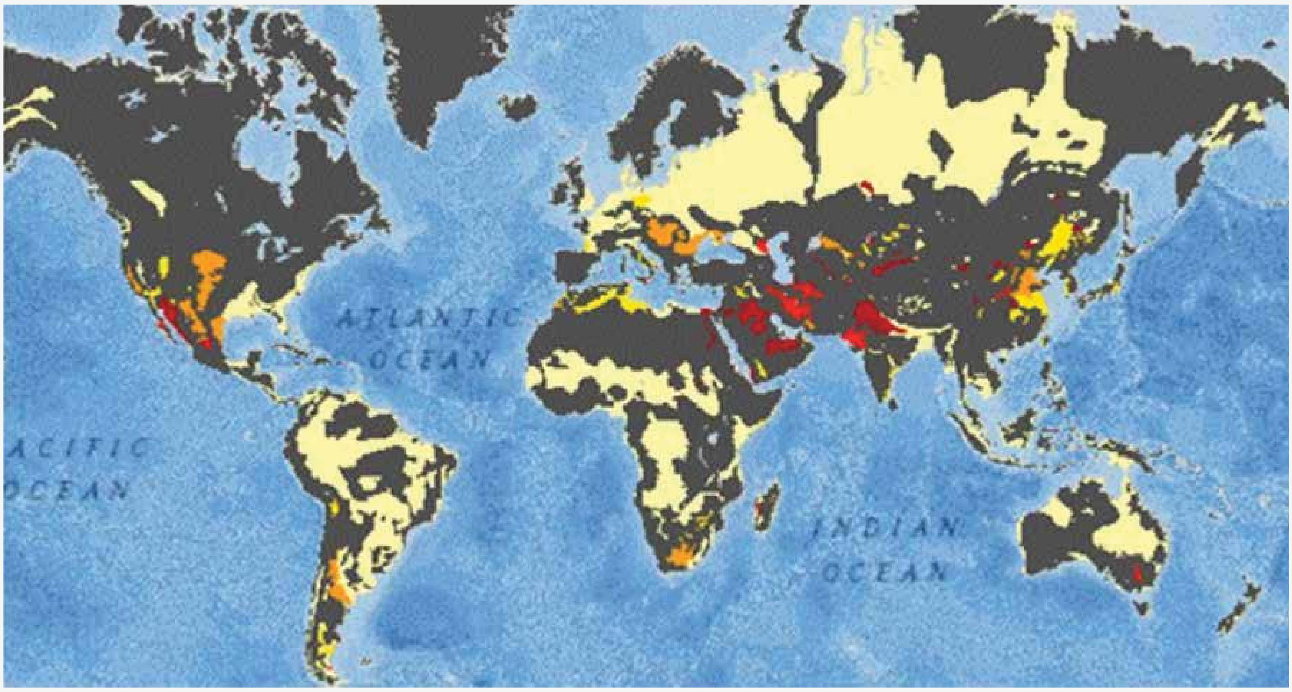
When the rate of removal exceeds the rate of recharge, the water table, or the level of groundwater in the aquifer, drops.

A distinction can be made between renewable and non-renewable groundwater sources. Renewable groundwater sources are periodically replenished when sufficient precipitation infiltrates the soils or when floodplains become inundated. When groundwater is extracted faster than its rate of replenishment, the aquifers gradually become depleted.

In addition, non-renewable or fossil groundwater sources are typically locked in deep aquifers that have little or no long-term source of replenishment. When this water is extracted, it is effectively mined and the aquifer will eventually be depleted.

Exhibit 8 shows regions experiencing groundwater stress, where extraction is greater than replenishment. The regions most affected include South Asia, the Middle East and North America.

Groundwater stress



- Low
- Low to medium
- Medium to high
- High
- Extremely high
- No data

Exhibit 8: Groundwater stress due to overexploitation of aquifers occurs primarily in South Asia, the Middle East and North America. Most of Africa has low groundwater stress. (Source: WRI, 2018b)

Globally, about 18 percent of gross irrigation water demand in the year 2000 was met with non-renewable groundwater extraction (Wada, et al., 2012). **Exhibit 9** shows the sources of water used globally for irrigation in 1960 and 2000, during which time the share of non-renewable groundwater increased from 12 percent to 18 percent.

In absolute terms, the use of non-renewable groundwater more than tripled, from 75 to 230 cubic kilometers per year.

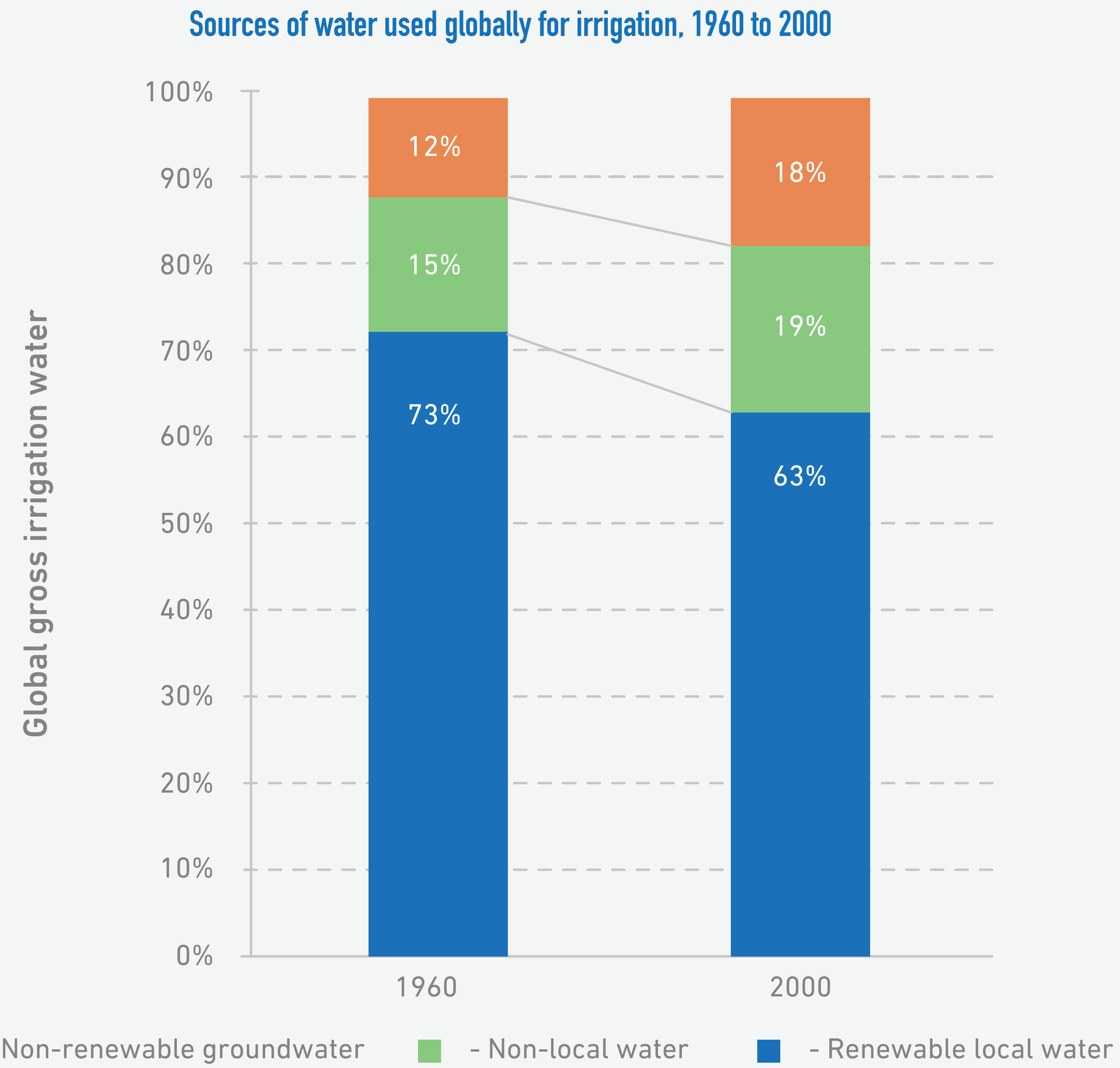


Exhibit 9: Between 1960 and 2000, the share of non-renewable groundwater increased from 12 percent to 18 percent of global gross irrigation water. The share of non-local water resources, transported to the regions via canals and pipelines for example, increased from 15 percent to 19 percent of global gross irrigation water. Renewable local water comprised a smaller share of global gross irrigation water in 2000 than in 1960. In absolute terms, gross irrigation water use increased two-fold (from 630 to 1,340 cubic kilometers per year) and non-renewable groundwater use increased three-fold (from 75 to 230 cubic kilometers per year), between 1960 and 2000. (Source: Wada, et al., 2012)

Relatively few countries, including India, Pakistan, and the United States, are responsible for most of the non-renewable groundwater use (Gleason, et al., 2012).

Exhibit 10 shows that in 2000 India used more non-renewable groundwater for irrigation than any other country. About 19 percent of India's irrigation water came from non-renewable sources.

Other countries used less amounts of non-renewable water, but it comprised larger proportion of their total irrigation water use. In both Pakistan and the United States, the share of non-renewable groundwater was 24 percent; in Iran it was 40 percent. In Libya and Saudi Arabia, more than 70 percent of irrigation water was sourced from non-renewable groundwater (Wada, et al., 2012).

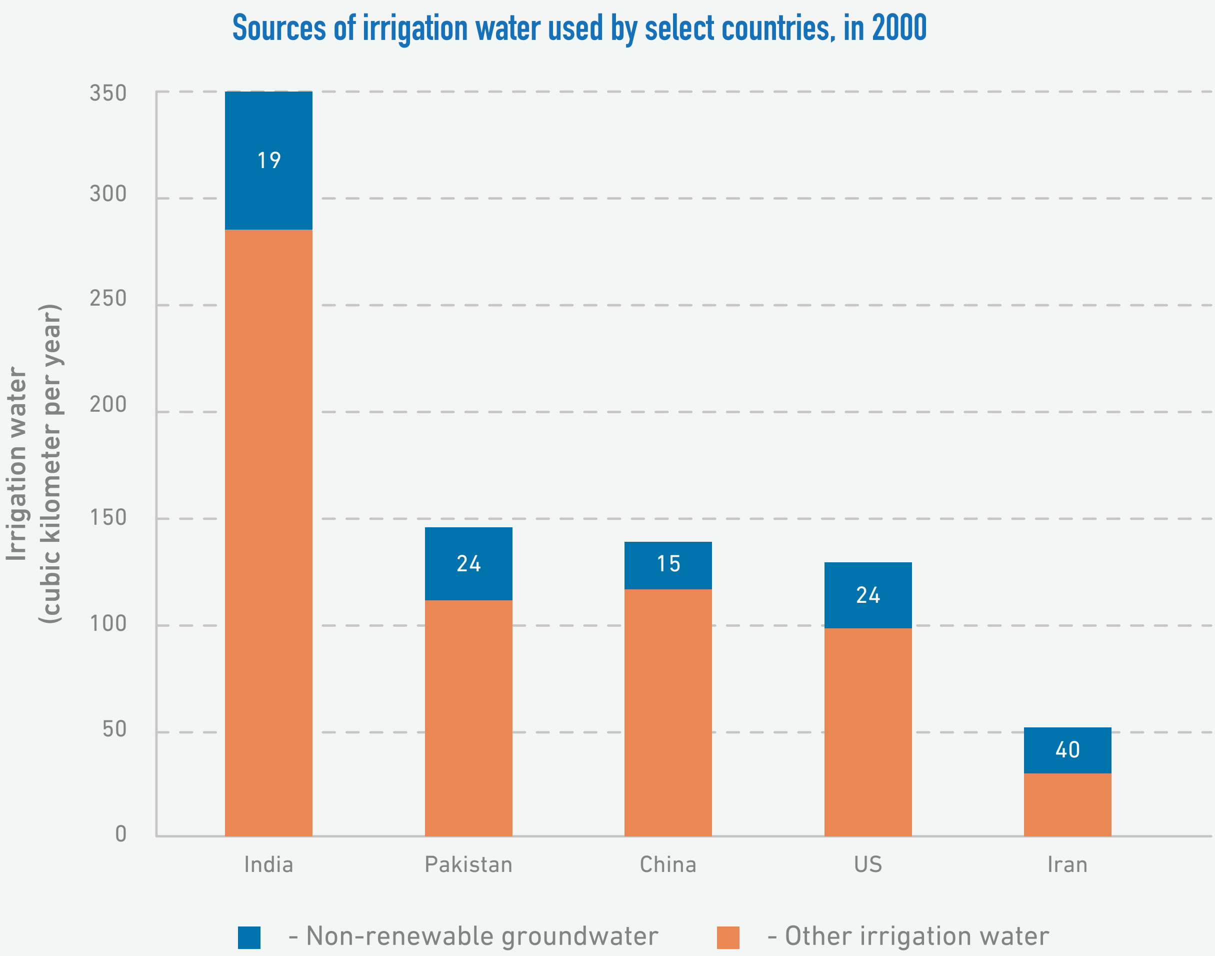


Exhibit 10: Non-renewable groundwater is a significant part of gross irrigation water use in several major countries. The numbers in the blue bars show the percentage of irrigation water that comes from non-renewable groundwater. 'Other irrigation water' includes non-local water and renewable local water. (Source: year 2000 data from Wada, et al., 2012)

Groundwater depletion affects global development primarily due to its impact on food security. It limits the amount of water available for agriculture and other human uses and makes the available water more difficult to obtain.

As groundwater supply becomes more limited, wells may go dry intermittently or constantly. Wells may need to be extended deeper to reach water and more energy is needed to pump water from greater depths.

Water quality of depleting freshwater aquifers may deteriorate due to intrusion of brackish water from surrounding aquifers.

Land surfaces may subside, or gradually lower in elevation, as aquifers below become depleted. Unsustainability of groundwater use for irrigation is a concern not only for countries that are using groundwater intensively, but also for the world at large since international trade directly links food production in one country to consumption in another.

As a human development challenge, South Asia is particularly affected by aquifer depletions (**Exhibit 11**). Groundwater use increased rapidly in South Asia after the 1960s, as a key component of Green Revolution agriculture, based on boreholes and motorized pumps.

Groundwater is now a major source of water in the region for agriculture, households and industry. Strategies for future food security in South Asia must account for eventual constraints to groundwater extraction.

Groundwater depletion in South Asia

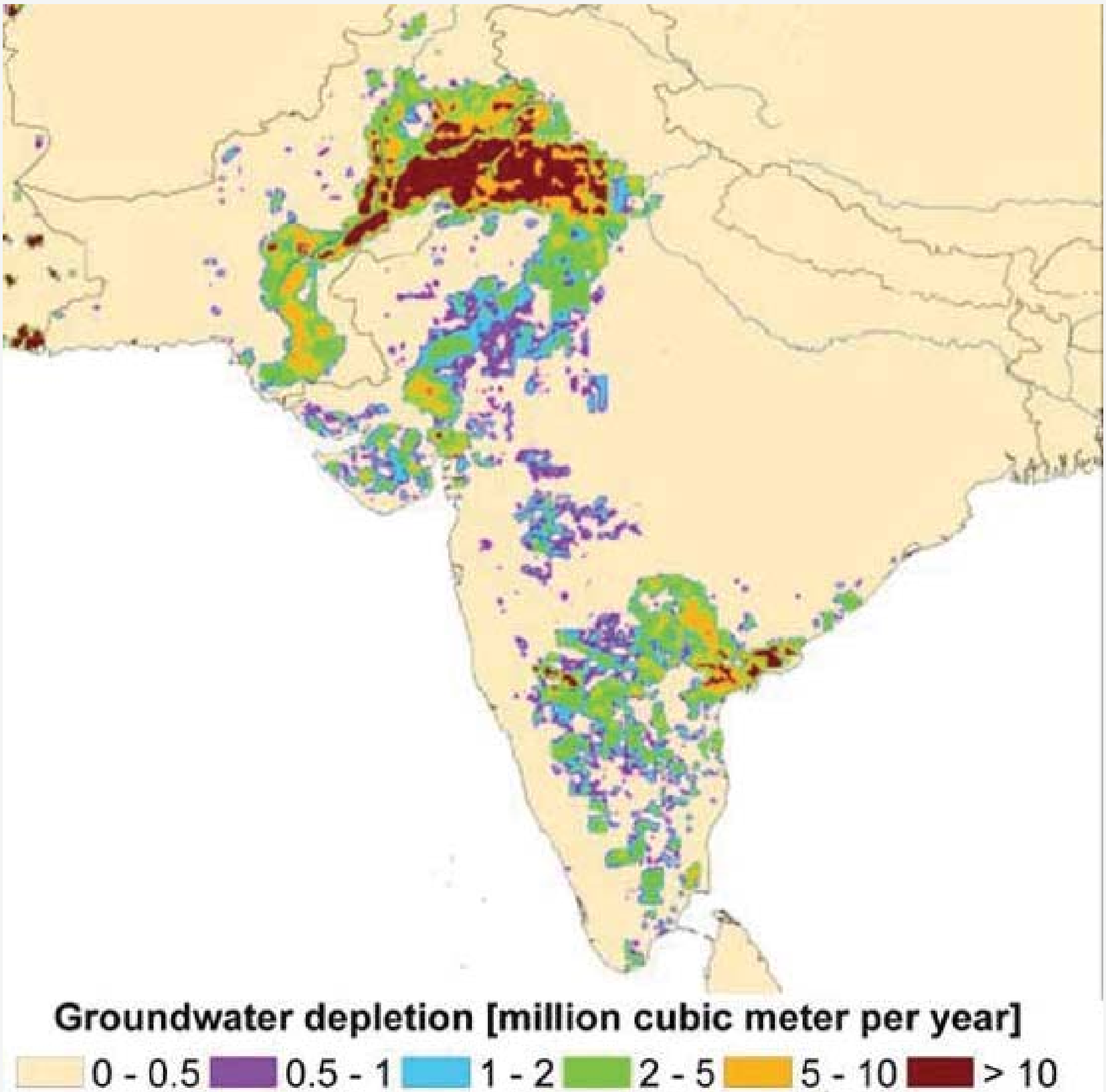


Exhibit 11: When abstraction of groundwater is greater than its replenishment, depletion of stock occurs. Current estimated groundwater depletion rate in South Asia is here shown in units of million cubic meters per year per grid cell (grid cells are 0.1 degree latitude by 0.1 degree longitude, or approximately 10 kilometers by 10 kilometers at the equator). (Source: Wada, et al., 2016)

Most of peninsular India is underlain by geologic formations often referred to as hard rock. This is a generic term applied to igneous and metamorphic rocks, such as granites, basalts, gneisses and schists.

In hard rock regions, limited quantities of groundwater are stored in the weathered soil and subsoil layers (typically tens of meters deep) that overlay the bedrock. The bedrock itself has zero primary porosity, but limited secondary porosity due to cracks and fissures where groundwater could enter.

The storage volume for groundwater in hard rock regions is thus very limited, confined to the shallow soil layer and some deeper cracks, and may deplete seasonally upon heavy pumping.

Groundwater in hard rock is characterized by limited productivity of individual wells, unpredictable variations in productivity of wells over relatively short distances and poor water quality in some areas. In hard rock regions, groundwater supply is limited and discontinuous, thus may not be available regardless of the number or depth of borewells.

Groundwater over-extraction in hard rock regions leads to rapidly falling water tables and seasonal depletion, imposing hard limits on groundwater extraction rates. In some regions of peninsular India, rising demand for groundwater vastly exceeds annually recharged amounts, leading to rapidly falling water table and many wells that are seasonally or permanently dry. Due to the high density of wells, interference between wells is common in hard rock areas where neighboring wells compete for limited groundwater.

In contrast to hard rock regions, alluvial regions have thick porous aquifers that contain large amounts of groundwater. Thick and unconsolidated alluvial formations that are conducive to recharge are found in the Indus-Ganges-Brahmaputra basins in Pakistan, northern India and Bangladesh. Within the alluvial aquifers of the Indus-Ganges-Brahmaputra basin, there is a strong distinction between the relatively arid northern region and the more humid eastern region. Groundwater over-extraction in the northern region is leading to steadily falling water tables, gradually requiring deeper wells and increased pumping effort.

This primarily affects the Punjab region in India and Pakistan, as well as western Rajasthan, northern Gujarat and Haryana states in India, where water tables in some areas are declining by about 1 meter per year.

Depending on the water table decline rate and the aquifer thickness, groundwater over-extraction can continue for many years. Alluvial formations in the Indus-Ganges basins are hundreds or even thousands of meters thick.

As technologies for deep well drilling are available, the constraining factor is the additional energy needed for pumping as the water table becomes deeper. Although abundant groundwater stores now exist in these alluvial formations, the extraction and use of this stored water for current and near-future requirements raises questions of intergenerational equity and how future generations of South Asians will access water.

Groundwater remains abundant in the eastern Ganges and Brahmaputra regions of South Asia, which have greater rainfall than the eastern Ganges and Indus regions. In these wetter regions, the phenomena often described as the Ganges Water Machine operates (Revelle & Lakshminarayana, 1975; Amarasinghe, et al., 2016):

The more groundwater that is withdrawn before the onset of the monsoon, the more space is created for water to recharge. This was confirmed to occur by Shamsudduha, et al. (2011), who found that increased groundwater extraction has increased overall extent of groundwater recharge in Bangladesh during recent decades. Thus, in the eastern Ganges and Brahmaputra regions, groundwater from alluvial aquifers does not face the problem of over-extraction and is unlikely to do so in the future.

Most regions of sub-Saharan Africa also have relatively abundant renewable groundwater resources (MacDonald, et al., 2012). Groundwater in these regions can be used as a poverty alleviation tool, though at present this is hindered by economic water scarcity, which is described in detail later in this chapter.

5. Urban water demand is increasing rapidly due to population growth and urbanization

The number of people living in cities worldwide is projected to increase by 58 percent from 2018 to 2050, due to a combination of overall population growth and increasing urbanization (**Exhibit 12**).

In Africa, the urban population is projected to increase by more than 170 percent by 2050, and in Asia by more than 50 percent. Currently, global urban population increases by about 80 million individuals per year (calculated based on UN, 2017 and UN, 2018). In Africa and Asia, urban population is currently increasing by about 19 million and 48 million people per year, respectively.

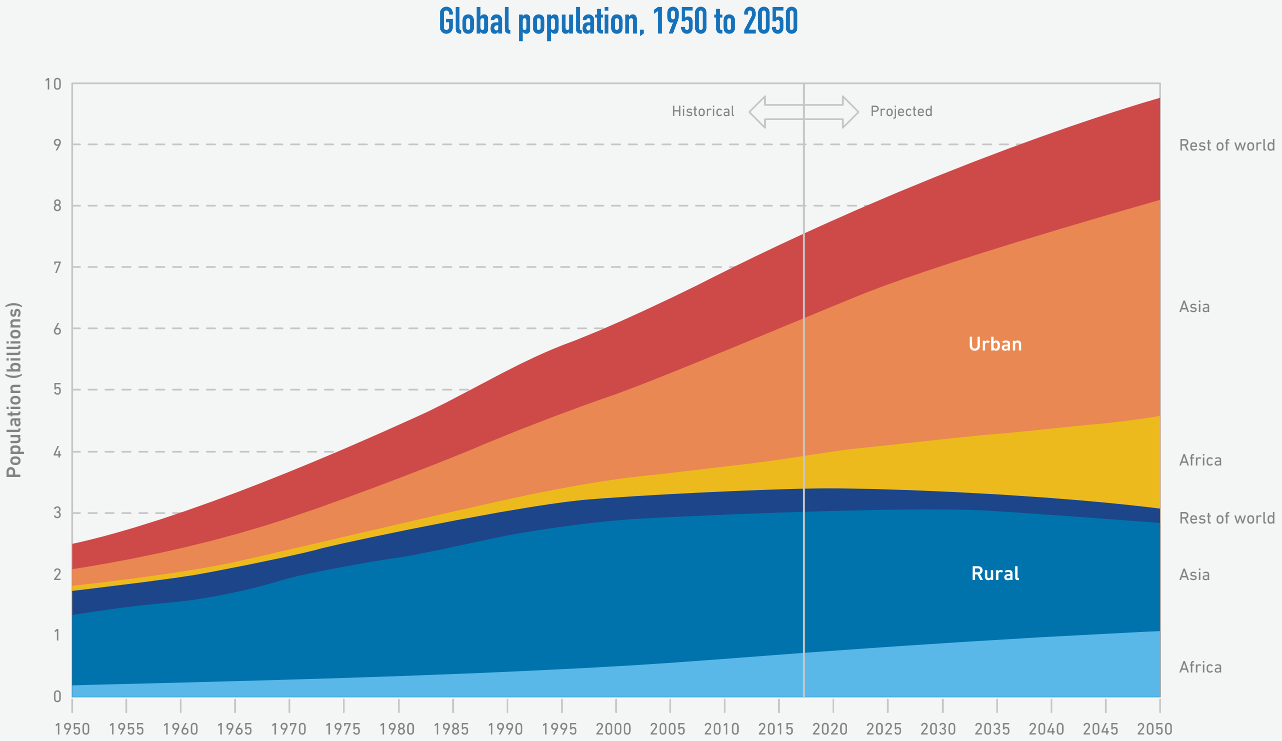


Exhibit 12: : Urban population is rising rapidly due to growing total population as well as increasing urban proportion, particularly in Africa and Asia. (Source: total population from UN, 2017 medium fertility projection; urban percentages from UN, 2018)

This increase in population is causing a rapidly growing demand for urban water consumption. Urban areas need water for both household use and industrial use. Household water use varies widely, depending on climate, affluence, household size and ease of access to water supplies.

The UK Environment Agency reports that UK households use is about 150 liters per capita per day, while households in Denmark, Finland, Netherlands, Germany and Austria use between 115 and 135 liters per capita per day.

The Bureau of Indian Standards recommends a minimum of 135 liters per capita per day for communities with water-based (meaning. flushed) sanitation (BIS 1993), while surveys show actual water consumption among Indian households varies widely both geographically and socio-economically, with an average of about 92 liters per capita per day (Shaban & Sharma 2007).

Municipal water utilities in Africa provide a wide range of per capita piped supply, ranging from 240 liters per capita per day in Johannesburg, South Africa to only 7 liters per capita per day in Bangui, Central African Republic (World Bank, 2012) (see **Exhibit 13**). Urban residents in underserved cities (like Bangui) must access needed household water from other sources, such as local wells and tanker truck deliveries.

Aggregated per capita urban water supply statistics mask the inequity between citizens, with the poorest residents barely securing water for subsistence, while the richest residents enjoy abundant water supply. This is described further in the section on economic water scarcity.

Continuity and per capita supply of select water utilities in African cities

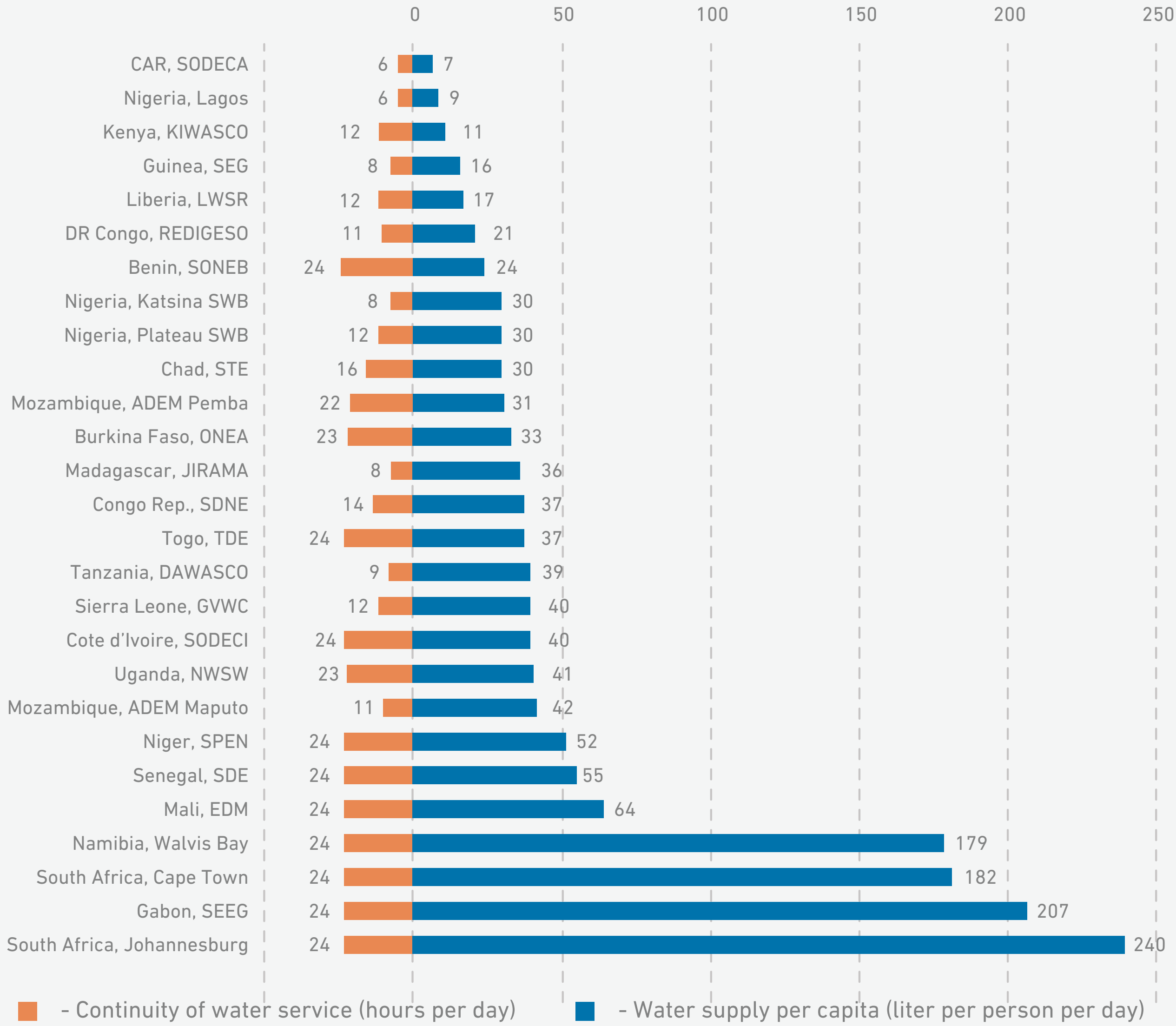


Exhibit 13: Per capita water supply by African municipal water utilities varies widely from city to city. In cities where insufficient water is supplied by utilities, residents must access needed water from other sources. (Source: World Bank, 2012)

In addition to household use, another important demand for urban water is industries. Particularly water-intensive industries include steel, textiles, pulp and paper. Some industries, located in urban areas, use water from municipal supply systems. Other industries obtain water from local surface and groundwater sources (see **Exhibit 14**). In cities with water stress, the industrial water demand competes with household water demand to obtain adequate essential water supply.

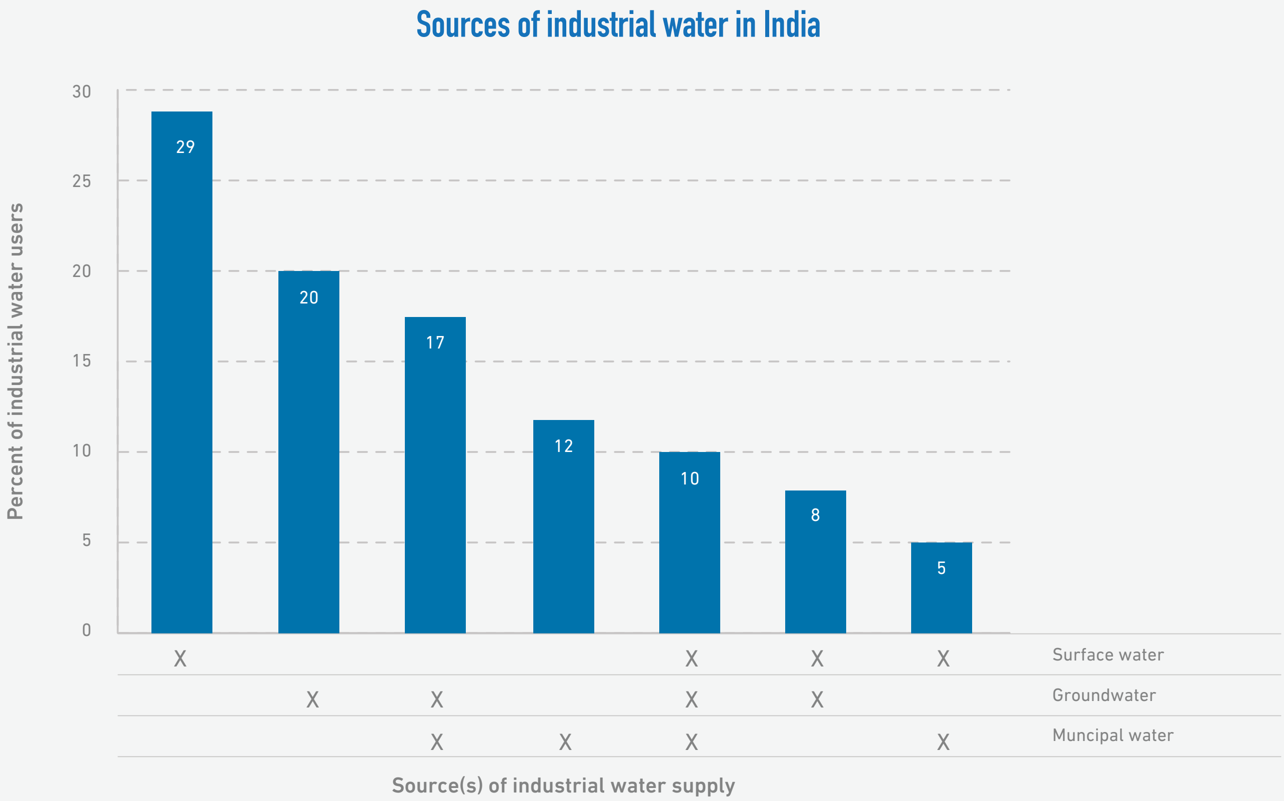


Exhibit 14: Indian industries access water from various sources, including surface water, groundwater and municipal water systems. (Source: data from Perveen, et al., 2012, based on survey of Indian industries)

Many cities in developing regions already struggle to provide adequate water supply to their citizens. As noted earlier in this chapter, current water use in some regions is approaching or exceeds local sustainable supplies of surface and groundwater. Rapidly rising urban water demand from growing cities contributes to this overexploitation.

Cities dependent on groundwater supplies for household water supply, such as Dhaka, Chennai, Nairobi and Addis Ababa observe falling water tables requiring increased drilling and pumping costs. Cities dependent on surface water, such as Bengaluru and Hyderabad, face intermittent or insufficient supply.

Reliable water supply is already challenging in many cities due to growing demand and aging and insufficient infrastructure. In 2019, the Indian city of Chennai ran out of water for its millions of residents, and in recent year major cities like São Paulo and Cape Town have nearly suffered the same fate.

Projections of future urban water supply and demand suggest these problems will intensify, with huge water deficits emerging in the coming decades in many cities (Flörke, et al., 2018) (**Exhibit 15**).

Mismatch between urban water supply and demand will impact human development in several ways. First, the health of (poorer) urban populations will suffer, due to drinking contaminated water or unsanitary conditions resulting from water scarcity.

Second, the economic potential of urban areas will be reduced, due to disproportionate spending (by municipalities, households and industries) to ensure adequate water supply.

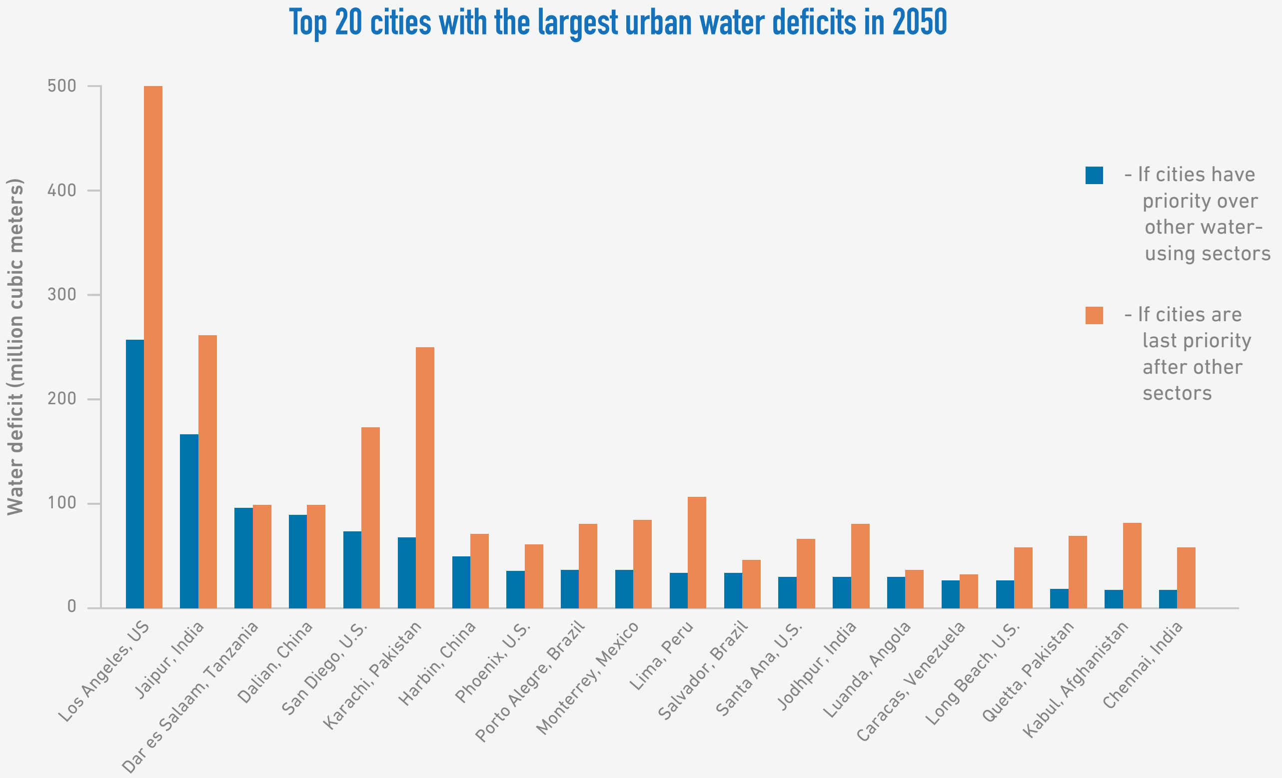


Exhibit 15: Numerous major cities are projected to experience large water deficits by 2050. (Source: Flörke, et al., 2018)

Although the absolute quantity of water supplied to urban residents is smaller than that used by agriculture, water use in cities is concentrated with a high level of use in a relatively small geographic area.

Furthermore, each liter of urban water generates more value in social and economic terms than a liter of irrigation water. This is because households require timely water access for essential household activities like drinking, cooking, cleaning and sanitation and because industrial activities generate relatively high economic returns from water use.

For example, urban health and hygiene depends on water for the functioning of modern sewage systems. An adequate and reliable supply of water to cities remains essential for civil living.

Within an area, cities tend to appropriate water from agriculture through many different formal and informal mechanisms due to the absolute need for household water coupled with the economic concentration of urban population (Molle & Berkoff, 2006).

6. Virtual water flows can partially overcome physical water scarcity

The importation of food, feed and fiber products from more water-abundant regions has long been a livelihood strategy for populations in some water-stressed regions. Bringing water-intensive products from elsewhere avoids the need to use scarce local water for their production.

Virtual water describes the water used to produce a crop, which then virtually flows with the harvested crop when it is transported elsewhere. Virtual water flow typically takes the form of market-based food trade but also occurs in the form of humanitarian food transfers.

Between countries, import and export of virtual water represents a potential lever for enhancing future global food security, depending strongly on economic factors. National food availability can increase without increasing national water stress by increasing imports or reducing exports of food products.

Presently, Australia and several North and South American countries are the greatest exporters of agricultural virtual water, while Japan and several European countries are the greatest importers (see **Exhibit 16**). Most African and South Asian countries are net importers of food calories (**Exhibit 17**).

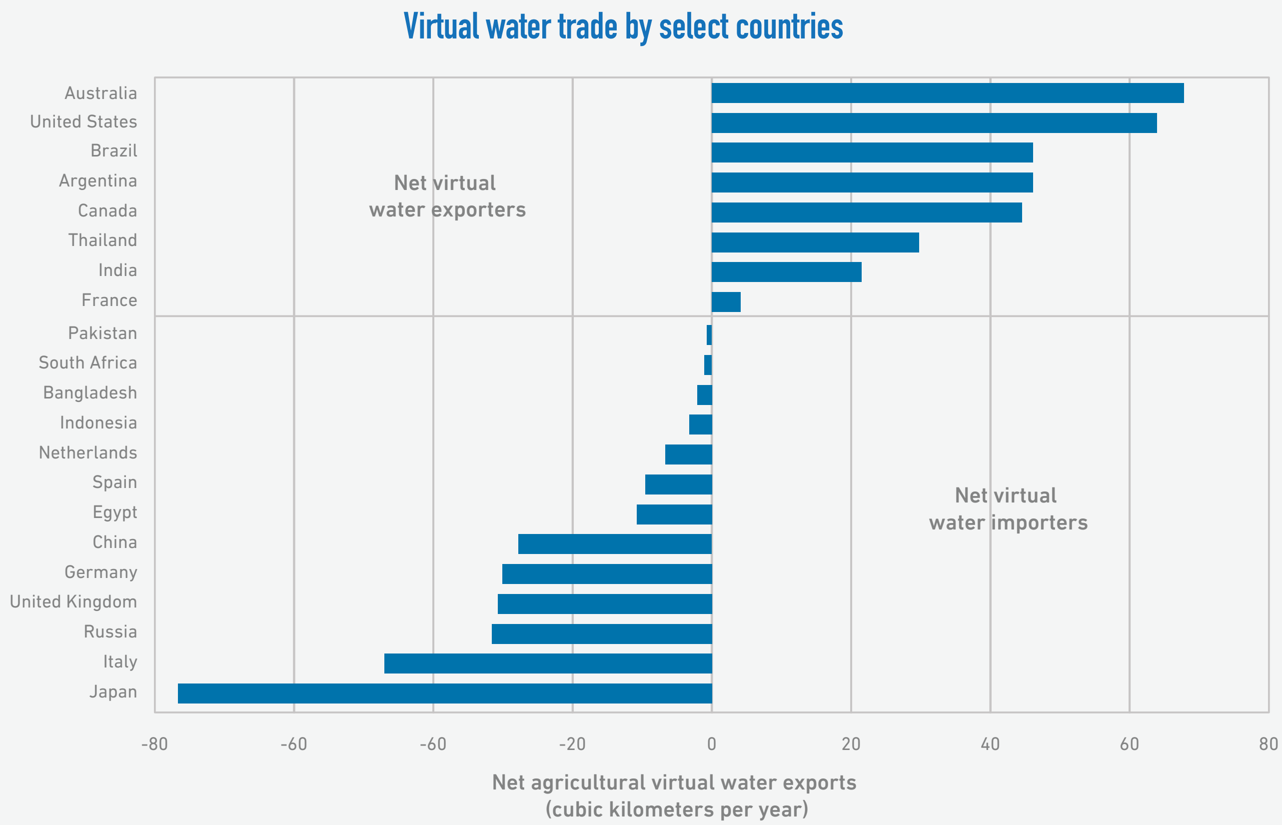


Exhibit 16: Virtual water flows between countries whenever water-intensive commodities, such as food, feed and fiber are traded internationally. Major exporters of agricultural virtual water include Australia and North and South American countries. Major importers of virtual water include Japan and several European countries. (Source: year 1997-2001 data from Chapagain & Hoekstra, 2008)

Percentage of net food imports in domestic food supply, measured in total calories

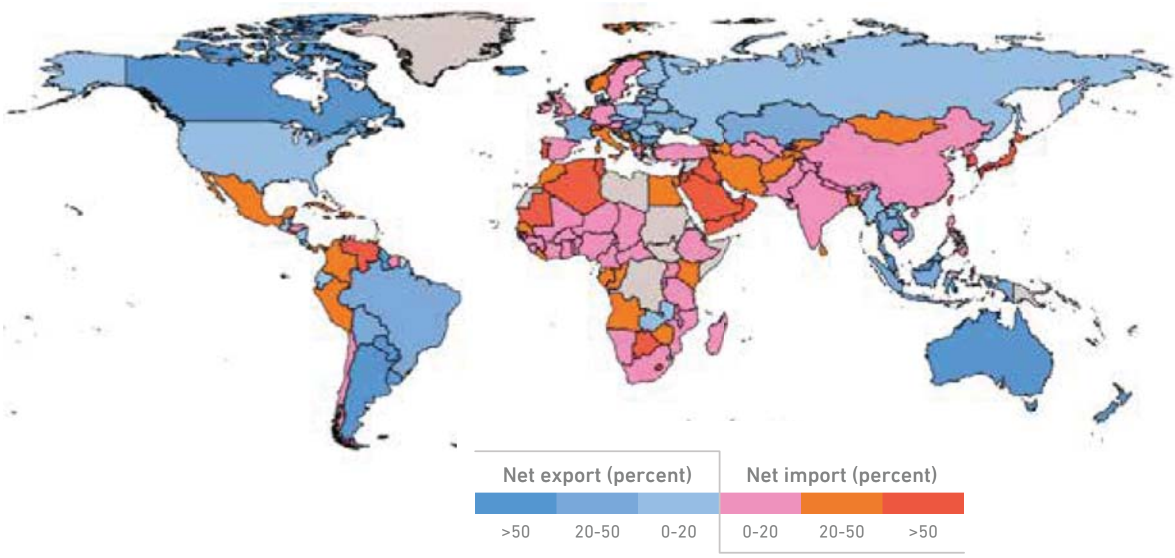


Exhibit 17: Percentage of net food imports in domestic food supply in total calories. Most African and South Asian countries are net importers of food. (Source: FAO, 2017)

Dependence on global food markets may prove risky, as many other rapidly growing nations also increasingly rely on the same markets. Furthermore, many countries that have abundant water have very little arable land resources and are therefore not able to use the available water for crop production (Kumar & Singh, 2005).

Relatively few countries have both high arable land availability and total water sufficiency, which are needed to create agricultural surplus and become a virtual water exporting country.

Within countries, significant virtual water trade also occurs. Within India, however, virtual water flows from water-scarce regions to water-rich regions. Among Indian states, Punjab exports the most virtual water while Bihar imports the most virtual water (see **Exhibit 18**).

Virtual water trade by Indian states

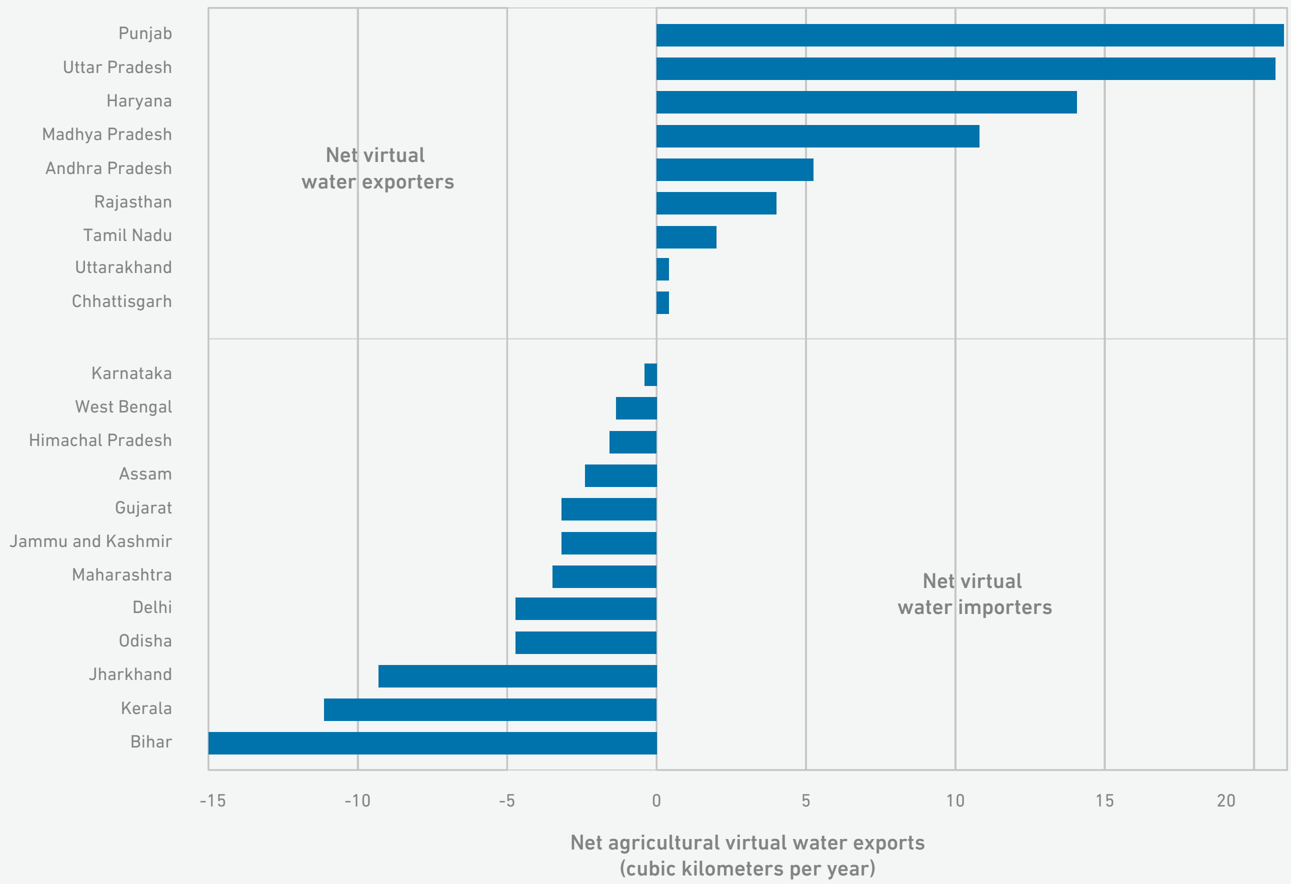


Exhibit 18: Water-intensive agricultural commodities are traded between Indian states and represent flows of virtual water from exporting to importing states. Among Indian states, Punjab and Uttar Pradesh export the most virtual water, while Bihar and Kerala import the most virtual water. (Source: year 1997 to 2001 data from Kampman, 2007)

The virtual water exported from Punjab state is from largely unsustainable groundwater, while Bihar state possesses abundant unutilized groundwater resources.

The reason for this mismatch is that the water-rich regions have relatively little arable land and are unable to fully utilize their abundant water (Kumar, et al., 2012).

Under such conditions, virtual water trade becomes a solution for land scarcity and cannot concurrently be used to solve water scarcity.

7. Rainwater harvesting is locally important during parts of the year, but has limited scope in drier regions

In many developing regions, the majority of annual rainfall occurs during just a few months of the year, while little rain falls during the remainder of the year. There are also large geographic variations in terms of the average annual rainfall, which determines the amount of rainwater resources available in any given region.

A further challenge is introduced by year-to-year variability in rainfall: drier areas not only receive less rainfall on average, but also have more variable rainfall from year to year around that average.

These three sources of rainwater variability—seasonal, geographic and year-to-year—pose significant challenges to the sufficiency of water supply. The rationale for capturing and storing rainwater is to overcome this strong variability in precipitation.

Water is fundamental to life, so reliable daily access is a must. Household water supplies that become exhausted during the dry season, or during a dryer-than-average year, are inadequate. Households may have a primary water source and several supplementary sources, but at least one source must be functional each day for healthy and hygienic domestic life.

All water supplies, including groundwater and surface water, ultimately originate from precipitation. For example, some rainwater infiltrates into the soil, from where it provides baseflow for perennial rivers, and from where it may be extracted as groundwater from wells during dry seasons.

Beyond this natural water cycling, however, it may be advantageous to use engineered infrastructure to directly capture rainwater during the rainy season and store it for later use.

This may take several forms, including small-scale surface storage (e.g. household-level rooftop capture and storage in tanks and farm-level capture of run-off and storage in ponds), large-scale surface storage (e.g. impoundment of river water in reservoirs above dams) and managed aquifer recharge (using surface structures to divert water run-off towards underground aquifers).

A related approach, atmospheric water capture, seeks to extract water vapor from the air even before it falls as rain.

While rainwater capture and storage will bring benefit to the user, it may negatively affect potential downstream users (Kumar, et al., 2008). Within closed river basins, capturing more rainfall upstream necessarily means that downstream users receive less water.

While likely inconsequential at a small scale, the creation of large dams and reservoirs or the eventual widespread implementation of rooftop rainwater capture would significantly alter regional hydrology and should be planned for accordingly.

Small-scale rainwater harvesting and storage

Rooftop collection, followed by household-level tank storage, is an option for rainwater capture and storage. It is instructive to compare the amounts of rainwater falling on house rooftops in different South Asian cities to the amount of water used by the households.

Potential rainfall capture volume is determined by the local precipitation and by the size and quality of the rooftop. In most parts of the world, the amounts of rainwater falling on house rooftops is small, compared to the amount of water used by the households.

In most areas, rooftop capture will likely be, at best, a supplemental source of household water (see **Exhibit 19**). Our analysis shows that household drinking water requirements could be satisfied by rooftop capture in most cities and for most house sizes, but total household water requirements could only be satisfied by large houses in the wettest cities.

Potential for rooftop rainwater capture in select cities

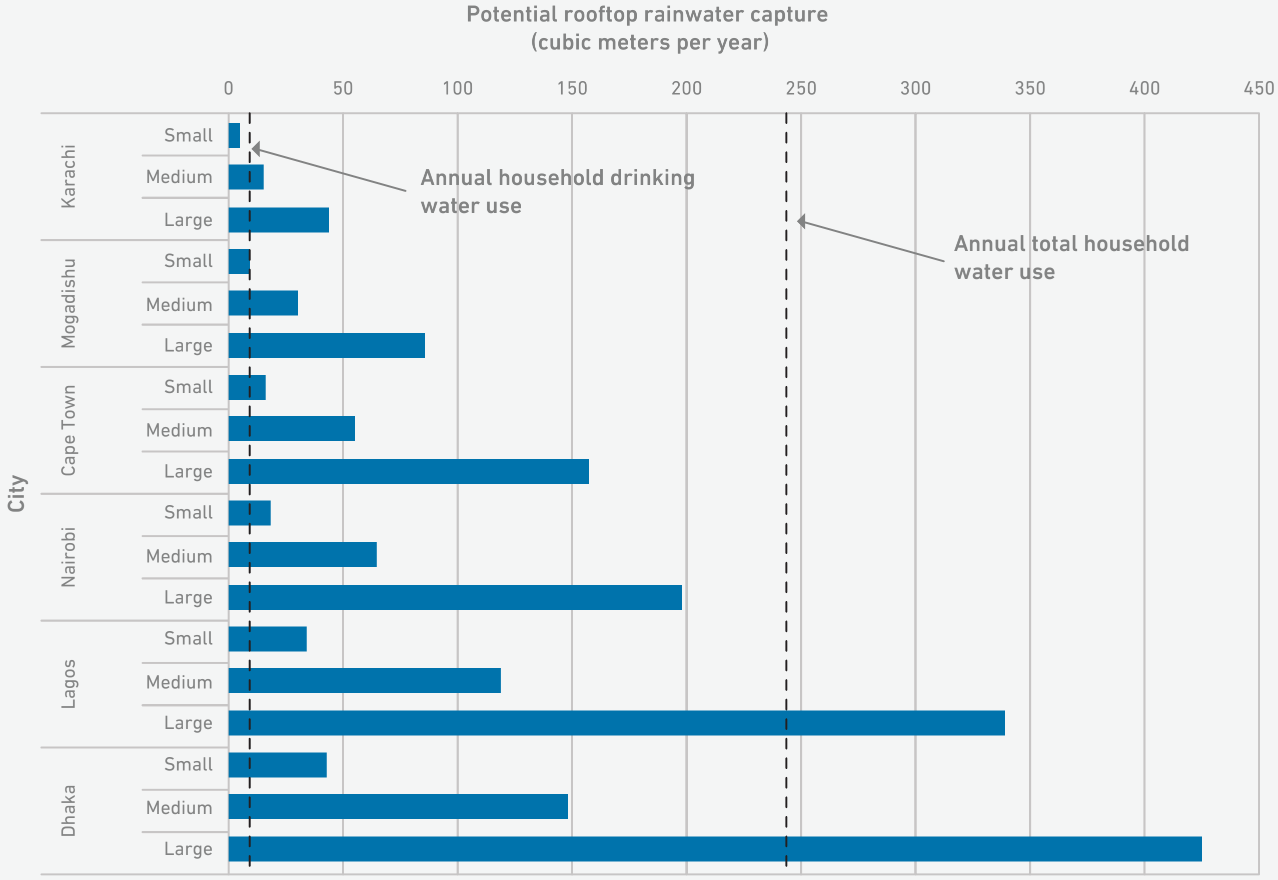


Exhibit 19: Rooftop rain capture can contribute a minor share of water supply for most households. The amount of rainfall that may be captured by a household depends on the local annual precipitation and the size of the rooftop capture area. The figure shows the potential for rainwater capture in six major cities for three different house rooftop sizes (small: 20 square meters, medium: 70 square meters, large: 200 square meters). Also shown is the estimated annual drinking water requirements (7 cubic meters per year) and total household water requirements (146 cubic meters per year) for a household of five people. (Source: ITT analysis based on average annual precipitation data from Wikipedia, 2018)

Large scale surface water storage
Where conditions are suitable, large quantities of river run-off can be captured behind large dams and stored in reservoirs from where it may later be released and used on demand.

Although some individual dams in South Asia and Africa are among the world's largest (e.g. Tarbela and Mangla Dams in Pakistan, Tehri and Bhakra Dams in India, Grand Renaissance Dam in Ethiopia, and Katse Arch Dam in Lesotho), the per capita water storage capacity in most South Asian and African countries is low compared to other global regions (see **Exhibit 20**).

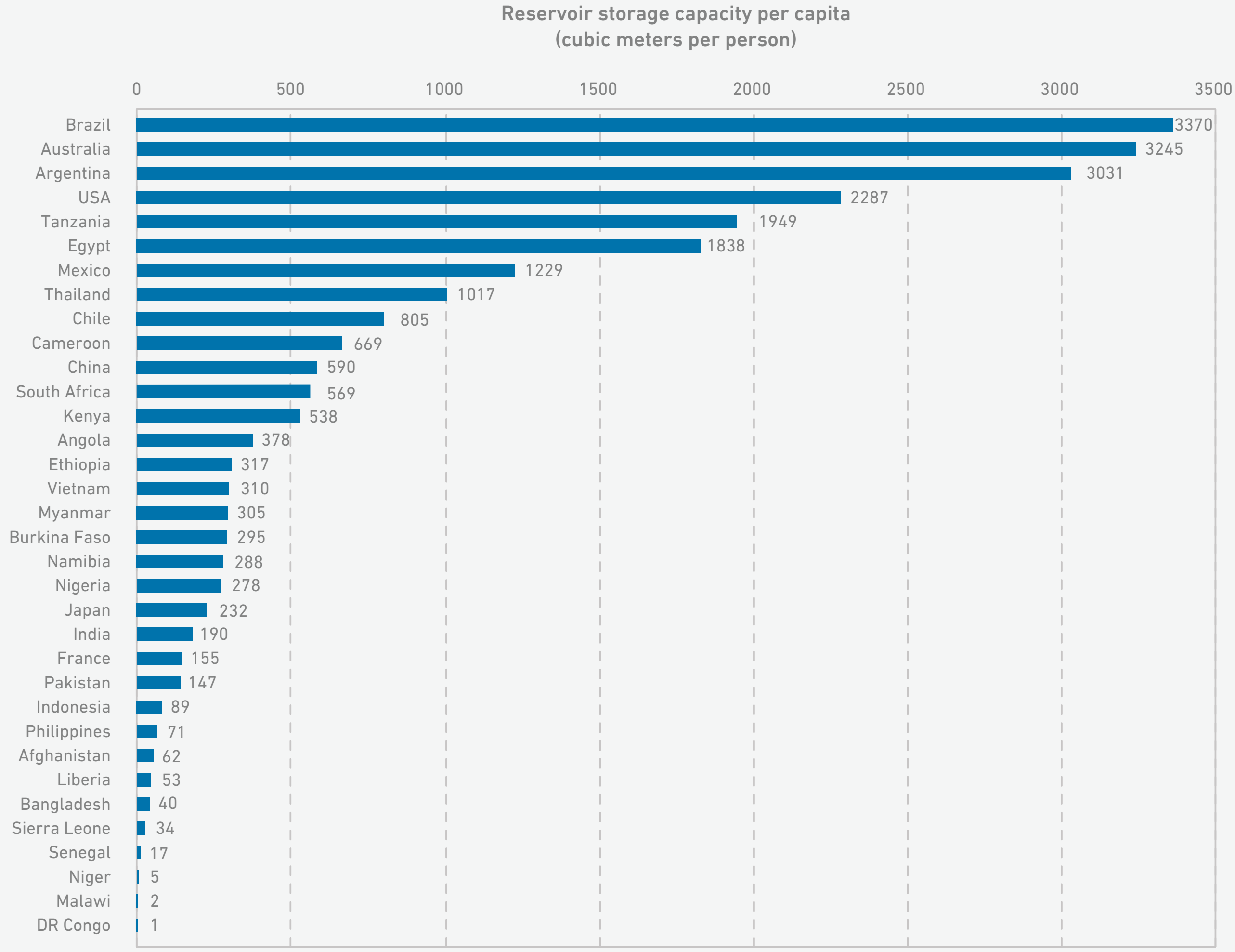


Exhibit 20: Per capita reservoir live water storage capacity for select countries. (Source: FAO, 2018a)

Potential for dam construction and reservoir creation is first determined by numerous physical factors such as landscape topology and geology, which are limiting in many regions. Decisions to build dams are also dependent on economic and social considerations.

Within each river basin, diminishing returns are found from creation of additional storage capacity as basins approach closure. Within closed basins, new dams will not increase total surface water supply but merely redistribute the supply.

Dams can also be an effective tool for river flood control. By altering the transport of fluvial sediments, dam construction also affects the geomorphology of rivers, the fertility of floodplains and the nutrient balance of rivers and estuaries (Dandekar, 2014).

While dam construction should not be dismissed as a technology for improving water security, neither should it be seen as a definitive solution. In river basins with current low storage capacity, adding well-designed dams will augment total usable water supply. In basins approaching or already at closure, which are typically the most water stressed, additional dams will not contribute to improving water security.

Managed aquifer recharging

Underground aquifers store vast amounts of water, which can be accessed by pumping from wells. The capacity for groundwater storage in most regions is much greater than surface reservoir storage capacity.

Some deep aquifers contain fossil water that was stored long ago and does not circulate, unless accessed and extracted by wells. Most aquifers, however, are dynamic and receive newer water via recharge mechanisms, while losing older water via natural discharge to rivers and oceans and groundwater pumping.

Some regions, particularly in South Asia, are currently extracting groundwater faster than the rate of natural recharge, leading to falling water tables. The rate of natural aquifer recharge is also diminishing, due to rapid urbanization and land use changes that have reduced the infiltration of water into the soil.

Managed aquifer recharge (MAR) seeks to increase the rate of groundwater recharge to allow greater rates of groundwater extraction without risk of water table decline.

MAR is achieved by reducing the fraction of rainwater that runs off the land surface, thus increasing the fraction that infiltrates through the land surface and enters the soil. This is typically implemented through engineered structures that slow the downstream flow of surface run-off water, allowing more of it to infiltrate into the ground (CGWB, 2007).

A wide range of structures are available at varying scales, including farm-level swales, check dams, percolation tanks and ponds, dams and barrages (see **Exhibit 21**).

Structures for managed aquifer recharge

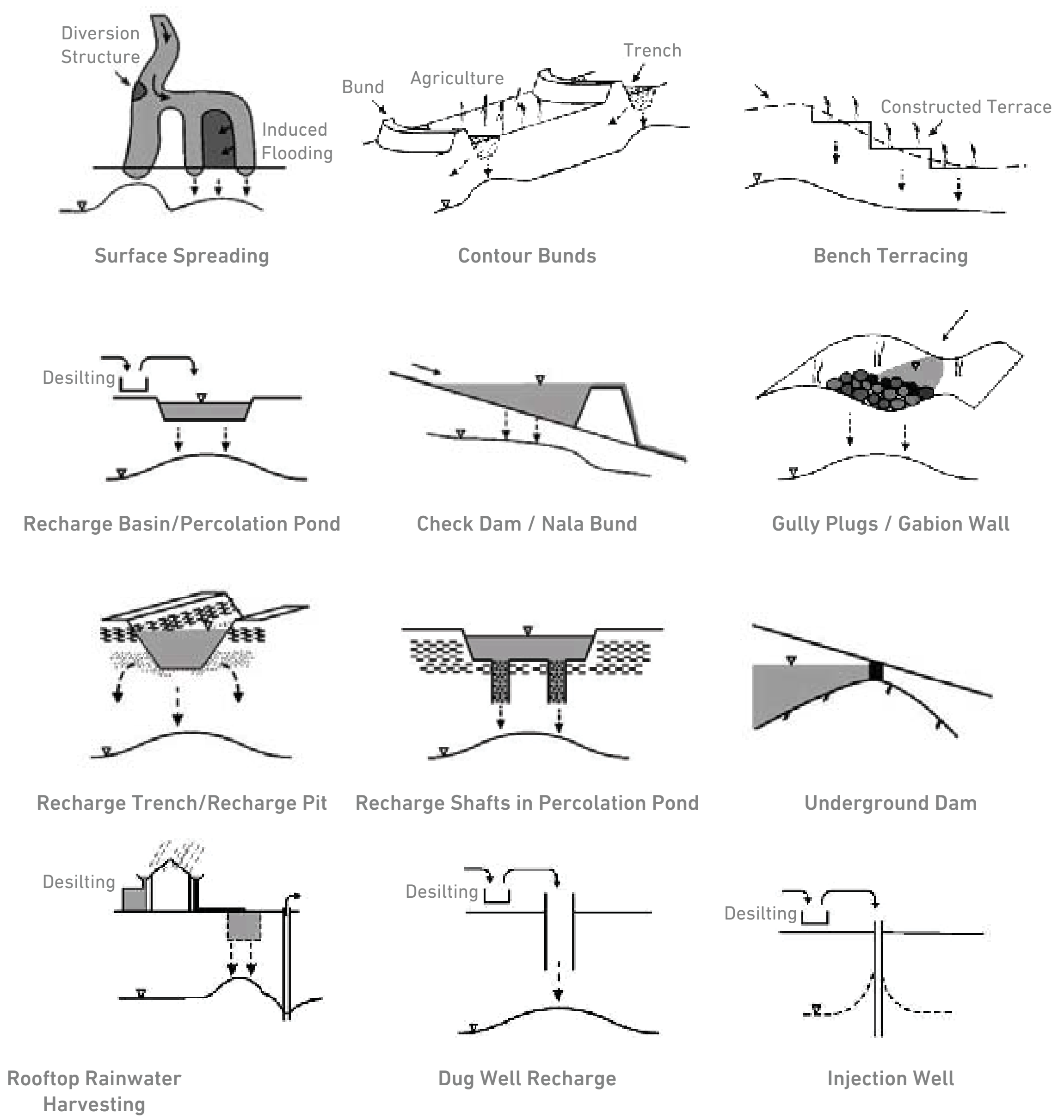


Exhibit 21: Types of managed aquifer recharge structures and their effects on the local water table. (Source: adapted from SaphPani, 2012)

MAR is suitable only in particular locations, because it requires three conditions: the availability of uncommitted surface water, the availability of underground storage space and the demand for groundwater (Shah, 2008). In dryer regions, the amount and timing of rainfall limit the amount of run-off that may be harnessed to recharge groundwater.

In regions with unsuitable geology, even if seasonal water is plentiful, there may be inadequate aquifer porosity to store significant water or there may be natural barriers between the surface run-off and underground aquifer.

In closed river basins, MAR will not increase total water supply even if local run-off and geology are suitable, because an upstream user's gain will lead to a downstream user's loss.

Furthermore, the effects of future climate change on aquifer recharging is uncertain. The amount, timing and intensity of precipitation are projected to change, though its effect on the partition of rainwater into run-off and infiltration will vary by location (see **Exhibit 22**).

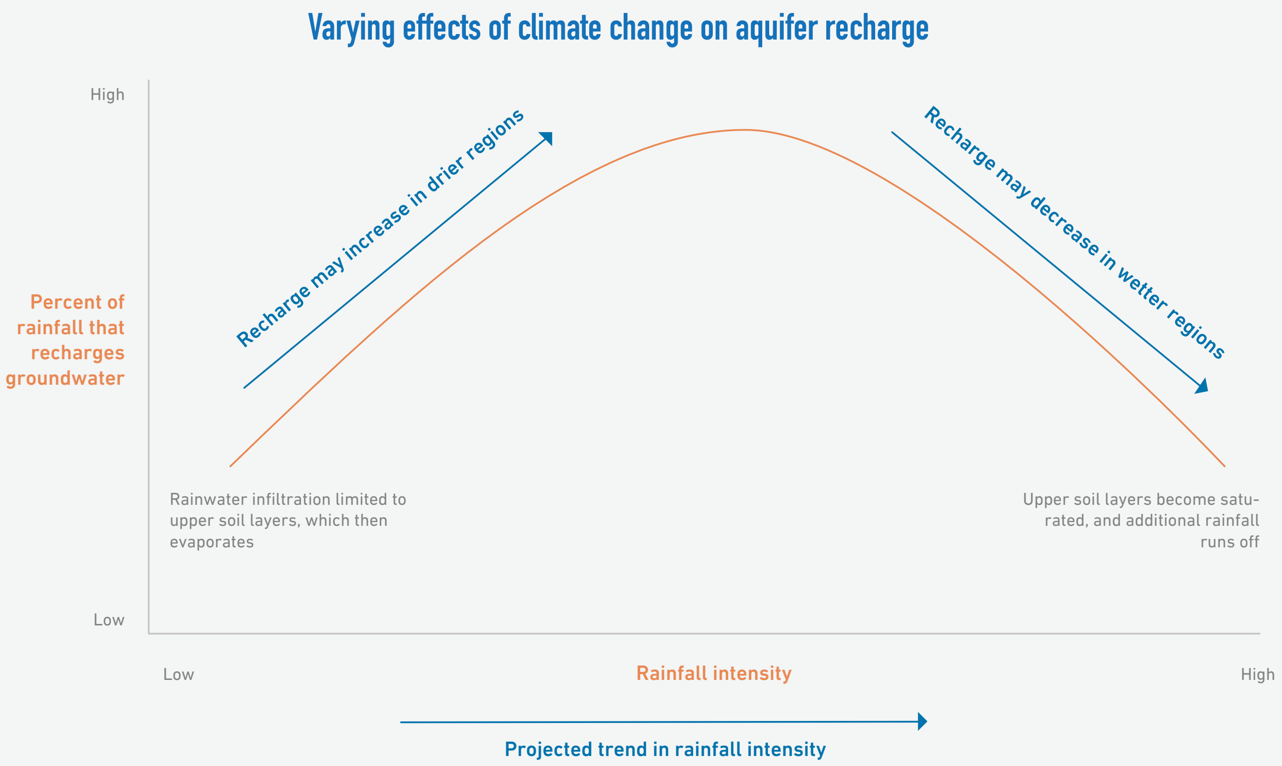


Exhibit 22: Rainfall intensity is projected to increase due to global climate change, which may have variable effects on groundwater recharge. (Source: ITT, 2018)

Nevertheless, where conditions are suitable, MAR may significantly contribute to regional water security by increasing allowable sustainable groundwater extraction rates. To be effective, however, popular mass action on a regional scale is required to cause significant improvement (Shah, et al., 2003). Ideally, groundwater should be considered a storage reservoir to smooth fluctuations and allow flexible access, not a stock to be depleted.

Atmospheric water capture

Capturing water vapor from the atmosphere is an appealing concept that is receiving substantial popular attention. Numerous methods have been proposed to access atmospheric water, including cooling a surface below the dewpoint of the ambient air, concentrating water vapor through use of solid or liquid desiccants and inducing convection in a tower structure (Wahlgren, 2001). Several types of air water generators are commercially available to provide limited quantities of drinking water, powered by either grid electricity (Peters, et al., 2013; Ecoloblue, 2017) or solar power (Zero Mass Water, 2017).

Although removing water from the atmosphere is technically possible, it is unlikely to scale as a significant source of water due to several fundamental physical challenges. First, the water vapor content per volume of air is very low (ranging from about 4 to 22 grams per cubic meter at different locations around the world), thus huge amounts of air must be handled to obtain significant water (Wahlgren, 2001). In reliably windy areas this air movement could take advantage of natural winds, though in less windy regions there will be a need for mechanical fans.

The second challenge is that water's latent heat of condensation is high, meaning that a large amount of heat energy is released when water vapor changes to liquid water (Miller, 2003). In fact, the same amount of energy that must be input to change liquid water to vapor, will be output when the vapor changes to liquid water.

To capture any significant amount of water from the air, there must be a way to reject large amounts of heat. To give a sense of scale, the latent heat released when vapor is condensed into 1 liter of liquid water is enough to raise the temperature of 1 liter of liquid water by more than 500 degrees Celsius[2]. Rejecting this amount of heat is not trivial, typically requiring active devices like heat pumps.

Atmospheric water capture can be achieved with both active and passive devices. In general, active devices powered by concentrated energy sources, such as electricity, can drive processes like heat rejection and air movement at a high rate. Passive water capture devices that use natural energy gradients, like wind and sunlight, that are less concentrated and more diffuse, will proceed at slower rates.

To capture significant amounts of water, passive air capture devices will necessarily have large active surface areas to compensate for slow unit process rates. This typically results in a large land footprint, high capital investment and/or fragility and risk of damage.

After a competition between 98 different teams to develop a device that harvests fresh water from the air, an XPRIZE of $1.5 million was awarded in 2018 to Skysource/Skywater Alliance (XPRIZE, 2018). While demonstrating that the process is indeed technically feasible, the competition also demonstrates that atmospheric water capture is far from the easiest or cheapest method of obtaining fresh water.

The winning technology uses more that 100 times the energy needed to obtain the same water from seawater desalination, and more than 250 times the energy needed to pump that amount of groundwater from a depth of 100 meters.[3] Fundamental physical challenges suggest that opportunities to narrow this huge performance gap, by radically improving atmospheric water capture processes, are limited.

Furthermore, the efficiency of atmospheric moisture harvesting is highly weather and climate dependent, varying with temperature, humidity, pressure and other factors (Gido, et al., 2016). The working conditions of the winning XPRIZE device is limited to relative humidity greater than 65 percent, and ambient temperature between 18°C and 41°C (Skysource, 2018).

Although the idea of using the atmosphere as a dependable year-round source of household water is attractive, in practice the water supplied by an atmospheric water generator would likely be highly seasonal and extremely expensive.

[2]However, the water would no longer be liquid if its temperature were raised by 500 degrees Celsius, so better to say that the heat would raise the temperature of 500 liters of liquid water by 1 degree Celsius.

[3]The Skywater device uses 230 kWh per cubic meter of water (Personal correspondence, 5 December 2018). Reverse osmosis seawater desalination uses 1.8 kWh per cubic meter (Elimelech & Phillip, 2011). Raising water 100 meters at 30 percent pumpset efficiency uses 0.9 kWh per cubic meter (ITT calculation).

KEY CHALLENGES

1. Growing demand for water

The absolute demand for water is increasing due to demographic, industrial and agricultural growth.

The number of people using household water is rising and projected to continue rising, especially in Africa (**Exhibit 23**).

Numerous new mega-cities will emerge, some in water-scarce regions with limited options for water supply. Industrial production is growing rapidly in Asia, as is industrial water use, with expectations of similar growth in Africa.

In regions of physical water scarcity, especially in parts of Asia, irrigation water needs are in conflict with urban water needs.

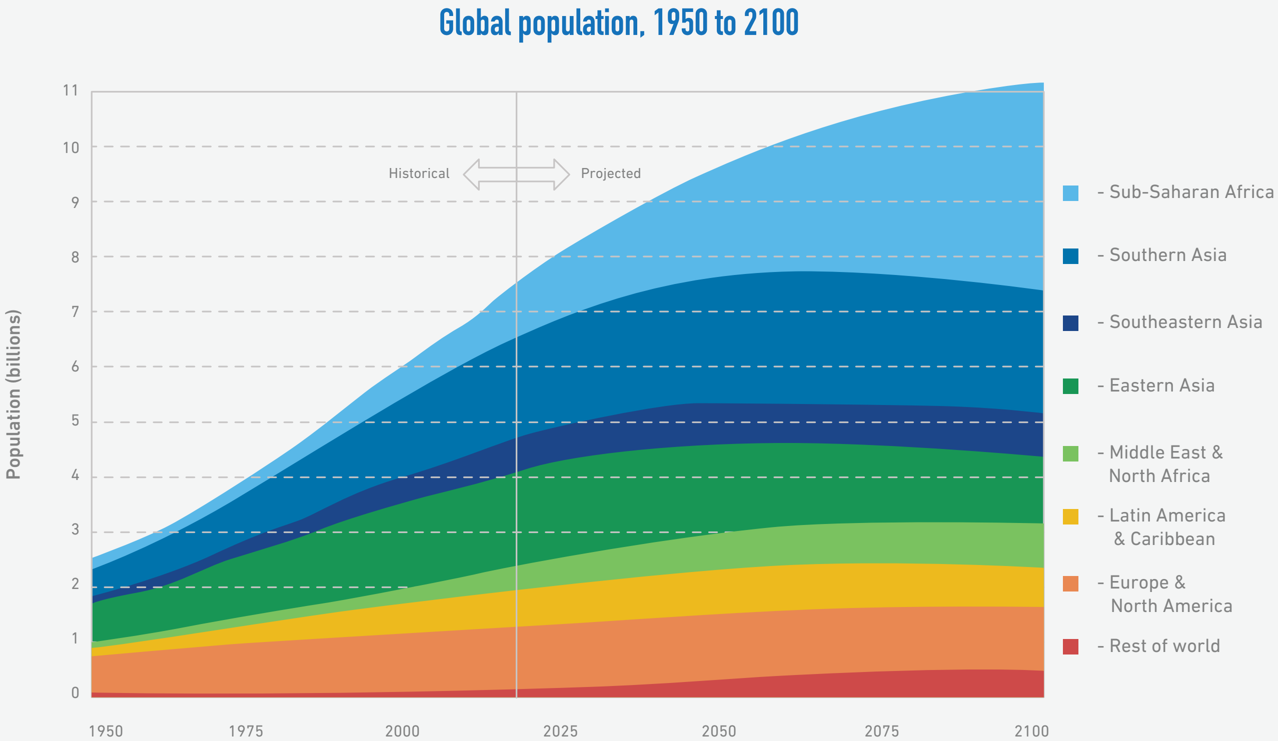


Exhibit 23: There is an expectation that global population will continue to increase during the 21st century. In particular, the population of sub-Saharan Africa is projected to increase by 370 percent between 2018 and 2100. (Source: UN, 2017, medium fertility projection)

2. Climatic variability

The availability of renewable water resources varies widely, geographically and temporally. Some regions are naturally much drier than others due to global water cycle differences. Variability across years and seasons are obstacles to reliable water supply. Global climate change is to some degree inevitable and will disproportionately impact the poor.

3. Firm geological constraints

Local absolute water resources are constrained, based on precipitation, topology and geology. The hydraulic boundaries of river basins seldom align with the political boundaries of social discourse, thus water conflicts arise. Groundwater storage is abundant and unutilized in some regions, such as sub-Saharan Africa, and overexploited and depleting in others, such as South Asia and North America.

SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

Physical water scarcity is a rapidly growing challenge, as water demand from households, farms and industries surpasses the amount of water that is locally available. The amount of renewable water, while previously adequate to meet the limited demand, is becoming insufficient to meet growing requirements for water in many regions. This is manifest in depleting groundwater aquifers and dry lakes and rivers.

The problem of physical water scarcity is exacerbated by global climate change, which is affecting the amount and reliability of precipitation. There is greater variability in weather patterns causing short term droughts of one or more years, and some regions will face long-term trends of reduced rainfall and water supply due to altered climate patterns.

Because water is essential to life, reliable access to the precious liquid must be ensured for all. Solutions to physical water scarcity will involve creating freshwater resources out of abundant yet under-appreciated liquids like seawater and wastewater.

Most water is used on farms, and therefore solutions must also enable the production of more food crops with limited amounts of irrigation water. Our analysis concludes that three technological breakthroughs can substantially reduce the burden of physical water scarcity.

Breakthroughs:

1 2 3 4 5 6 7 8 9 10
11 12 13 14 15 16 17 18 19 20
21 22 23 24 25 26 27 28 29 30
31 32 33 34 35 36 37 38 39 40
41 42 43 44 45 46 47 48 49 50

1 A low-cost system for precision application of agricultural inputs, ideally combining water and fertilizer

In some regions like South Asia, the Green Revolution has brought unfortunate consequences including over-exploitation of groundwater resources and over-application of synthetic fertilizers. In other regions like sub-Saharan Africa, the Green Revolution has not arrived and there is under-utilization of groundwater resources and ongoing nutrient mining of soils. There is need for a low-cost, robust, scalable technology to precisely meter and distribute irrigation water and fertilizer to field crops.

This would allow farmers to apply the right amounts of water and nutrients (not too much or too little) at the right time to maximize economic returns and reduce nutrient loss. If made affordable, precision application systems for irrigation and fertilizers, calibrated to local crop type and soil conditions, could be a very effective way to increase agricultural yields, while also reducing negative impacts on the environment.

Enabling better management of the timing and formulation of irrigation and fertilization in cropping systems would ensure that water and nutrients are available where and when needed by the plant roots. Crop yields respond very well with initial inputs of fertilizer, but as additional nutrients are supplied the marginal yield increase becomes smaller.

Optimal results occur somewhere along that gradient, depending on the cost of fertilizer and seeds, land and selling price of harvested crops. For maximum returns, it is necessary to not just apply the right quantity of fertilizer, but to also apply it at the right time and place for optimal nutrient uptake by the plant. This would also protect watersheds and populations downstream from farm fields, by greatly reducing runoff.

The efficiency of using agricultural inputs, such as fertilizer is low in conventional farming. It is estimated that overall efficiency of applied fertilizers is about 50 percent for nitrogen, less than 10 percent for phosphorus and about 40 percent for potassium. The rest is wasted as runoff.

The mismatched timing between availability of nitrogen and crop need for nitrogen is likely the single greatest contributor to excess nitrogen loss in annual cropping systems. Ideally, nutrients should be applied in multiple small doses and when plant demand for them is greatest.

Current State

Development Stage: Engineering

Time to market (years)

<3 4-6 7-10 10+

Deployment: Challenging

Associated 50BT Chapters

Food Security Global Change

SDG Alignment

Impact

Increased Access to Food (# of People)

<1M 10M+ 100M+ 1B+

New Income Generated (# of People)

<1M 10M+ 100M+ 1B+

Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

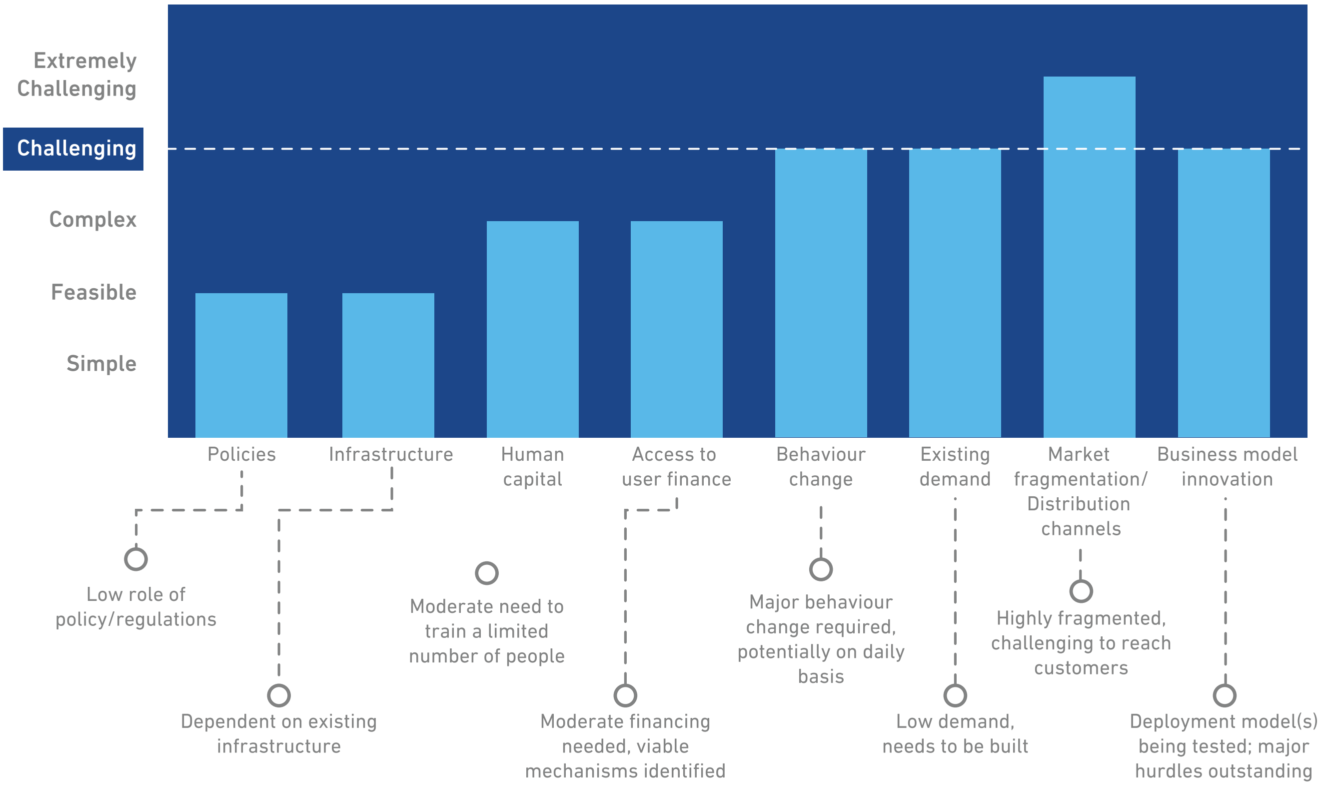
In principle, variations of existing programmable irrigation and fertigation systems used in industrialized countries can be adapted to the needs of smallholder farmers. Already, small-scale drip and sprinkler systems—along with other methods for increasing water usage efficiency—are beginning to emerge in markets like India. Cultivated area under drip irrigation in India has grown from 71 km^2 in 1992, to 2,460 km^2 in 1998, to 18,970 km^2 in 2010, up to 33,700 km^2 in 2015. The cost of such systems will continue to drop as scale of production increases.

This breakthrough would be strongly leveraged by three other breakthroughs, 5 Low-cost shallow groundwater drilling technologies, 6 Affordable solar-powered irrigation pumps, and 9 Low-cost soil nutrient analysis device. Overall, such devices would help farmers better predict crop nutrient requirements, better schedule irrigation and fertilizer applications, and avoid over-fertilization and nutrient runoff. If complemented with adjusted crop rotation patterns and additional biotic complexity, it could improve the plant community's ability to take up more of the available nutrients.

However, there is limited evidence to suggest that users—farmers or otherwise—will be interested in spending money on technologies to conserve water when the resource itself is available free of cost. The potential for saving fertilizer can prove to be a positive incentive, although the current demand for fertilizers is very low in sub-Saharan Africa.

It will face some deployment challenges that are common to the African smallholder farmer market, including structural barriers such as a fragmented market of farmers, limited access to finance for potential users, and lack of training to install, use and maintain the technology. The difficulty of deployment in this case would be CHALLENGING.

Breakthrough 1: Difficulty of deployment



2. A very low-cost scalable technique for desalinating brackish water

This breakthrough focuses on developing and enabling systems for very low-cost, high-efficiency desalination of brackish water resources. Households, industries and farms can utilize such systems to provide additional freshwater supplies for water-constrained regions. The introduction of very low-cost desalinated water could enable sustainable irrigation in vast regions of the world that contain brackish groundwater.

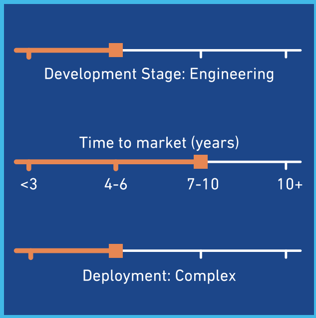
Desalination is increasingly used to provide household and industrial water in regions with scarce freshwater but abundant salt water. Most current desalination facilities are located in the Middle East, use seawater as feedwater and are powered by fossil fuels. The city of Chennai in southern Indian gets about a quarter of its municipal water from reverse osmosis seawater desalination plants.

Conventional desalination methods typically use seawater as feed. Seawater desalination technologies based on membranes, such as reverse osmosis, are approaching the thermodynamic limits of efficiency and have limited opportunity for further improvement. It is unlikely that major technology breakthroughs will fundamentally alter the seawater desalination landscape. Additionally, desalinated seawater is too expensive to use as irrigation water for crop production.

In contrast, there are large potential efficiency gains by using brackish water as feed. There are major opportunities for significant reductions in brackish water desalination cost and energy use through innovative electrochemical or other emerging techniques. The minimum theoretical energy requirement for desalination varies with the salinity of the feedwater—less energy is fundamentally needed to desalinate brackish water compared to seawater. Electromagnetic desalination processes such as electrodialysis (ED) and capacitive deionization (CDI) are limited to low-salinity feedwater, but potentially have much lower cost and energy than pressure or thermal techniques. They offer many advantages when used with brackish feedwater, such as high water recovery and high brine concentrations.

They also require little or no feedwater pre-treatment and membrane fouling can be prevented by reversing the electrode polarities. However, electromagnetic processes only remove ions from the water, leaving organics and colloids in suspension—this is a concern for household water, but less so for irrigation water. Furthermore, the selection and configuration of membranes is currently highly dependent on feedwater characteristics, thus must be adapted to local conditions of feedwater composition and concentration.

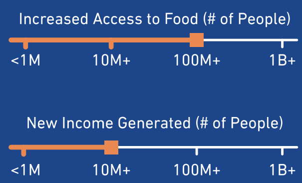
Current State



Associated 50BT Chapters

SDG Alignment

Impact



Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

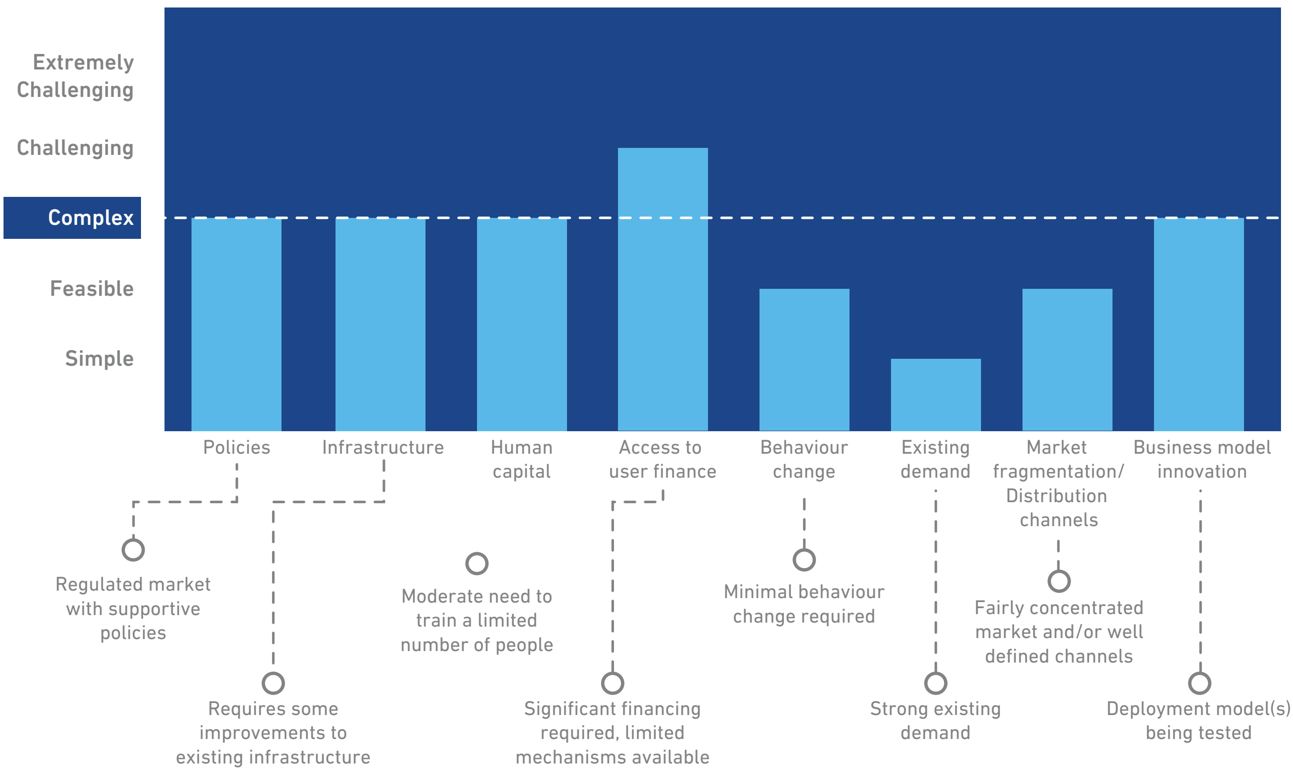
Concerted R&D efforts can overcome current obstacles to enable a major source of low-cost freshwater in regions with brackish resources. The appropriate unit scale of desalination facilities may vary depending on the application (such as household, irrigated farm, urban water utility). The salinity of the product water may also vary depending on the purity requirements of the end uses.

Costs can be further reduced by matching the salinity of the product water to the salinity thresholds for different uses; in other words, removing only enough salt to make the water viable for its intended use. Ideally, facilities will be powered by onsite renewable energy sources, such as photovoltaic solar arrays, to provide reliable and sustainable operation. Developing appropriate business models will be essential to ensure economic sustainability and continuing impact.

End-uses for the desalinated water will include drinking, cooking, washing and other domestic uses and industrial water uses. Efficient techniques for large-scale desalination of brackish water resources will also enable the use of desalinated water for production of agricultural crops using efficient irrigation techniques.

Substantial research and development work is required and we expect that it will take seven to ten years for this breakthrough to be ready. Deployment challenges include access to finance and policies regarding location and discharge streams. We rate the difficulty of deployment, COMPLEX.

Breakthrough 2: Difficulty of deployment



5 Medium to large-scale sewage treatment process with recovery of water (and ideally nutrients and energy)

This imperative calls for the development and deployment of novel sewage treatment facilities that are net sources, rather than sinks, of resources. Primarily this applies to water resources, for treating and reusing the wastewater collected in sewer systems. Systems should enable reuse of the treated water for secondary purposes including industrial, recreational and agricultural applications. A secondary focus is on energy resources, where sewage treatment facilities could operate with net zero energy inputs, and could even have the capability to produce energy for societal use. The recovery of nutrient resources from sewage, such as phosphorus or nitrogen, may also be a goal. Integrated sewage treatment can be viewed as a way to harvest clean, renewable sources of water, energy or nutrients while disposing of a waste product.

There is a great need for a low-cost, sustainable and scalable sewage management process for deployment in fast-growing cities in developing regions. In India, for example, less than 38 percent of the sewage that is generated is treated before being discharged into water bodies. The amount of resulting sewage in the environment is contributing to the country's health problems, including diarrheal outbreaks among children and lifelong stunting and wasting.

The massive organic and nutrient loading also has adverse environmental effects and leads to the destruction of ecological productivity of water bodies. Simultaneously, many growing cities have difficulty meeting the water needs of households and industries, due to physical constraints to water supply manifest as closed river basins and depleting groundwater stocks.

The quantities of wastewater generated in major cities are enormous, thus reusing this water for other purposes is a major lever for enhancing water security. For example, if 80 percent of the wastewater collected by urban sewage networks in India were reused, an additional water resource of 18 cubic kilometers per year would be obtained (ITT, 2018). What is lacking is an effective and affordable sewage treatment method that can rapidly scale up in developing regions.

Conventional wastewater treatment methods are a major resource sink, and should not be held as models for scalable sanitation methods for fast-growing cities in low-income countries. In the United States, for example, about 1.3 percent of all electricity is used for sewage treatment. This is a wasted opportunity, because raw sewage contains about six times more chemical energy than the amount of electrical energy required to treat it.

The most appropriate method of treatment for wastewater will depend largely on the intended use of the recycled wastewater and the scale of the treatment facility. Major reuse applications include agriculture (food and non-food crops), industry, and groundwater recharge, for which increasing effluent quality is required, respectively. For agricultural purposes, nutrient removal (or partial nitrogen removal) can be left out of the treatment process, whereas reuse in industrial applications or groundwater recharge requires nutrient and solids removal.

Current State

Development Stage: In-Market Small Scale

Deployment: Challenging

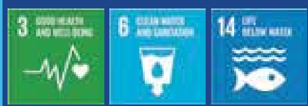
Associated 50BT Chapters

Water Security

Global Health

Gender Equity

SDG Alignment



Impact

Lives Saved (# of People/Year)

<1M 10M+ 100M+ 1B+

Health Improved (# of People)

<1M 10M+ 100M+ 1B+

Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

Groundwater recharge applications may also require removal of micro-pollutants as well as organic carbon. In terms of costs, the higher the quality of treated effluent, the higher the total capital and operational costs are. Generally, larger treatment plants have an increased efficiency, which lowers the lifecycle costs and environmental impacts per cubic meter of treated water.

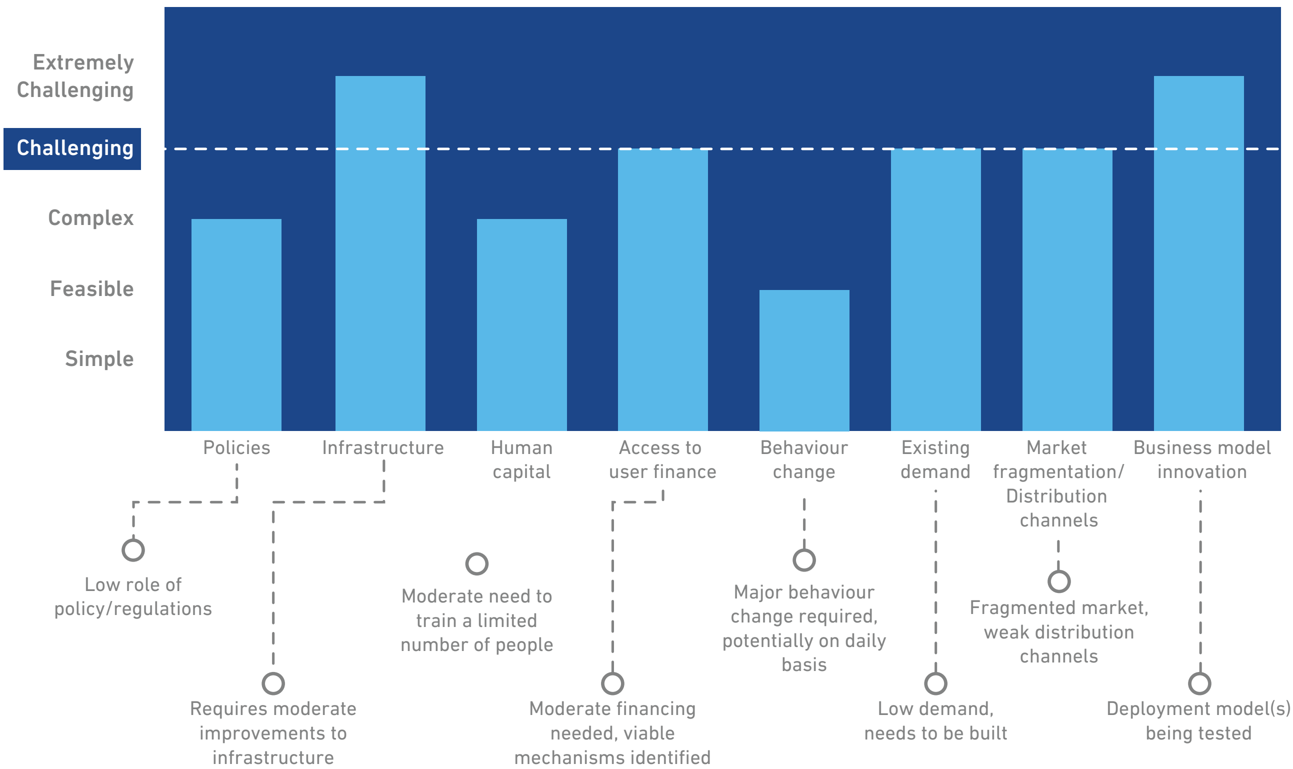
Novel sewage treatment methods followed by wastewater reuse is a potentially important lever for enhancing water security. Reusing wastewater brings two important benefits: less pollution entering water bodies, and less need for freshwater withdrawals. However, in the areas where it is currently practiced, wastewater reuse is typically considered as a temporary solution for acute needs, instead of implemented as a long-term solution to improve water security.

Important criteria for successful treatment technologies include the extent of land area required, the economic resources needed for capital and O&M, and the quality requirements for the reused water. Land area requirements, in particular, may be an impediment to scale-up of some technologies. Different technology solutions may be appropriate for different settings as the scale increases from household to neighborhood and metropolitan level.

There are many challenges to sanitation infrastructure deployment, and business models should not expect to extract high-value content from sewage. Sanitation systems tend to have fairly high up-front costs and require skilled labor to install and maintain. Distribution channels are also poorly defined. In addition, significant public investment is likely to be still required.

Some promising technologies have entered the market, and others should become market-ready in the coming years. Given the lack of proven models and the growing scale of the urban sanitation problem, the level of difficulty for deployment is CHALLENGING.

Breakthrough 5: Difficulty of deployment



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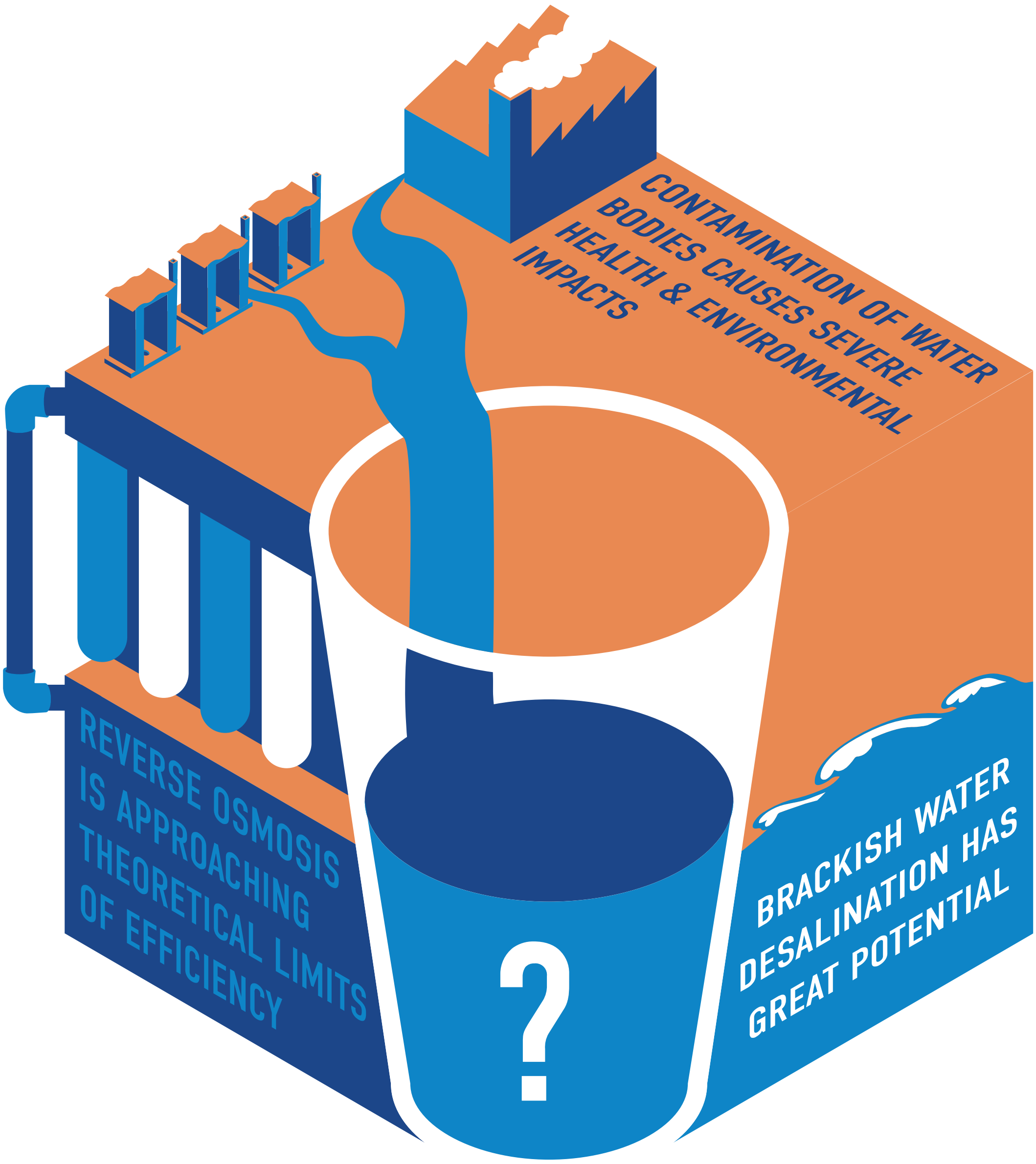


WATER QUALITY

INTRODUCTION

Clean water is essential for healthy living, but is hard to obtain in many regions of the world.

Much water is unsuitable for use because it contains contaminants, either natural minerals like salt or arsenic, or pollutants like sewage or chemical waste.

The overwhelming majority of water on Earth is saline, in the oceans and seas, and cannot be directly used by households or farms. The size and ubiquity of the resource, however, suggests that effective techniques for desalination are critical to overcome water constraints.

In addition, groundwater in some parts of the world, such as Bangladesh, naturally contains dangerous levels of arsenic, which must be removed prior to safe consumption.

By using rivers, lakes and oceans as a dumping ground for inorganic pollutants and biological wastes such as sewage, human society has significantly changed the quality of water. Discharge of untreated sewage into rivers is common in urban areas.

Water contamination by fecal pathogens causes diarrhea and other diseases, resulting in hundreds of thousands of deaths annually, primarily among children. Other important water quality challenges include exposure to diverse waterborne toxins from industrial effluent and agricultural run-off of fertilizers and pesticides.

Five technology breakthroughs can significantly reduce the burden of poor water quality:

- Breakthrough 1. A low-cost system for precision application of agricultural inputs, ideally combining water and fertilizer
- Breakthrough 2. A very low-cost scalable technique for desalinating brackish water
- Breakthrough 3. Network of low-cost distributed monitoring sensors to measure and map air and water quality
- Breakthrough 4. Sustainable, affordable, household-level fecal waste management system
- Breakthrough 5. Medium to large-scale sewage treatment process with recovery of water (and ideally nutrients and energy)

Water pollution is typically an unintended consequence of other activities; people do not intend to cause pollution, but disposing of waste products into a nearby water body is often the most expedient and inexpensive form of disposal. The traditional approach to waste disposal considered that "the solution to pollution is dilution", which was effective when the amount of waste was small relative to the capacity of the environment to assimilate it. However, this approach is ineffective at larger scale, when the huge quantities of waste overwhelm natural processes and leave water bodies polluted.

CORE FACTS AND ANALYSIS

1. Fecal contamination of water bodies causes severe health and environmental impacts

Human fecal matter can contain a range of harmful pathogens, including viruses, bacteria, protozoa, and helminths (see **Exhibit 1**). These pathogens cause diarrhea and other diseases. Almost 1.7 million people die each year due to diarrheal diseases, primarily children (GHDX, 2018).

The vast majority of diarrheal deaths occur in South Asia and sub-Saharan Africa (see **Exhibit 2**). Diarrheal disease burden is highly concentrated in a small number of countries, with 78 percent of deaths occurring in just 10 countries, including India, Nigeria, DR Congo and Ethiopia. Human fecal matter also spreads soil-transmitted helminths (STH), which affect roughly 1.5 billion people globally.

In addition to mortality, the indirect burden of diarrheal disease and STHs is significant; they are a major contributor to malnutrition, which in turn is believed to underlie 45 percent of all childhood deaths.

Continued exposure to fecal contamination can lead to chronic conditions, such as malnutrition and stunting in children due to environmental enteropathy, in which the body uses much of the energy and nutrients from food to fight off ingested fecal pathogens rather than absorbing them for growth and development (Harris, et al., 2017).

Stunted height indicates that vital organs, such as the brain and kidneys, are not developing properly and has been associated with a lower intelligence quotient (IQ) and a higher risk of developing diseases later in life (Schmidt, 2014).

Fecal contamination of water bodies imposes great economic cost on societies, mainly from healthcare expenses and health-related opportunity costs.

Pathogen type	Important pathogens	Characteristics
Viruses	**Rotavirus**	Viruses are infectious pathogens that can only replicate after infecting other living cells. Rotavirus is the single most important pathogen associated with diarrheal disease.
Bacteria	***ST-Enterotoxigenic E. coli, Shigella, Aeromonas, V. cholera, C. jejuni***	Bacteria can grow on food and in water and sewage under the right conditions. Some bacteria are seasonal, with major spikes in the wet season.
Protozoa	***Cryptosporidium Parvum***	Protozoa are advanced organisms that are transmitted through cysts that are extremely robust, able to survive for long periods outside of the body and resistant to chlorine purification.
Soil-transmitted Helminths	**Roundworm (*Ascaris lumbricoides*), whipworm (*Trichuris trichiura*), hookworm (*Necator americanus*** and ***Ancylostoma duodenale*)** and certain types of **tapeworm (*Taenia*)**	Soil-transmitted helminths (STH) are parasites that do not cause diarrhea, but rather live in the body, generally the intestines, and cause enteric inflammation. Eggs must mature in soil before becoming infectious to humans, however, they are extremely persistent and can survive for weeks to months on crops and soil, and years in fecal matter.

Exhibit 1: Fecal waste contains four major types of pathogens: viruses, bacteria, protozoa and helminths. (Source: ITT, 2018)

Global deaths due to diarrhea, by region

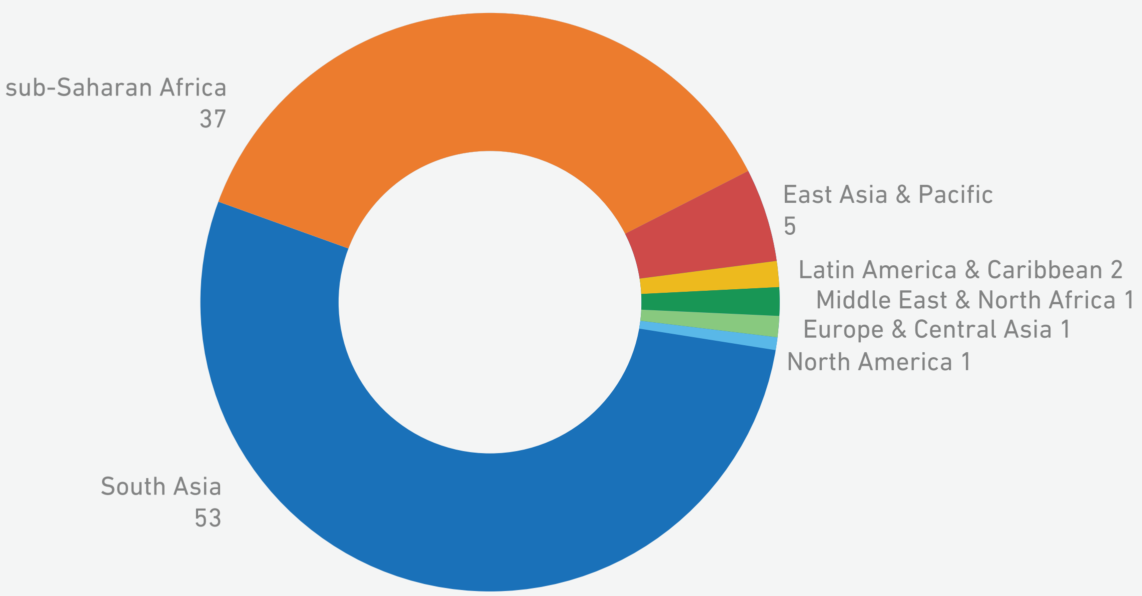


Exhibit 2: Of the 1.7 million deaths per year due to diarrheal disease, more than half occur in South Asia and another third are in sub-Saharan Africa. (Source: GHDX, 2018)

People typically become infected by ingesting the pathogens, thus fecal contamination of surface and groundwater significantly increases the likelihood of infection.

Fecal pathogens colonize the human gut, where they then grow and replicate. Their transmission begins when the individual carrying the pathogen(s) defecates.

From the point of defecation, the fecal pathogens may come into contact with another person via several transfer pathways, including surface and groundwater, flies, crops and the soil—from where they then enter the body through drinking water, food or via dirty hands (see **Exhibit 3**).

Fecal-oral pathogen flow model

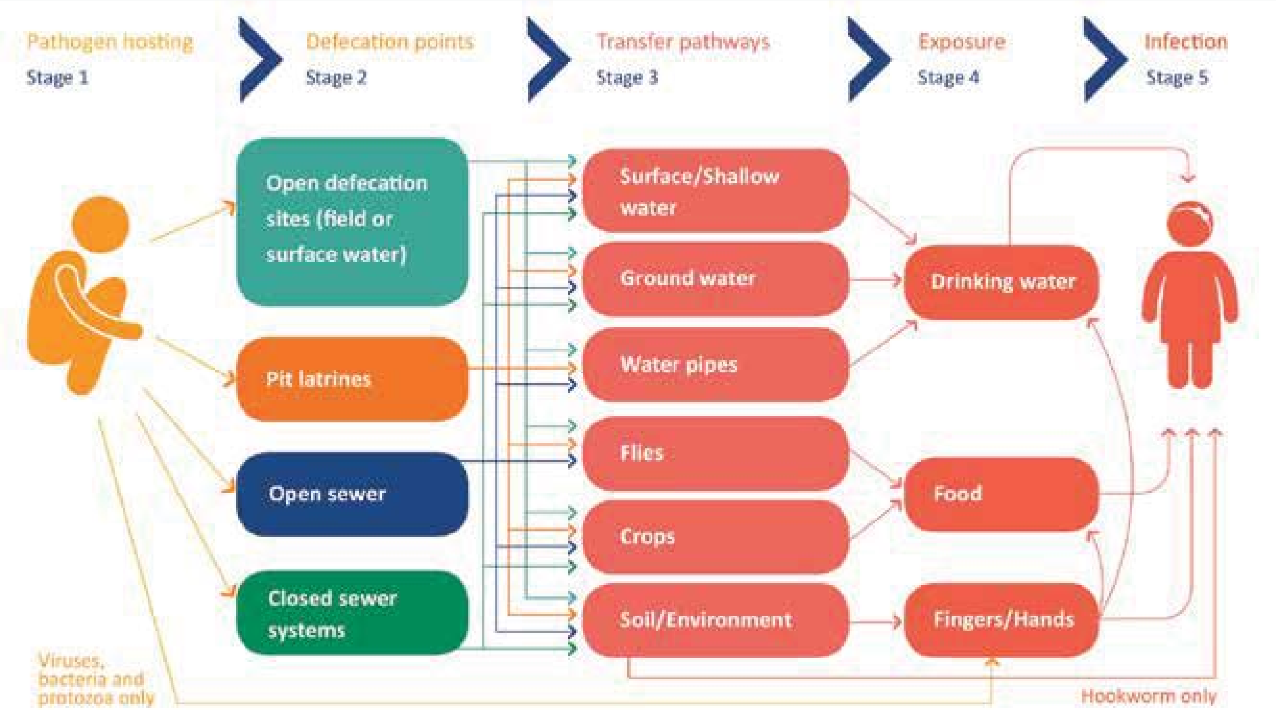


Exhibit 3: Fecal-oral pathogen flow model, showing multiple pathways for infection by fecal pathogens.

Globally, the incidence rates of diarrhea have decreased since the 1990s (see **Exhibit 4**).

Incidence rate of diarrhea among children

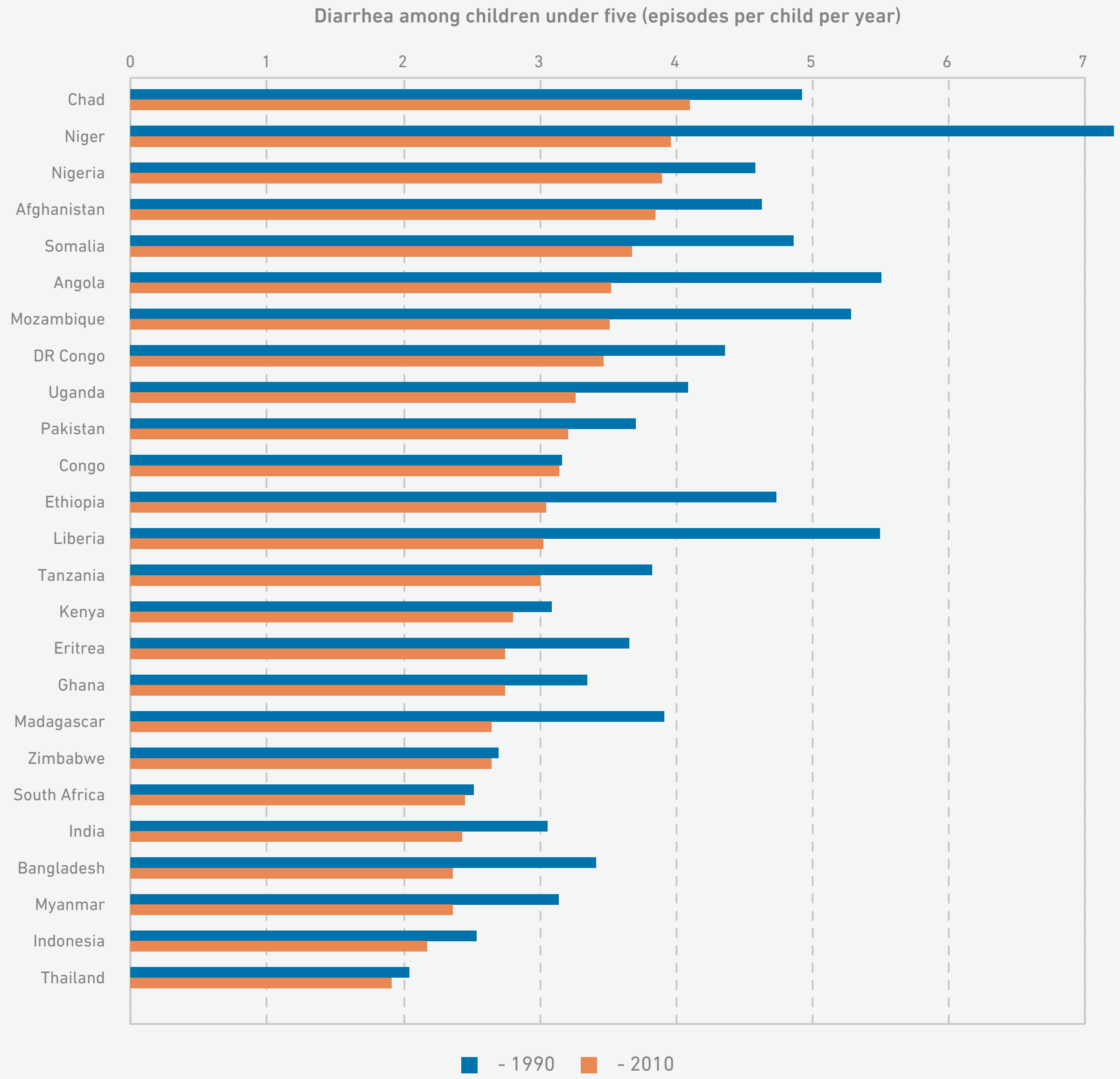


Exhibit 4: The rate of incidence of diarrhea in children under 5 has been declining in the world since 1990. (Source: Fischer-Walker, et al., 2012)

The high organic and nutrient loads placed on rivers due to sewage disposal are increasing, resulting in significant ecological disruption. The high organic load of fecal waste and other domestic effluents leads to a high biochemical oxygen demand (BOD) of the water.

The high nutrient load (primarily nitrogen and phosphorus) in the sewage results in eutrophication of water bodies, which is ecologically destructive and leads to anoxia and dead zones.

These environmental impacts are discussed in more detail in the sections on agricultural runoff and industrial effluent.

2. Global scale-up of improved sanitation remains elusive

Key sanitation indicators show positive long-term trends in most developing countries, such as increasing access to improved sanitation facilities and decreasing rates of open defecation.

Much effort has been made in recent decades to improve sanitary conditions. Still, there are large population segments that lack adequate sanitation facilities, particularly in rural areas (JMP, 2018) (see **Exhibit 5**).

The number of people with improved sanitation facilities is increasing in all countries. However, in some countries the number of people without improved sanitation is also increasing (**Exhibit 6**). In these countries, which include Kenya, DR Congo, Ethiopia and Nigeria, the population growth rate is faster than the sanitation improvement rate.

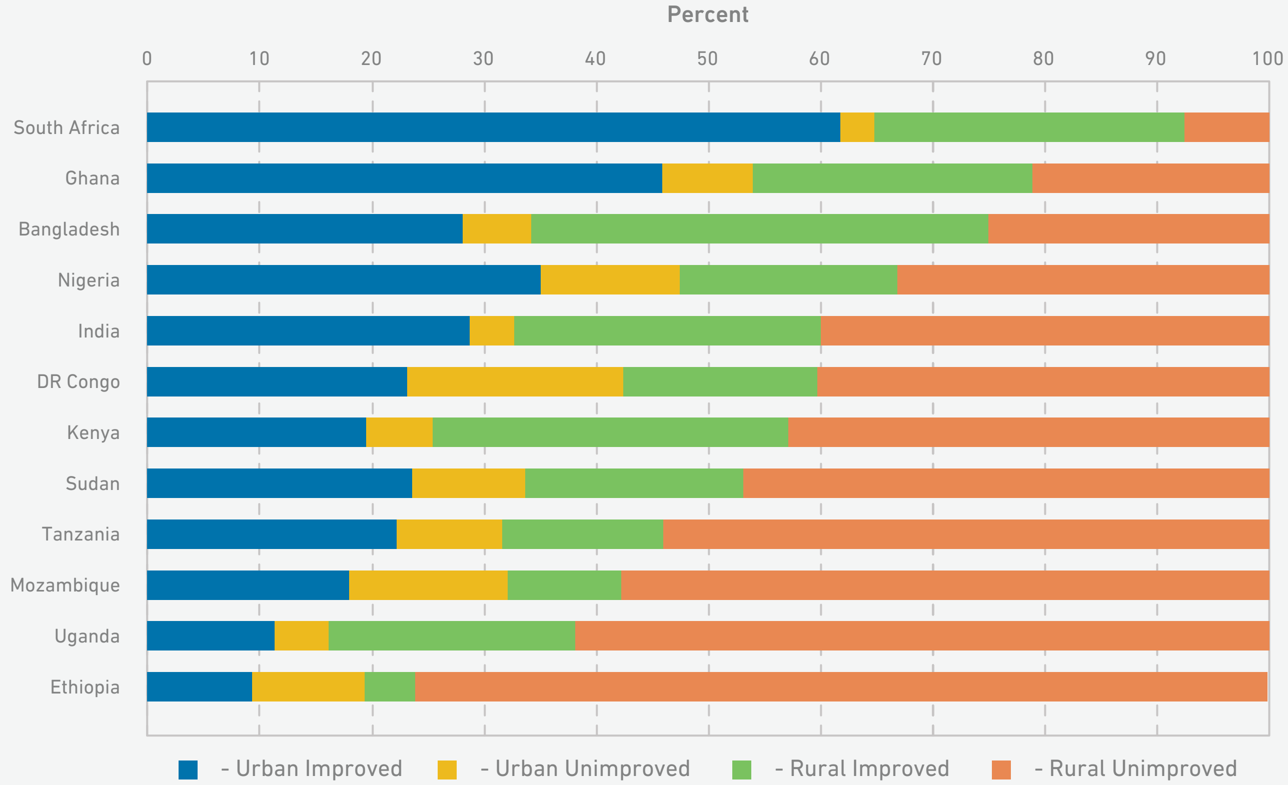


Exhibit 5: Sanitation coverage varies widely among low-income countries. (Source: year 2015 data from JMP, 2017; "Improved" and "Unimproved" sanitation is based on WHO/UNICEF JMP categories. Here, "Improved" sanitation includes Safely Managed, Basic and Limited facilities; "Unimproved" sanitation includes Unimproved facilities and Open defecation)

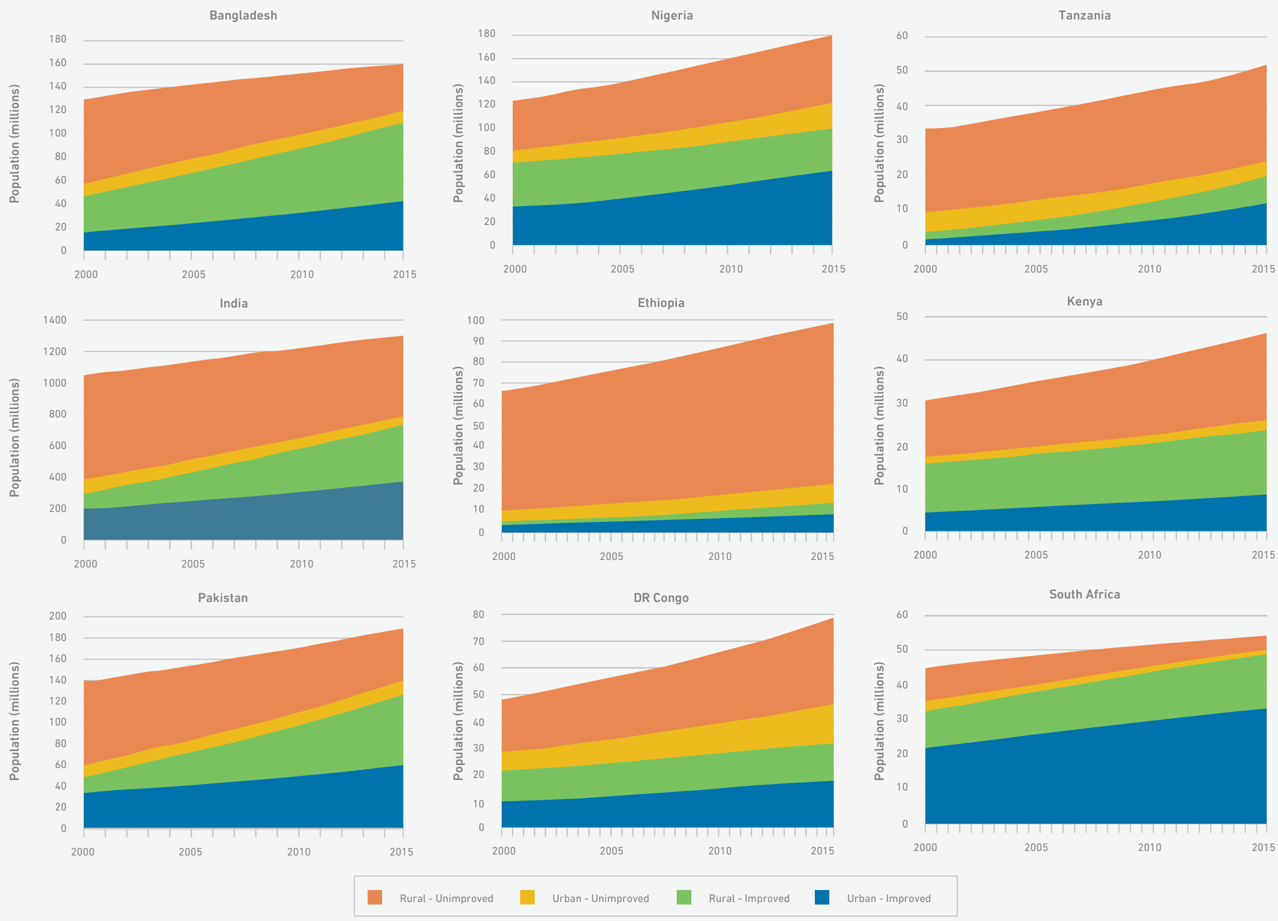


Exhibit 6: In all countries, the number of people with improved sanitation facilities is increasing. In some countries, including Kenya, DR Congo, Ethiopia and Nigeria, the number of people without improved sanitation is also increasing because the population growth rate is faster than the sanitation improvement rate. (Source: JMP, 2018)

Open defecation rates have been steadily decreasing in recent decades. The number of people practicing open defecation declined from 1,230 million in 2000 to 890 million in 2015 (JMP, 2018).

Still, open defecation is commonplace in many countries, primarily in rural areas and to a lesser extent in urban areas (see **Exhibit 7**).

Rural open defecation rates exceed 75 percent in some countries, such as Niger, Namibia, Chad, Eritrea and Benin. The practice has been in use for millennia and is culturally accepted, despite its detrimental health effects at current population levels.

Idyllically envisioned as a regular opportunity for quiet contemplation in nature while completing biogeochemical cycles, open defecation becomes problematic when the amount of human waste exceeds the capacity for assimilation into the natural surroundings.

Open defecation was the norm during our species' long evolutionary history and was an effective sanitation strategy while population density remained low.

As the number of people increased, the continuation of open defecation has led to spatial concentrations of human fecal waste at unpleasant and unhealthy levels.

Prevalence of open defacation

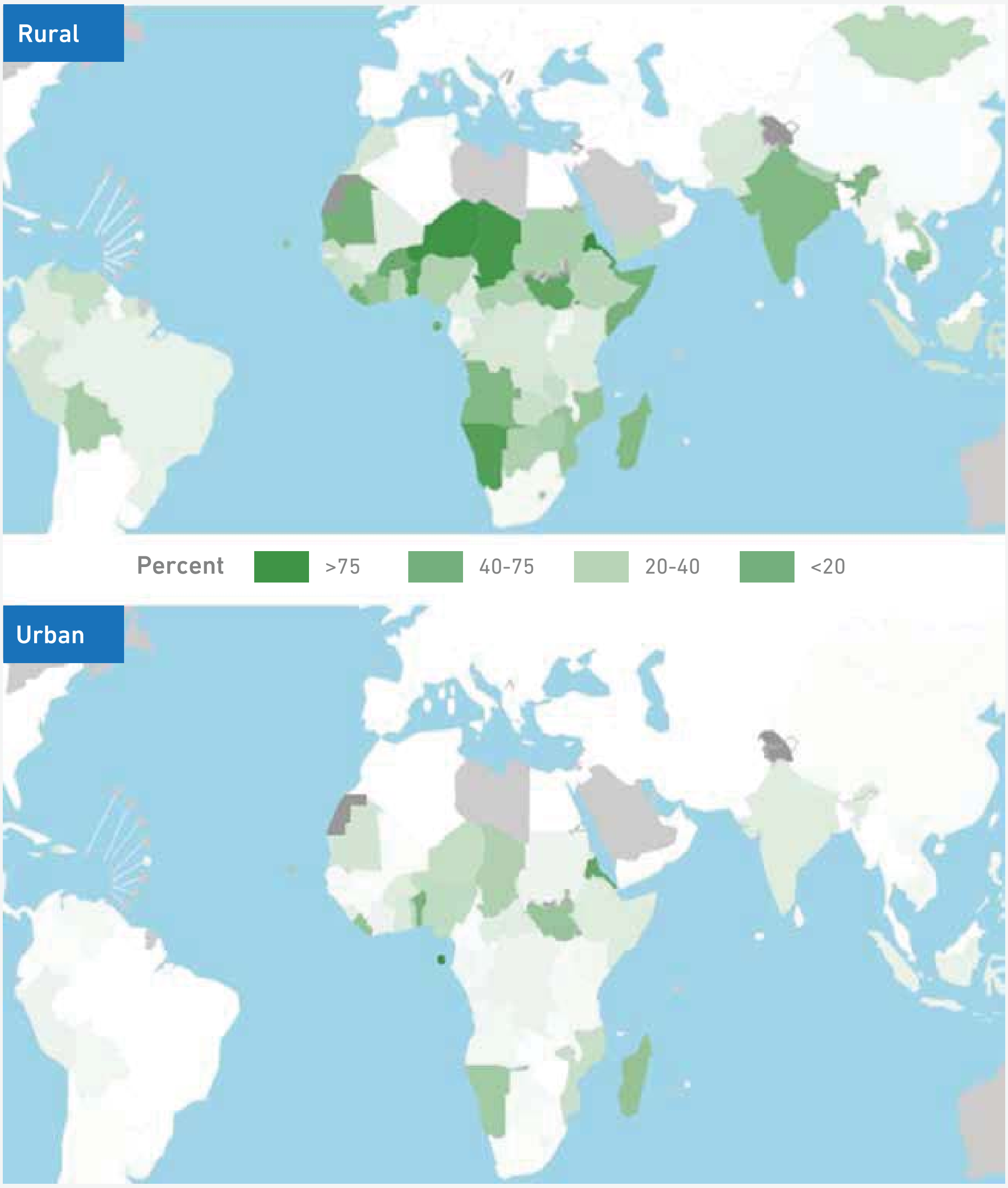


Exhibit 7: Despite important reduction in open defecation rates during recent decades, large shares of the African and South Asian population continue to practice open defecation. It is particularly prevalent in rural populations but also occurs among urban populations. (Source: JMP, 2018)

3. Sanitation technologies are available for managing fecal waste in rural and urban areas

Disposal of human fecal waste is a longstanding and ongoing challenge, and fecal waste management is one of the many necessary steps in improving the water security and public health of a region.

A three-pronged approach of improving sanitation, water supply and hygiene is increasingly seen as the solution to improving water quality and public health. **Exhibit 8** illustrates the relationship between these three sectors and the various pathways of disease transmission (Tilley, et al., 2014b).

Specifically, drinking water can be contaminated at three main points: the source, in transit (i.e. through pipes) and in the home through improper storage. Food becomes contaminated in farm fields when open defecation occurs in fields or when farmers irrigate with wastewater, in markets due to unhygienic conditions and in the home when the food comes into contact with contaminated hands or flies.

Thus, fecal waste management is one of three important interventions required to prevent the spread of disease originating from fecal pathogens. Worldwide, the UN projects that for every $1 spent on sanitation, more than $5 in value is returned to society (WWAP, 2017).

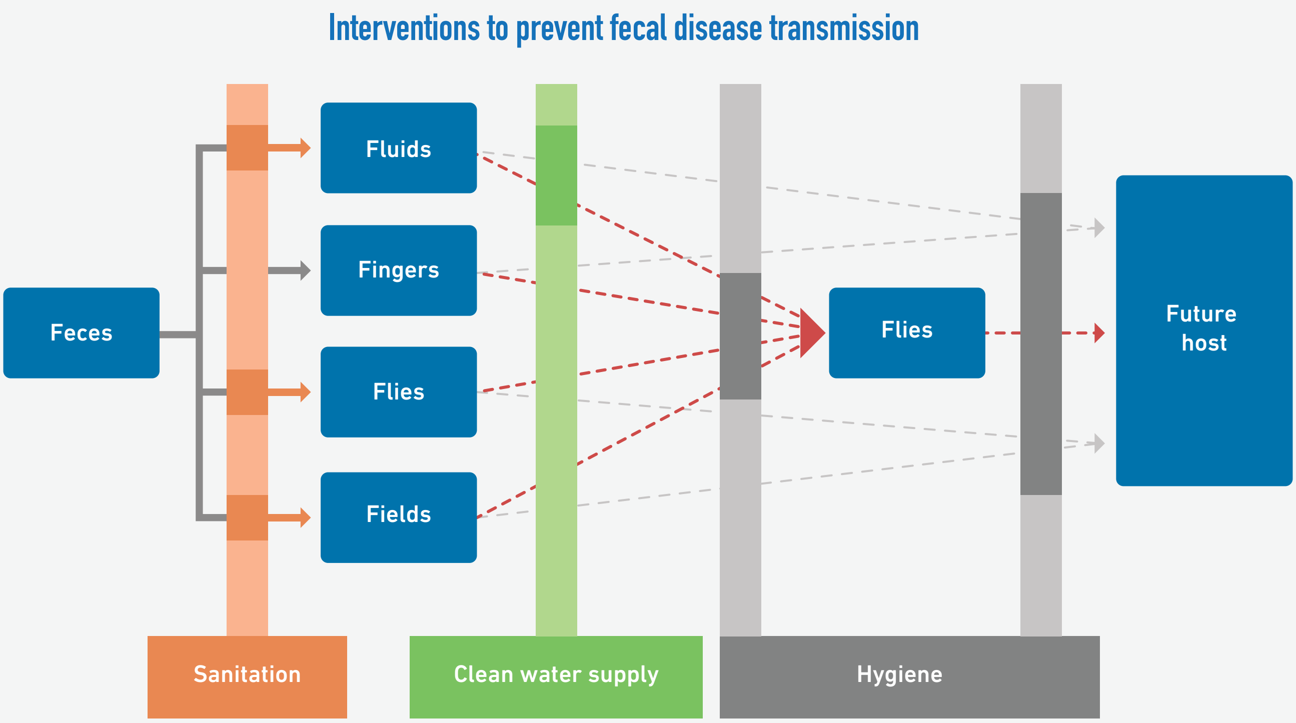


Exhibit 8: There are many pathways for disease transmission, which can be broken by interventions in the water, sanitation and hygiene sectors. "Fields" can refer to surfaces both inside and outside the home and "fluids" includes drinking water and other water that comes into contact with humans, such as water used for bathing or recreation. (Source: adapted from Tilley, et al., 2014b)

The types of systems and technologies used to collect and treat fecal waste depend on how densely populated an area is and the resources available to households and local authorities to devote to sanitation practices (see **Table 1**).

Rural areas are typically less densely populated, thus distributed small-scale on-site fecal waste management techniques are appropriate.

In more densely populated urban areas, a more appropriate solution is water-based transport of fecal waste through sewer networks to centralized sewage treatment facilities (although discharge of untreated sewage into rivers is more common in practice).

Peri-urban areas share some characteristics of both urban and rural areas where the best sanitation management option for such areas will depend on the specific population size and density, distance to an urban center and various environmental factors such as soil type and groundwater table depth.

	Sanitation method	Human health risk			
		Initial hygenic separation	Secondary exposure risk	Surface water contamination	Ground water contamination
On-site decentralised	Open defecation	Very High	Very High	Very High	Medium
	Simple pit latrine (not emptied)	High	Medium	Low	Very High
	Improved pit latrine (safely emptied)	High	Low	Very Low	Very High
	Improved pit latrine (unsafely emptied)	High	High	High	Very High
	Pour flush + single pit (safely emptied)	Very Low	Very Low	Very Low	Very High
	Pour flush + single pit (unsafely emptied)	Very Low	High	High	Very High
	Pour flush + twin pit (safely emptied)	Very Low	Very Low	Very Low	Very High
	Pour flush + twin pit (unsafely emptied)	Very Low	High	High	Very High
	Pour flush + septic tank (safely emptied)	Very Low	Very Low	Very Low	High
	Pour flush + septic tank (unsafely emptied)	Very Low	High	High	High
	Pour flush + vermi-filter (safely emptied)	Very Low	Very Low	Very Low	Medium
	Pour flush + vermi-filter (unsafely emptied)	Very Low	Medium	Low	Medium
Off-site centralised	Sewer network to river	Very Low	High	Very High	Low
	Sewer network + primary treatment	Very Low	Medium	High	Low
	Sewer network + secondary treatment	Very Low	Low	Low	Very Low
	Sewer network + tertiary treatment	Very Low	Very Low	Very Low	Very Low

Legend: Very Low | Low | Medium | High | Very High

Table 1: A range of on-site and off-site sanitation technologies are available, each providing a different level of health risk reduction. Health risk is described here as a function of the initial hygenic separation of the fecal waste and the opportunities for secondary exposure to the fecal pathogens, which include the risks of surface and groundwater contamination. The methods used for pit emptying and fecal residue management have a major impact on overall health risk. (Source: ITT analysis)

Rural sanitation

In rural areas, decentralized on-site sanitation systems for individual households are most appropriate since they do not require a sewer connection, are relatively affordable and can safely contain the fecal waste when managed properly.

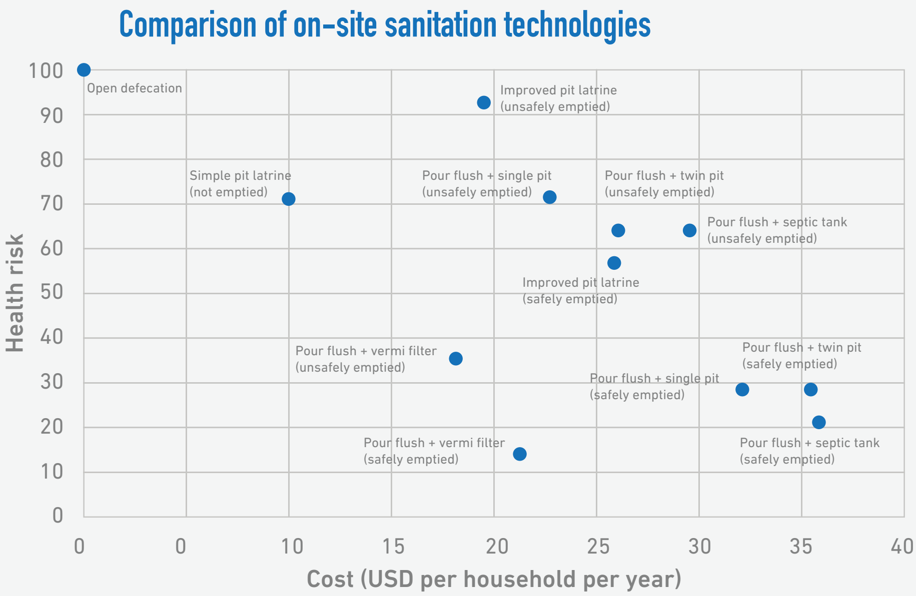
A wide range of on-site sanitation technologies has been developed, including pit latrines (single and twin pit), pour-flush pit toilets (with septic tanks and single and twin leach pits), vermi-filtration toilets, dry composting toilets and anaerobic baffled reactor toilets.

The cost and performance of various on-site sanitation systems are compared in **Exhibit 9**. Lifecycle costs include the initial capital cost, plus ongoing operations and maintenance costs, primarily for emptying of fecal sludge.

In general, health risks are reduced as the cost of the on-site sanitation system increases. An exception to that trend is vermicomposting toilets, which provide high performance at low cost largely due to enhanced decomposition of fecal matter by earthworms leading to less waste build-up and less frequent emptying, thus lower maintenance costs.

Toilets with leach pits are simple and foolproof and are appropriate for hesitant users who have recently switched from open defecation. More sophisticated on-site waste management technology, such as the vermi-filtration toilet, provide greater overall sanitation protection and are appropriate for experienced users.

Thus, a phased approach may be needed with the long-term goal of universal sanitation coverage with highly effective local waste processing capabilities.



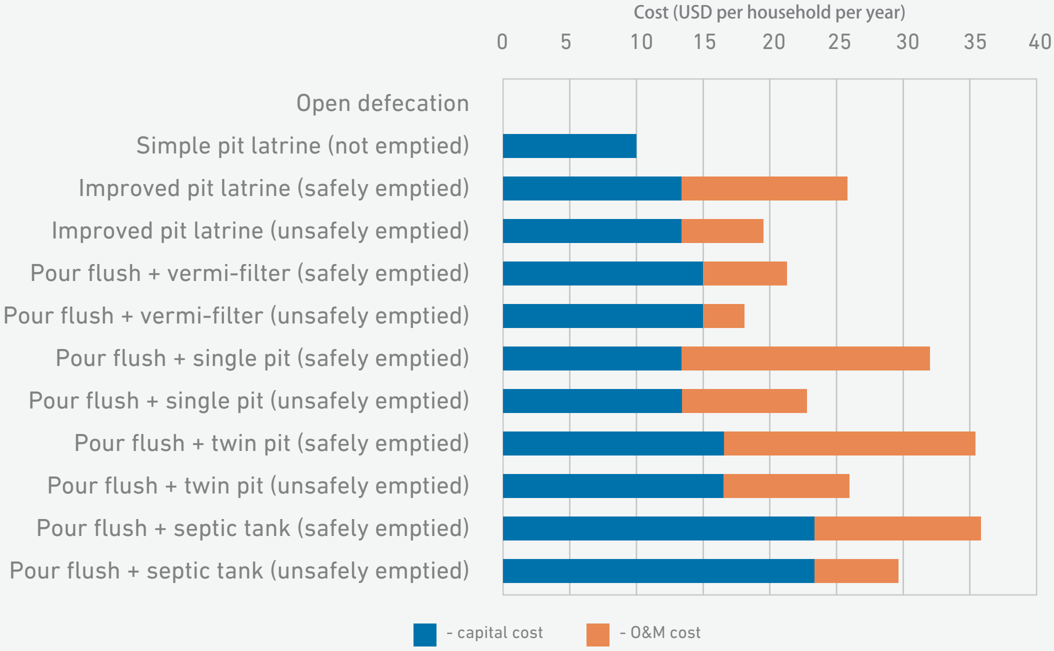


Exhibit 9: A range of on-site sanitation technologies are available—more expensive technologies generally provide greater health risk reduction. The lifecycle cost of sanitation options includes both the capital and the operations and maintenance costs, which vary significantly between technologies (Source: ITT, 2018)

Decentralized on-site sanitation systems should be viewed as a long-term solution to rural sanitation, rather than an interim fix, and given a high priority in resource allocation. In order for on-site sanitation systems to be effective, mechanisms must be developed to regularly empty the sanitation facilities and transport the fecal sludge, as necessary, to appropriate sites for reuse or disposal. From toilet siting and construction, to sludge emptying and transport, to final treatment and disposal of waste, each step of the sanitation service chain is critical in achieving effective sewage management (Blackett, et al., 2014).

Urban sanitation
Urban fecal pollution is largely caused by untreated wastewater from sewage networks discharging into surface water bodies near cities (Kotloff, et al., 2013). In India, for example, wastewater treatment plants currently treat only about 38 percent of all wastewater generated in cities (CPCB, 2015) (see **Exhibit 10**).

Thus, 62 percent of the collected sewage, more than 14 cubic kilometers per year, flows untreated into Indian rivers (CPCB, 2015). This is due to a lack of installed capacity and a lack of maintenance and operation of existing plants. In Bangladesh, only 17 percent of collected sewage is treated, however the discharged sewage is diluted more effectively due to the relative water abundance of the country (WWAP, 2017).

An additional source of fecal pollution is open defecation, which places the entire urban population at risk even if it is practiced by a small percentage of residents. Crowding in cities further exacerbates the risks associated with untreated sewage and urban open defecation.

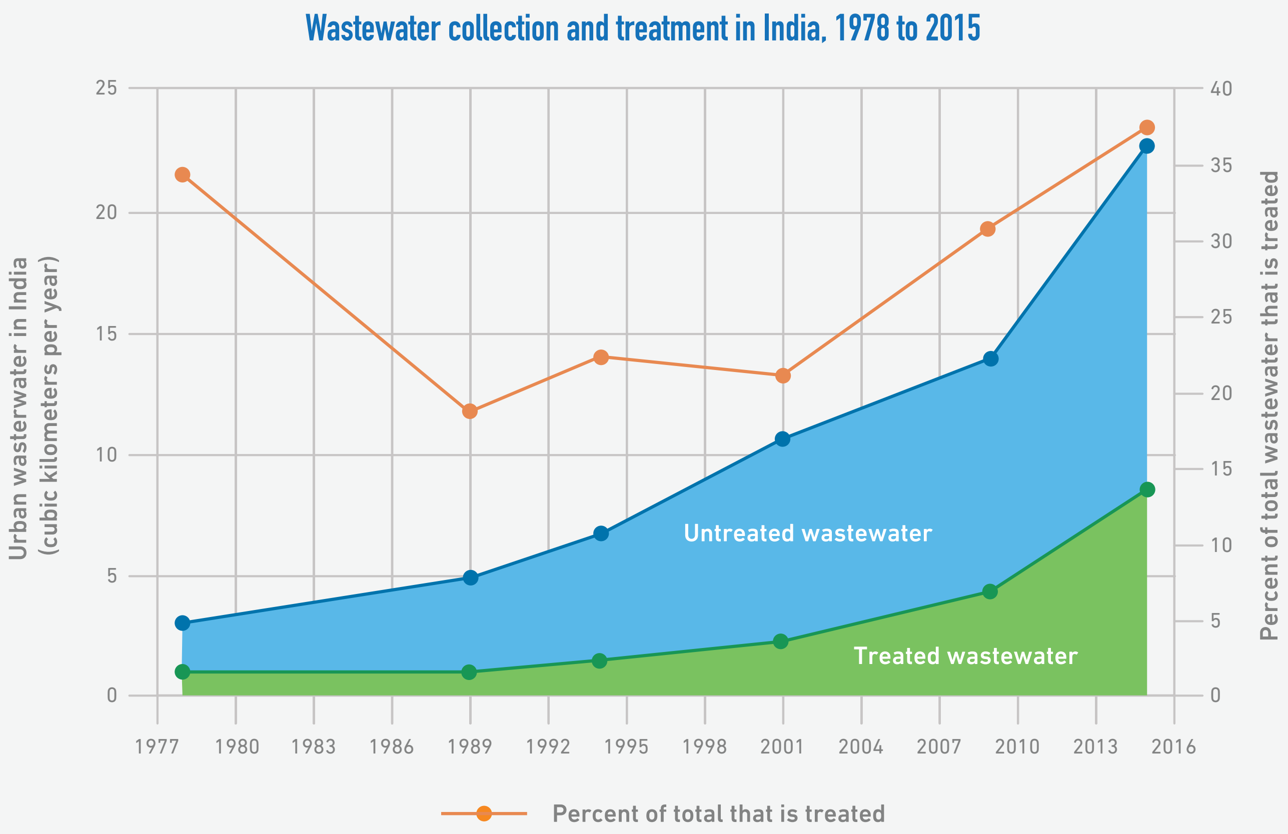


Exhibit 10: Despite the rapidly growing capacity of sewage treatment facilities in India, less than half of total wastewater collected is treated prior to discharge. Rapid growth in total wastewater collection in India is due to the rise in urban population and the increase in percentage of urban households with sewer connections. (Source: Central Pollution Control Board, 2005, 2009, 2015)

Densely populated urban centers typically use centralized sewage treatment systems, which collect wastewater from many households and transport it out of the urban area, ideally to facilities for treatment. Such systems require large upfront costs and high operational and maintenance costs, as well as large investment of human capital. Wastewater is collected and usually conveyed in sewer pipes to outside the city center.

There, it may either empty directly into a river without any treatment, which is most common in developing regions, or it may be treated followed by discharge to a river. Wastewater may be treated to primary, secondary or tertiary levels, with progressively better water quality. It may also empty into a wetland, or the wastewater may be treated and reused for various purposes (e.g. agriculture, aquaculture, municipal water) (WWAP, 2018).

Sewage treatment can consist of a combination of physical, chemical and biological processes to remove solids, pathogens and biochemical oxygen demand (BOD). Physical processes (primary treatment) include the use of gravity as well as physical barriers, such as filters and membranes, to separate out large solids. Membrane systems typically require high energy consumption and high levels of operation and maintenance.

Biological processes (secondary treatment) contain a variety of microorganisms that decompose the sewage; these processes can operate under either aerobic or anaerobic conditions. Aerobic conditions require more energy for aeration but produce sludge as a by-product, which can be applied to fields as a fertilizer or soil conditioner. Anaerobic processes require less energy and produce less stabilized sludge, but the methane produced as a by-product can be captured and used as an energy source (WWAP, 2017).

Combining aerobic and anaerobic processes, such as using UASB and ASP in a sequence, in a single plant can help save energy costs and improve effluent quality (von Sperling et al., 2001). Chemical processes (tertiary treatment) are often used for disinfection (e.g. ferric salts to remove BOD and solids) or to remove nutrients (e.g. iron-sulphate to remove phosphorus). Constructed wetlands are engineered to mimic the natural purifying abilities of wetlands and estuaries and can treat sewage to the secondary degree (WWAP, 2018). All of these processes can be combined in sequence to obtain the cleanest effluent (UNEP, 2016).

Centralized, large-scale sewage treatment systems are quite expensive, energy intensive and typically require skilled personnel to operate and maintain the plants. Conventional wastewater treatment methods are a major resource sink. In the United States, for example, about 1.3 percent of all electricity is used for sewage treatment (Heidrich, et al., 2011). This is a wasted opportunity, because raw sewage contains about six times more chemical energy than the amount of electrical energy required to treat it (Korth, et al., 2017).

The chemical energy contained in wastewater can be exploited in several different ways. Methane harvesting from anaerobic digestion is a well-known energy saving and energy producing method. Its drawbacks are requirements of high concentrations of organic matter, warm wastewater temperatures (i.e. >20 °C) and a high minimum flow rate. Newer energy generation methods include microbial electrochemical technologies, such as microbial fuel cells and microbial electrolysis cells, the use of microalgae for biodiesel and anaerobic membrane bioreactors, which can produce methane from low concentrations of sewage (Rao, et al., 2017). Alternative methods include the combined use of micro- and macro-organisms, such as vermicomposting, in which the compost can later be retrieved to recover nutrients.

Table 2 summarizes the characteristics of various off-site sewage management technologies and their suitability for use in different geographic and economic settings. Important selection criteria for treatment technology include the land area available, the economic resources available for capital and O&M and the quality requirements for the reused water. Prior to entertaining tertiary treatment at any location, it is advised that sewage treatment plants are first deployed with the capacity to treat all wastewater in that area to the level of secondary treatment (BOD less than 20 milligram per liter, suspended solids less than 30 milligram per liter).

Once there is high coverage of secondary treatment across the region, resources may be allocated to upgrade the plants to complete tertiary treatment (BOD less than 10 milligram per liter, suspended solids less than 15 milligram per liter, total fecal coliforms less than 2500 most probable number per 100 milliliters) (CPCB, 2005). Regardless of which sewage treatment system is used, the costs of not implementing and not investing adequate funds in sewage management are typically far greater than the costs of doing so, especially when the direct and indirect effects to public health, socioeconomic development and environment impacts are considered (WWAP, 2017).

Technology Type	Land Requirement	Capital Costs	O&M Costs	Energy Requirement	Effluent Quality	Advantages	Disadvantages
Activated Sludge Process (ASP)	0.15-0.25 hectares/MLD installed capacity	$41K-82K /MLD capacity	$6K-10K/year/ MLD installed capacity	180-225 kWh/ML treated	BOD: 10-20 mg/L Suspended solids: 20-50 mg/L	Low land requirement; resistant to organic and hydraulic shock loads; high reduction of BOD and pathogens; high nutrient removal possible; high quality effluent; biogas can be harvestedt	High energy consumption; high capital and operating costs; requires skilled personnel to operate and maintain; prone to complex chemical and microbiological problems
Trickling Filter (TF)	0.25-0.65 hectares/MLD installed capacity	Relatively lower than ASP	Slightly lower than ASP	180 kWh/ML treated	Comparable to ASP	Simple process; requires small land area; can be operated at a range of organic and hydraulic loading rates; efficient reduction of ammonia-nitrogen concentrations; low power requirements	Prone to clogging; regular operator attention necessary; potential for odour and vector problems; high capital costs; requires skilled personnel to operate and maintain; pre- or primary treatment required
Waste Stabilisation Pond (WSP)	0.8-2.3 hectares/MLD installed capacity	$31K-93K/MLD capacity	$1K-2K/year/ MLD installed capacity	Energy required for the operation of screen and grit chamber - negligible compared to ASP	BOD: 30-50 mg/L Suspended solids: 75-125 mg/L	Low O&M costs; low O&M capital; high BOD and pathogen removal; construction can take place by unskilled laborers; no electrical energy required	Requires large surface area; effluent contains nutrients and cannot be discharged into surface waters; prone to smelling, long processing time depending on climate
Upflow anaerobic sludge blanket (UASB)	0.2-0.3 hectares/MLD installed capacity	$52K-72K/MLD capacity	$2K-4K/year/ MLD installed capacity	10-15 KWh/ML sewage treated	BOD: 30-40 mg/L Suspended solids: 75-100 mg/L	Can absorb organic and hydraulic shock loading; low sludge production; biogas can be captured; little energy consumption; low land demand; can be constructed underground; effluent rich in nutrients	Sensitive to power cuts since constant electricity is required; operation and maintenance by skilled personnel; difficult to maintain proper hydraulic conditions (upflow and settling rates must be balanced); not adapted for cold climates
Rotating biological contactor (RBC)	0.008 hectares/MLD installed capacity			Very low compared to ASP	Comparable to ASP	High contact time and high effluent quality, stable process - resistant to shock hydraulic and organic loading; shorter process time; low land requirement; ease of installation and commissioning; simple to operate and maintain; low sludge production	Requires continuous electricity supply (but less than TF or ASP); high capital and O&M costs; must be protected against sunlight, wind, rain and freezing temperatures; odour may occur; requires skilled technical labour to operate and maintain; requires primary treatment (settling)

Technology Type	Land Requirement	Capital Costs	O&M Costs	Energy Requirement	Effluent Quality	Advantages	Disadvantages
Sequencing Batch Reactor (SBR)	0.1-0.15 hectares/MLD installed capacity	Higher than ASP	Higher than ASP	150-200 kWh/ML treated	BOD: <5 mg/mL suspended solids: <10 mg/mL	Equalisation, primary clarification, biological treatment, and secondary clarification can be achieved in a single reactor vessel; operating flexibility and control; minimal footprint	Requires higher level of sophistication of operate; higher level of maintenance; aeration device can clog
Fluidised Aerobic Bed (FAB)	0.06 hectares/MLD installed capacity	$62K-103K/MLD installed capacity	$10K-15K/year/MLD installed capacity	99-170 kWh/ML sewage treated	BOD: <10 mg/mL suspended solids: <20 mg/mL	No sludge recycling and monitoring of mixed liquor suspended solids (MLSS); allows for continuous, automatically controlled operations	Expensive to construct and maintain; reactor walls may erode
Submerged Aerobic Fixed Film (SAFF) reactor	0.05 hectares/MLD installed capacity	$145K/MLD installed capacity	$24K/year/MLD installed capacity	390 kWh/ML treated	BOD: <10 mg/mL suspended solids: <20 mg/mL	More compact than conventional STPs	High energy use
Membrane Bioreactor (MBR)	0.035 hectares/MLD installed capacity	$62K-103K/MLD installed capacity	$12K-16K/year/MLD installed capacity	180-220 kWh/ML treated	BOD: <5 mg/mL suspended solids: <10 mg/mL	Low footprint; high effluent quality; high loading rate capability	High O&M costs; high energy costs; membranes are complex and can foul
Duckweed Pond System (DPS)	2-6 hectares/MLD installed capacity	Similar to WSP	$4K/year/MLD installed capacity	Very low compared to ASP	BOD: <10 mg/mL suspended solids: <10 mg/mL	Easy to harvest; less sensitive to surrounding environmental conditions; high nitrogen removal; excess duckweed can be used for animal feed	Duckweed can die-off if not designed properly
Root Zone Treatment System (RZT)	0.1-0.2 hectares/MLD installed capacity	$21K-31K/MLD installed capacity	$1K/year/MLD installed capacity	Very low compared to ASP	BOD: <5 mg/mL suspended solids: <5 mg/mL Colourless	Low cost, high pathogen removal	Requires pre-treatment (settling)
Anaerobic Baffled Reactor + RZT	0.7-0.8 hectares/MLD installed capacity	$21K/MLD installed capacity	<$1K/year/MLD installed capacity	N/A	BOD: <5 mg/mL suspended solids: <10 mg/mL	No electrical energy required; resistant to organic and hydraulic shock loads; low O&M costs; high reduction of BOD; low sludge production; RZT provides high reduction of nutrients	Requires large land area

Table 2: There is a wide range of off-site sewage treatment technologies that may be used in cities and peri-urban areas. (Source: adapted from CSE, 2011, with inputs from Nhapi, et al., 2003 and Tilley, et al., 2014a; costs are in US dollars; MLD = million liters per day; ML = million liters)

While numerous hard technologies are required to manage fecal waste, there is an equally important soft side to sanitation that involves devising and implementing effective policies and understanding mechanisms to influence technology adoption and behavior adaptation.

For example, the government of India spent more than 1 billion U.S. Dollars from 2014 to 2016 in an attempt to end rural open defecation by subsidizing a toilet for each household under the Clean India Mission (Gopalakrishnan, 2015). Improved sanitation at the household level has little benefit to the growth and health of children if other households in the community do not also use improved sanitation facilities (Andres, et al., 2014).

A variety of soft sanitation tools are available, including participatory planning tools, hygiene awareness and behavior change and sanitation promotion to create demand (Peal, et al., 2010).

4. Purification is necessary before water contaminated with fecal matter could be safely consumed

Microbial pathogens that are present in water must be killed, deactivated or physically removed before the water can be safely consumed. There are numerous ways this can be achieved at various scales, including through chemical, thermal, radiation and filtration methods (see **Table 3**).

Approach	Process	Appropriate scale	Observations
Chemical	Chlorine	All scales	May produce disinfection by-products; turbidity can inhibit effectiveness
	Zinc	Household	Requires removal of precipitated material
	Iodine	Household and community	May produce disinfection by-products
	Ozone	Municipal	May produce disinfection by-products
	Silver and copper nanoparticles (e.g. MadiDrop)	Household	Silver is readily absorbed by the body, but it is unclear whether it causes long -term harm; does not form disinfection by-products
	Combined coagulation (e.g. PuR)	Household	Simple technology, but requires constant input of chemicals
Thermal	Boiling	All scales	Energy intensive
Ultraviolet (UV) Radiation	Solar disinfection (e.g. SODIS)	Household	Turbidity and cloud cover can inhibit effectiveness
	UV Waterworks	Household and community	Turbidity can inhibit effectiveness
Filtration	Membrane filter (e.g. reverse osmosis)	All scales	Removes pathogens and many inorganic contaminants
	Ceramic pot	Household	Low cost
	Rapid sand filter (larger particles) and Slow sand filters (drinking water quality)	Community and municipal	Rapid sand filters can be used as pre-treatment step followed by chlorine, ozone, etc.
	Pressure filters	Municipal	May require pre-treatment (i.e. settling or pre-filtration)

Table 3: Numerous methods are available to kill or remove pathogens from drinking water. (Source: based on Gadgil, 1998; Fewtrell, 2014; Amrose, et al., 2015; US EPA, 2018)

Many of these technologies are combined together to achieve better drinking water quality. For example, ceramic filters can be lined with silver and copper nanoparticles to ensure all pathogens are killed and filtered out. Another example is chloramination, which is the combined use of chlorine dioxide and UV radiation. Chlorine is the most and ozone is the second most widely used water disinfectant.

Chemicals used as disinfectants will sometimes react with naturally occurring chemicals in a water source to produce by-products that are harmful to human health. Some common by-products are bromate, chlorite, haloacetic acids and trihalomethanes. Many of these by-products are toxic and/or carcinogenic (US EPA, 2018). Activated carbon filters may be used secondarily to adsorb and remove some of these by-products.

Water quality testing is carried out to ensure that drinking water is safe. The basic WHO drinking water guideline is that no E. coli should be detected in a 100-milliliter sample. Other microbes and indicators can be used to assess water safety (see **Table 4**). It is important to note that these refer to established textbook methods, which may be difficult to successfully implement in many developing countries due to various challenges.

For example, intermittent treated water supply can create pressure gradients that draw contaminants into the pipes, resulting in unsafe delivered water. Furthermore, water sources that are treated onsite (meaning point-of-use treatment) can become contaminated in the household from unhygienic storage or incorrect handling.

Contaminant	Potential Health Effects	Sources of Contamination
Cryptosporidium	Gastrointestinal illness (e.g. diarrhoea and vomiting)	Human and animal feces
Giardia lamblia	Gastrointestinal illness (e.g. diarrhoea and vomiting)	Human and animal feces
Viruses (enteric)	Gastrointestinal illness (e.g. diarrhoea and vomiting)	Human and animal feces
Legionella	Legionnaire's Disease, a type of pneumonia	Occurs naturally in water; multiplies in heating systems
Total Coliforms	Not a health threat, but used to indicate if other potentially harmful bacteria may be present	Occur naturally in the environment as well as in feces
Heterotrophic plate count (HPC)	No health effects. HPC is an analytic method used to measure variety of bacteria in a water sample	HPC measures bacteria that are naturally present in water
Turbidity	Measure of the cloudiness of water; used to indicate water quality and filtration effectiveness. Higher turbidity levels are associated with higher concentrations of pathogens	Soil runoff

Table 4: Water can be analyzed for the presence of microbial contaminants and other quality indicators to determine its suitability for drinking. (Source: adapted from US EPA, 2018)

5. Arsenic and fluoride are natural elements that contaminate some groundwater

Arsenic
In parts of the world, the underground geological formations comprise of minerals containing arsenic or fluoride, resulting in groundwater containing these natural toxins (see **Exhibit 11**). Inorganic arsenic is naturally present at high levels in the groundwater of a number of countries, including Argentina, Bangladesh, Chile, China, India, Mexico and the United States.

In South Asia, due to the deposition of silt from the Himalayas containing arsenopyrite, arsenic-bearing aquifers are prevalent in southern Bangladesh, the Indus basin of Pakistan and the Indian states of West Bengal, Bihar and Uttar Pradesh. Highly populated river deltas in Vietnam and Cambodia, as well as parts of the United States and Latin America, also contain high levels of arsenic in groundwater.

Presence of arsenic in groundwater

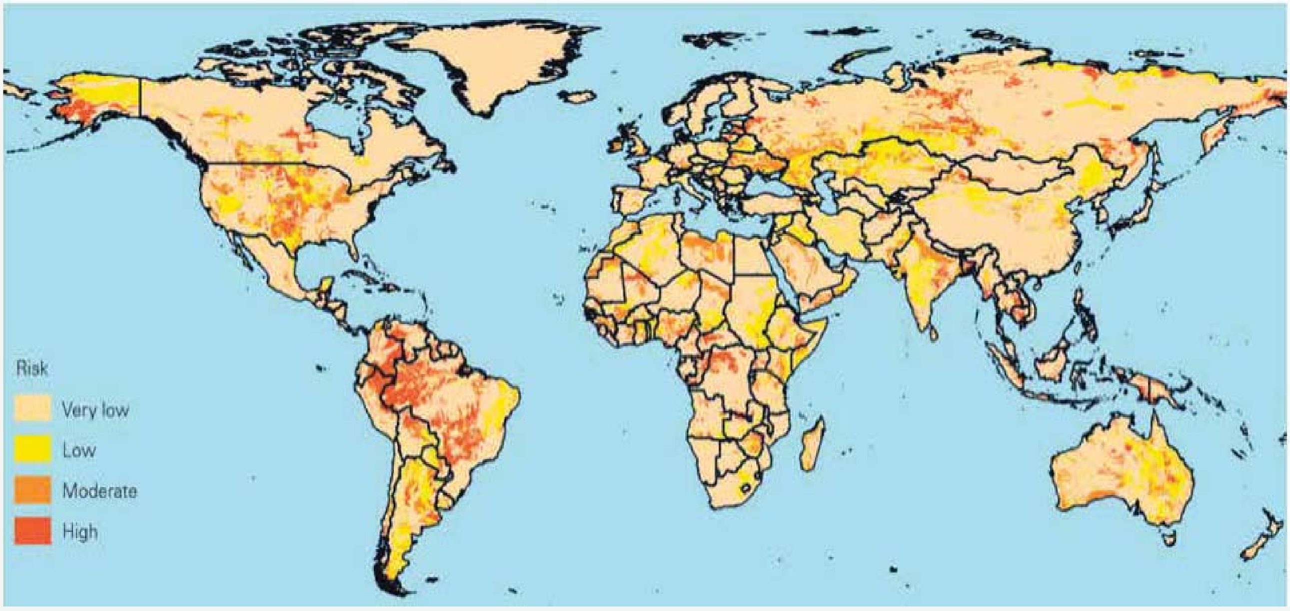


Exhibit 11: Groundwater supply in some regions is contaminated by arsenic. (Source: Schwarzenbach, et al., 2010)

An element on the Periodic Table, arsenic (atomic number 33) is quite mobile in the environment. Although it exists in several forms, the most prevalent forms of arsenic found in groundwater are arsenite [As(III)] and arsenate [As(V)] (Nicomel, et al., 2016). Consumption of water, including both drinking water and cooking water, with elevated arsenic levels over a prolonged period can result in serious health conditions, including skin lesions, hyperkeratosis, melanosis and cancer in different organs, which in some cases has been fatal (NIH, 2017). The probability and severity of health effects increase with exposure level and duration.

Groundwater in problem areas naturally contains arsenic compounds. Until recent decades this caused no problems because groundwater from deeper strata was largely inaccessible.

Prior to the 1960s and 1970s, surface water or shallow well water was typically used for household consumption. As surface waters in rivers, lakes and ponds became more polluted by sewage, borewells were widely constructed to access deeper unpolluted groundwater in order to avoid diarrheal diseases. This inadvertently resulted in wide exposure to arsenic in drinking water (Smith, et al., 2000).

Beginning in the 1980s and 1990s, chronic diseases were observed among households using water containing arsenic. The first cases related to arsenic-contaminated water were observed in the early 1980s in Bangladesh and eastern India and first reported in the medical literature in 1984 (Garai, et al., 1984). The problem of arsenic-contaminated groundwater was further documented during the 1980s and 1990s. In 2000, World Health Organization researchers declared it as "the largest mass poisoning of a population in history" (Smith, et al., 2000).

There is substantial uncertainty around the number of people affected by arsenic. There is also large variation in the level of exposure. Estimates of affected populations are broad and range from 35 to 80 million people in Bangladesh, 50 to 200 million in India and 50 to 60 million in Pakistan (Smith, et al., 2000; Argos, et al., 2010; Chakraborti, et al., 2013; Podgorski, et al., 2017).

Both the WHO and the USEPA specify that no more than 10 micrograms per liter (10 parts per billion) of arsenic can be present in drinking water for safe consumption. It is very difficult to detect arsenic levels below 10 micrograms per liter with current measurement technologies.

The most common current arsenic removal technologies can be grouped into five categories: oxidation, ion exchange, activated alumina, membrane and coagulation/co-precipitation/adsorption (Rahman & Al-Muyeed, 2009). Some promising technologies, such as electrocoagulation, are emerging.

Each of these technologies has trade-offs in terms of water characteristics (i.e. change in pH, concentrations of arsenic, iron, phosphate, silicate and calcium), operation and maintenance complexity and aesthetic water quality. The arsenic concentration of the feed water is a key factor influencing the removal efficiency and cost. Technologies that demonstrate high removal efficiencies when treating moderately arsenic-contaminated water may not be as efficient when treating highly contaminated water (Shan, et al., 2018).

In terms of effectiveness, oxidation-filtration and ion exchange technologies have shown poor efficacy, while zerovalent iron and other adsorption technologies work well. Users give coagulation-coprecipitation-filtration technologies mixed reviews (Amrose, et al., 2015).

Despite the popularity of reverse osmosis (RO) for removing other water contaminants, conventional RO only partially removes arsenic because of the small size of arsenic ions relative to salt ions. It would be possible, in principle, to pass the water through the RO membrane multiple times to remove more arsenic. However, achieving the very low concentration required for arsenic (10 micrograms per liter) would make the cost prohibitively high.

Most arsenic-removal technologies are available at the community and household level. The most widely used household arsenic removal systems use zerovalent iron, such as the SONO filter. However, many household users complain of low flow rate and occasional clogging. Community-level treatment typically exists as column filters containing media, such as activated alumina, granular ferric hydroxide or hybrid anion exchange.

A major concern regarding arsenic removal technologies is that the collected arsenic must be disposed of after it has been removed from a water source. Unfortunately, this disposal practice is often unregulated and arsenic waste is sometimes dumped in ponds or open fields.

The arsenic concentration of these wastes varies widely but can reach 7.5 grams per kilogram (Amrose, et al., 2015). This is roughly a million times more concentrated than the maximum allowable arsenic concentration in safe drinking water. An effective large-scale arsenic removal program will require a method for responsible disposal of the collected arsenic.

Several arsenic mitigation interventions have been studied in recent years to assess their feasibility from technological, institutional and community-adoption perspectives. Researchers found that overwhelmingly, communities prefer borewells as a water source, even if their contamination status is unknown (Inauen, et al., 2013; Johnston, et al., 2014; Hossain, et al., 2015).

In Bangladesh, arsenic levels in groundwater are typically stratified, with low concentrations near the shallow water table, maximum concentrations typically 20 to 40 meters below ground and very low concentrations deeper than about 100 meters (Ravenscroft, et al., 2005). Aquifers that are 100 to 200 meters deep thus offer safe water in the near- to medium- term, but are susceptible to long-term downward arsenic intrusion with intense groundwater pumping.

While experts are better understanding the health effects of arsenic-contaminated drinking water, they are less certain regarding the impacts of using arsenic-contaminated groundwater for irrigation. Studies show little correlation between arsenic in irrigation water and arsenic in produce such as rice, vegetables, fruits and pulses (Senanayake and Mukherji, 2014; Bhattacharya et al., 2010).

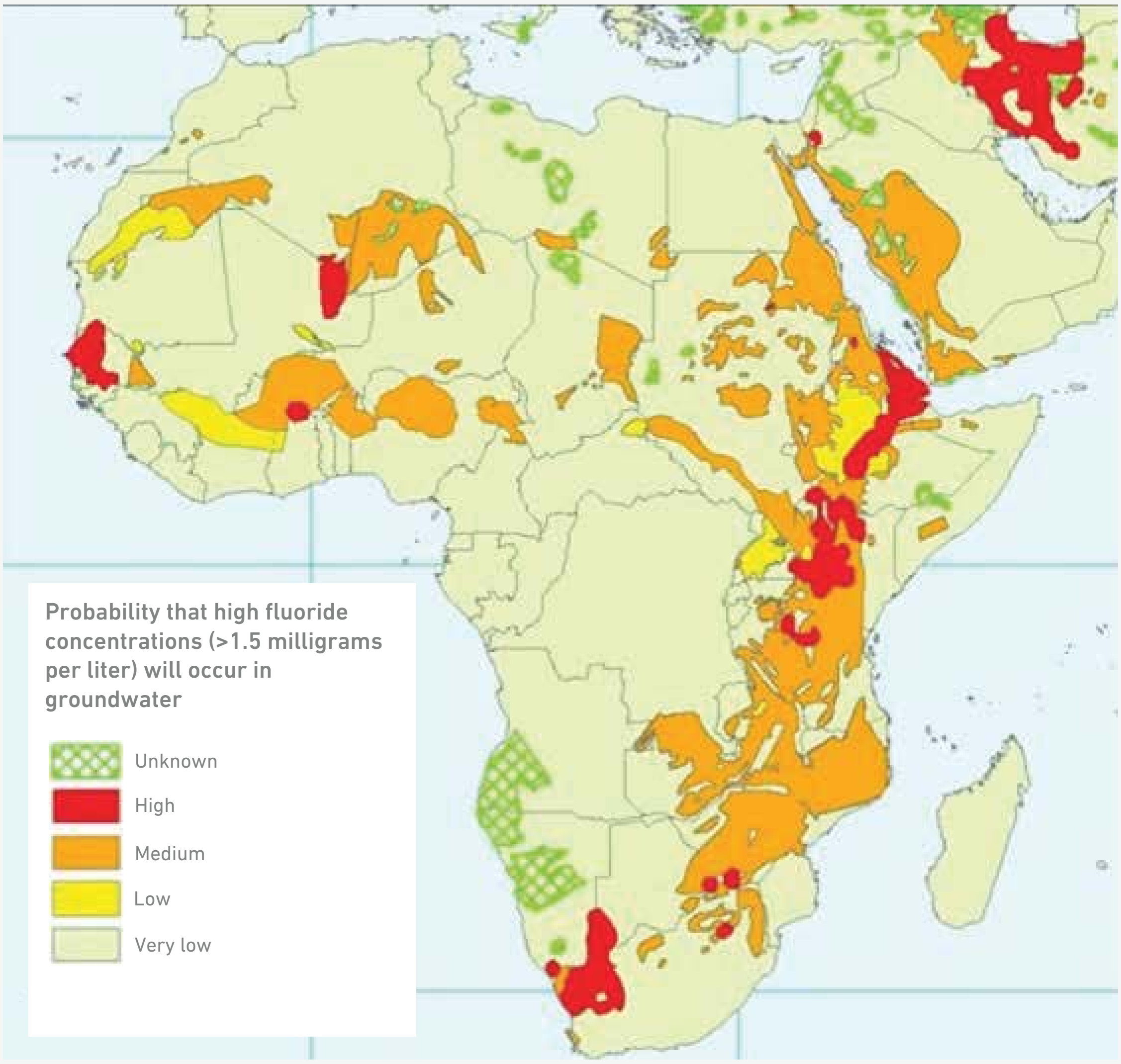
The amount of arsenic available for crop uptake is influenced by multiple factors, including soil redox potential, pH, organic matter content, soil microbes and the levels of iron, manganese, phosphorus and calcium carbonate in the soil.

Arsenic that is taken up by plants tends to accumulate primarily in the plant roots with progressively less accumulating in stems, leaves and grains. Thus, root vegetables, such as potatoes, accumulate a higher amount of arsenic than other crops. The most important impact of irrigation with arsenic-contaminated water may be the significant long-term reduction in yields (Huhmann, et al., 2017).

Fluoride

Fluoride is another naturally occurring element that is present in some groundwater. Fluoride is an anion of the element fluorine (atomic number 9) with the chemical formula F^- and occurs naturally in some groundwater. Fluoride contamination is highly prevalent in hyper-arid and humid areas of Asia and Africa. Mumtaz, et al. (2015) reported that more than 66 million people in India are exposed to high concentrations of fluoride in groundwater. The worst affected areas in India include Rajasthan, Gujarat, Telangana and Andhra Pradesh states. In Africa, the worst affected countries include Senegal, Kenya and South Africa (IGRAC, 2018) (**Exhibit 12**).

Presence of fluoride in groundwater



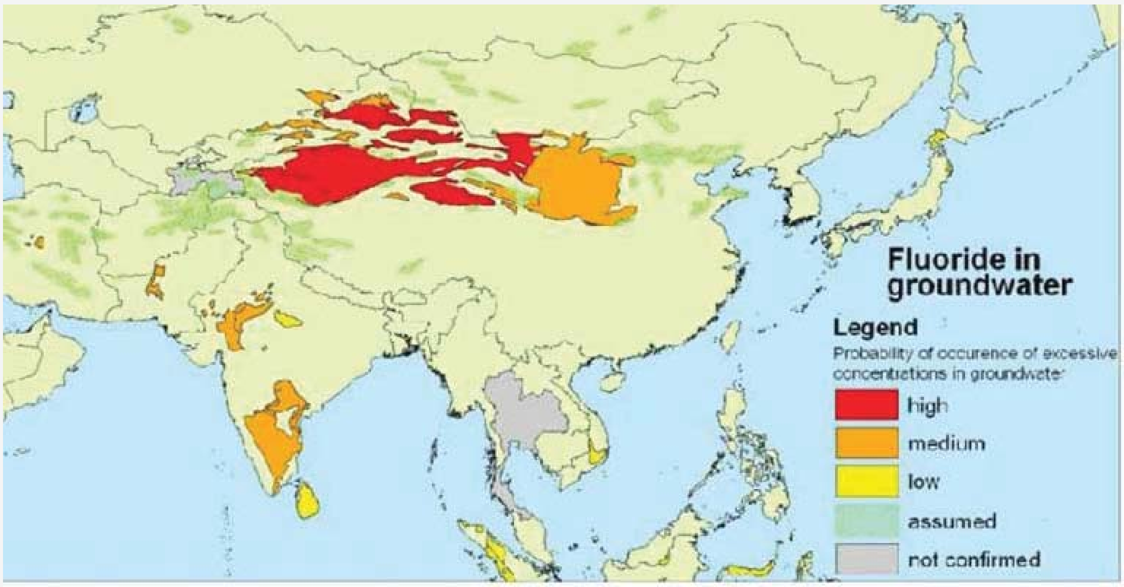


Exhibit 12: Fluoride contamination in groundwater varies widely across Africa and Asia. (Source: IGRAC, 2018)

When present in drinking water at concentrations of 0.8 to 1.0 milligram per liter, fluoride is beneficial for calcification of dental enamel, thus reducing tooth decay. At higher concentrations (1.5 to 2.0 milligrams per liter), fluoride has adverse effects and leads to dental fluorosis. At still higher concentrations (3 to 6 milligrams per liter), skeletal fluorosis occurs, affecting bones and ligaments. WHO recommends a maximum fluoride concentration in drinking water of 1.5 milligram per liter.

Various defluoridation techniques have been developed, including coagulation, adsorption, ion-exchange, electrochemical and membrane-based methods. The coagulation technique uses reagents, such as aluminum salts, lime, calcium and magnesium salts, poly aluminum chloride and alum to precipitate fluoride through a chemical reaction in which the precipitated fluoride coagulates and can then be removed.

These chemical processes include coprecipitation, in which fluoride is simultaneously precipitated with a macro-component through crystal formation, adsorption, occlusion or mechanical entrapment. The Nalgonda technique is a coagulation-defluoridation technique that has seen limited acceptance because it is relatively difficult to maintain and operate. This is a common problem with defluoridation technologies.

Adsorption processes involve continuously cycling fluoride-contaminated water through columns containing an adsorbent, such as bone char, activated alumina, activated carbon, activated bauxite, ion-exchange resins, fly ash, super phosphate and tricalcium phosphate, clays and soils, synthetic zeolites and other adsorbent minerals. The cyclic sorption tends to aggregate and concentrate the fluoride, which can then be disposed of safely.

Electrochemical processes include electrocoagulation and electrosorptive techniques. During electrocoagulation processes, Al^{3+} ions are released from aluminum electrodes through an anodic reaction, which generate aluminum hydroxides that adsorb fluoride ions near the electrodes, resulting in a fluoride complex that can then be easily removed. Electroadsorptive techniques only differ from adsorption techniques in that an electric field is applied to the adsorbent bed, which increases its adsorption capability.

The use of membrane technologies in defluoridation is relatively new and includes reverse osmosis, nano- and ultrafiltration, electrodialysis and Donnan dialysis. These processes typically have high operational costs compared to other defluoridation techniques (Ayoob, et al., 2008; Mumtaz, et al., 2015).

6. Water contaminated by agricultural runoff impacts health and the environment

Farming practices associated with the Green Revolution use large amounts of pesticides and fertilizers; some of these run off from the farm and contaminate surface and ground water.

The use of pesticides has grown significantly in recent decades, with approximately 2.3 million tons of industrial pesticides now used annually (Pure Earth, 2018). Although farm workers are the ones most exposed via inhalation or skin contact, pesticides also affect large numbers of people when these substances are washed by rain or irrigation into streams, lakes and groundwater, where they can be ingested through drinking water. Central and South America are most affected by pesticide runoff, followed by Asia; Africa is less affected due to relatively low levels of pesticide use.

There are many different kinds of pesticides with a range of health impacts, including skin irritations, respiratory and pulmonary problems, vision loss, damage to nervous and immune systems, birth defects, disruption of the hormonal system and many different forms of cancer. Many agricultural pesticides are classified as persistent organic pollutants (POPs), which are organic compounds that do not degrade readily and therefore persist in the environment. They tend to bioaccumulate in organisms, meaning that they remain in individual organisms and build up over time. As smaller organisms are consumed by larger organisms, the POP concentrations increase with each trophic level. This becomes harmful to humans who consume upper trophic level fish.

Another important agricultural water pollutant is fertilizer, primarily nitrogen and phosphorus. Nitrogen pollution poses a direct health threat when in the form of nitrate (NO_3). High levels of nitrate in drinking water have been linked to methemoglobinemia in infants, various cancers in adults and toxic effects on livestock (Carpenter, et al., 1998; Richard, et al., 2014; Schullehner, et al., 2018). Phosphorus in water is not considered to be directly harmful to humans and animals, and no drinking water standards have been established for phosphorus (Carpenter, et al., 1998). Toxicity caused by phosphorus in freshwaters is indirect, due to algal blooms stimulated by phosphorus pollution.

Just as fertilizing agricultural fields can stimulate crop growth, increasing the levels of nitrogen and phosphorus nutrients in rivers, lakes and estuaries can cause excessive growth of aquatic organisms. Known as eutrophication, the nutrients enable the growth of huge blooms of algae that dominate aquatic ecosystems, seriously degrading water quality (Smith, 2003). Algal blooms are problematic since they blanket the water's surface and block sunlight from reaching underlying aquatic plants, killing them. Once the algae die off, the bacterial degradation of their biomass consumes the oxygen in the water, causing hypoxia that results in the death of fish and other aquatic organisms.

More than 400 marine dead zones resulting from nutrient runoff are reported worldwide, having approximately doubled each decade since the 1960s (Diaz & Rosenberg, 2008). Large algal blooms and hypoxia characterize the Arabian Sea, where a recent change in algal species is thought to have resulted from the massive organic and nutrient loads entering the sea from Karachi, Mumbai and other cities along the coasts of India and Pakistan (Gomes, et al., 2014).

Many cyanobacteria (also known as blue-green algae) also produce toxic compounds that are hazardous to humans and domesticated animals. Mass blooms of toxic cyanobacteria occur regularly in water subject to nutrient runoff, with the timing and duration of the bloom season varying by location.

In recent decades, the amount of reactive nitrogen in rivers has increased dramatically (Green, et al., 2004; MEA, 2005), with river basins in North America, continental Europe and South and East Asia showing the greatest change (**Exhibit 13**). Africa suffers little from nitrogen pollution, mainly because fertilizer use in Africa is still very low.

Increase in nitrogen runoff leading to aquatic dead zones

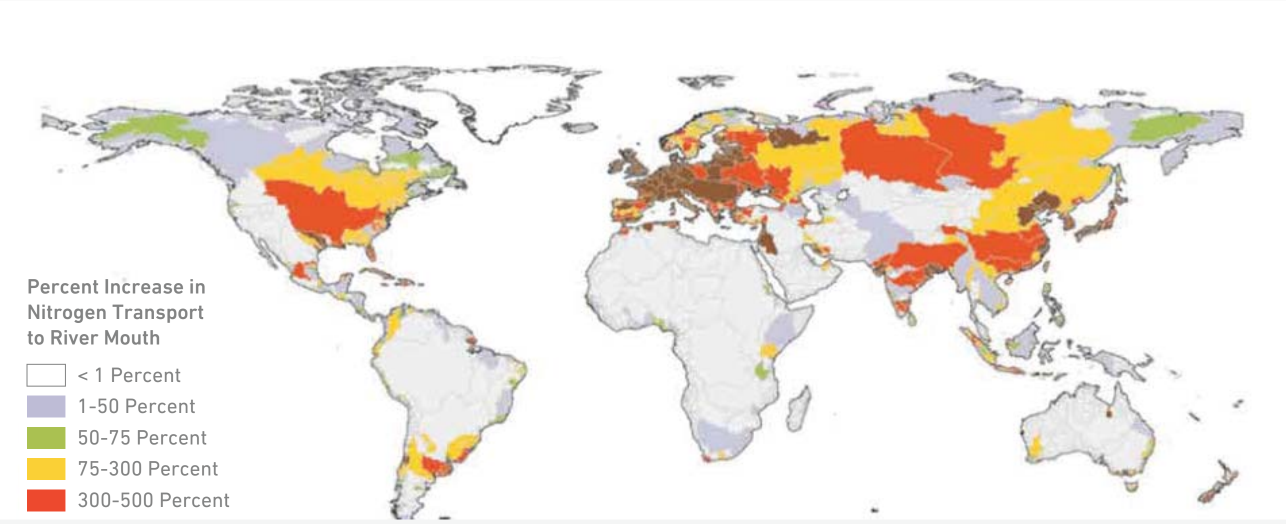


Exhibit 13: Reactive nitrogen flows in many river systems have increased dramatically in recent decades—primarily due to fertilizer runoff from agricultural lands—especially evident in Europe, Asia and North America. This has led to dead zones in waterways. (Source: MEA, 2005)

In addition to nitrogen, another important source of water pollution is the chemical element phosphorus, which is an essential nutrient for plant growth. Phosphorus fertilizers are important because of the slow natural cycling of the element, the low solubility of natural phosphorus-containing compounds and the essential nature of phosphorus to living organisms. Traditional sources of agricultural phosphorus are animal manure and guano (bird droppings).

Exhibit 14 shows that phosphate rock mining expanded considerably after 1950 and is now the dominant source of phosphorus fertilizer, an essential input to intensive agriculture (Cordell, et al., 2009). Phosphorus runoff is a major cause of eutrophication. For example, the water supply for the city of Toledo, Ohio, U.S. was interrupted for several days in August 2014 due to an algae bloom caused largely by phosphorus fertilizer runoff.

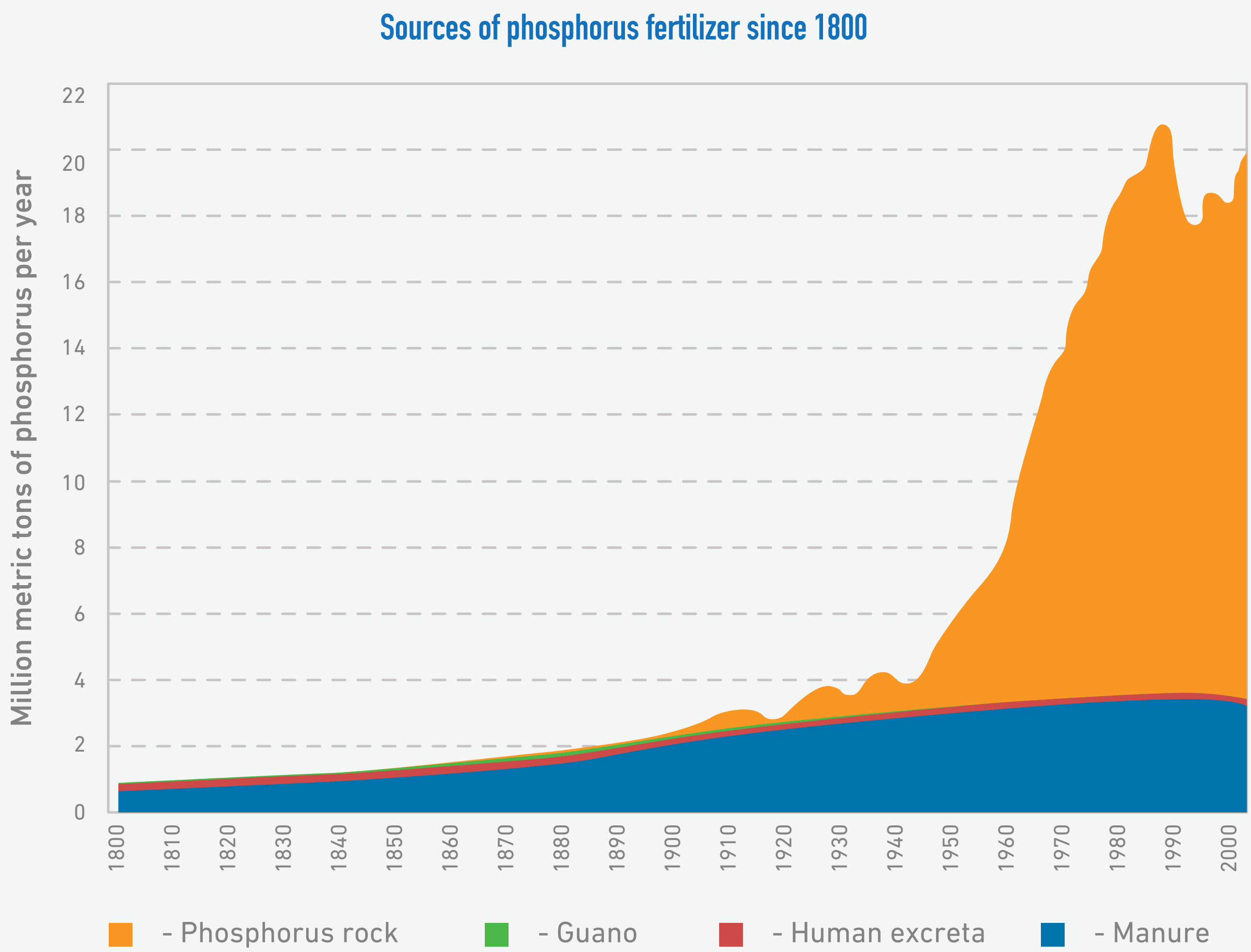


Exhibit 14: Mining of phosphate rock expanded considerably after 1950 and is now the dominant source of phosphorus fertilizer used in agriculture. (Source: Cordell, et al., 2009)

In conventional agricultural practice, roughly 20 percent of nitrogen (N) fertilizer and 5 percent of phosphorus (P) fertilizer runs off of farmlands and contaminates surface water (NRC, 2000; MEA, 2005,). Within India, the amount of P entering Indian surface water from fertilizer runoff is roughly equal to the amount of P from human feces and urine discharged from sewers, while the amount of N from Indian fertilizer runoff is about six times more N than from sewers (see **Exhibit 15**).

Excess of P typically causes more eutrophication than N, as in aquatic ecosystems P is the limiting nutrient more often than N.

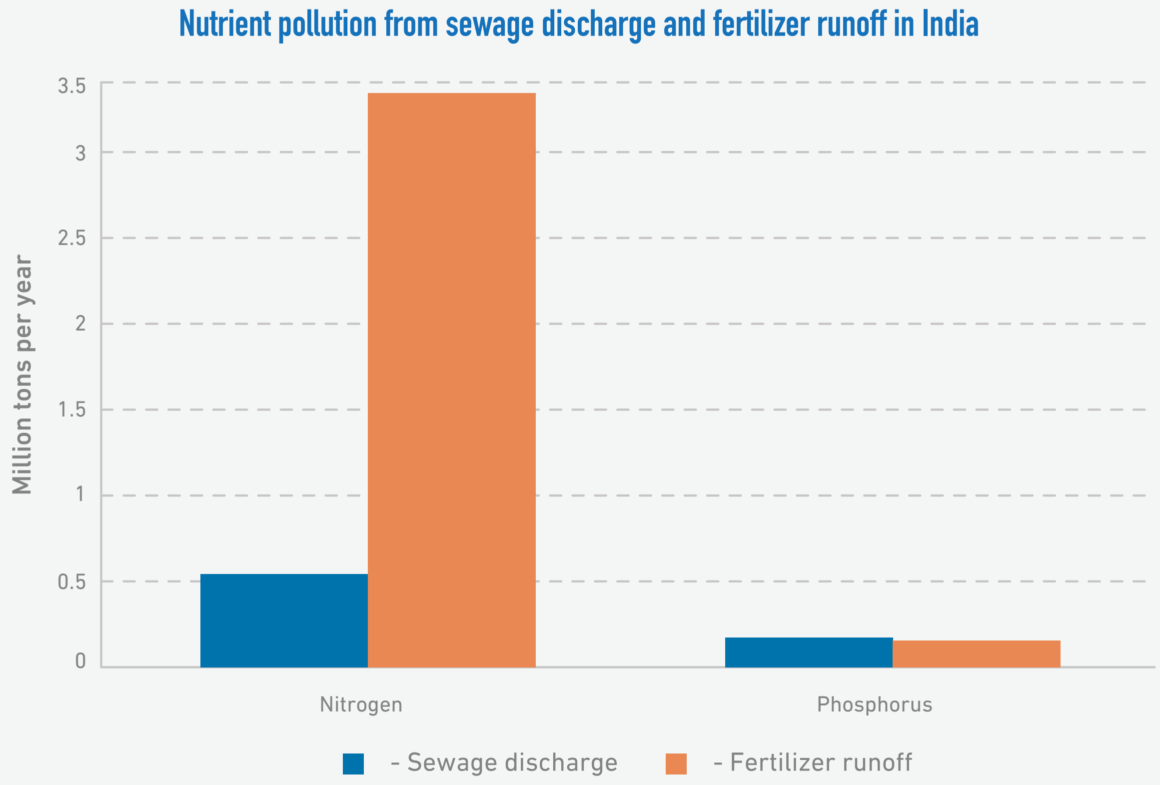


Exhibit 15: Fertilizer runoff from Indian farmlands releases about six times more N, and about equal amounts of P, compared to human waste discharged from Indian sewers. (Source: ITT analysis based on: For fertilizer runoff, all-India fertilizer consumption from Fertiliser Association of India, 2016, percent run-off of N and P from NRC, 2000 and MEA, 2005; For sewage discharge, all-India population from UN, 2017, urban percentage from UN, 2018, urban sewer connection rate from JMP, 2017, average per capita feces and urine discharge from Rose, et al., 2015, percent nutrient content of feces and urine from Rose, et al., 2015)

Implementation of global best practices would significantly reduce the percentage of applied fertilizer that runs off. Appropriate nutrient management, by applying fertilizers in the proper amount at the right time and via a suitable method, can significantly reduce the potential for runoff (FAO, 1996). Other good practices include planting cover crops and buffer strips, employing conservation tillage practices and managing livestock waste (UN, 2017).

Climate change may, however, impact efforts to improve farm nutrient management, as N run-off is projected to increase due to changes in precipitation patterns (Sinha, et al., 2017). Management of paddy straw and other crop residue is a strong lever for improvement in some areas. In many regions, farmers typically burn crop residue, losing important potential nutrients as well as causing significant air pollution (Lohan, et al., 2018). Proper management of crop residues can improve soil health and reduce fertilizer consumption, particularly nitrogen.

7. Diverse industrial effluents cause health and environmental impacts

Rapid industrial and agricultural expansion in many developing countries during recent decades has resulted in a diverse range of chemical contaminants that increasingly pollute surface and groundwater. Industrial effluent typically originates from discrete and concentrated point sources, such as individual facilities, while agricultural runoff comes from diffuse non-point sources across large areas.

This means that there are variances in exposure patterns between the two and as such each type of effluent requires a different potential solution.

Industrial pollution is increasing globally, because the overall industrial production in numerous diverse industrial sectors is growing faster than the adoption of best practice cleaner industrial processes.

Effluent is discharged from a range of industrial sectors: distilleries, sugar, textiles, electroplating, pesticides, pharmaceuticals, pulp and paper, tanneries, dyes, petrochemicals and steel (see **Table 5**). These effluents are diverse and contain a wide range of chemical and biological contaminants with potential human health effects.

Industry	Typical content of effluent
Pulp and paper	• Chlorinated lignosulphonic acids, chlorinated resin acids, chlorinated phenols and chlorinated hydrocarbons - about 500 different chlorinated organic compounds identified • Colored compounds and absorbable organic halogens (AOX) • Pollutants characterized by BOD, COD, suspended solids (SS), toxicity and colour
Iron and steel	• Cooling water containing ammonia and cyanide • Gasification products - benzene, naphthalene, anthracene, cyanide, ammonia, phenols, cresols, and polycyclic aromatic hydrocarbons • Hydraulic oils, tallow and particulate solids • Acidic rinse water and waste acid (hydrochloric and sulphuric)
Mines and quarries	• Slurries of rock particles • Surfactants • Oils and hydraulic oils • Undesireable minerals, i.e. arsenic • Slimes with very fine particulates
Food industry	• High levels of BOD and SS concentrations • Variable BOD and pH depending on vegetable, fruit or meat and season • Vegetable processing - high particulate, some dissolved organics, surfactants • Meat - strong organics, antibiotics, growth hormones, pesticides and insecticides • Cooking - plant organic material, salt, flavourings, coloring material, acids, akalines, oil and fat
Brewing	• BOD, COD, SS, nitrogen, phosphorus - variable by individual processes • pH variable due to acid and alkaline cleaning agents • High temperature
Dairy	• Dissolved sugars, proteins, fats and additive residues • BOD, COD, SS, nitrogen and phosphorus
Organic chemicals	• Pesticides, pharmaceuticals, paints and dyes, petro-chemicals, detergents, plastics, etc. • Feed-stock materials, by-products, product material in soluble or particulate form, washing and cleaning agents, solvents and added-value products such as plasticizers
Textiles	BOD, COD, metals, suspended solids, urea, salt, sulphide, H2O2, NaOH • Disinfectants, biocides, insecticide residues, detergents, oils, knitting lubricants, spin finishes, spent solvents, anti-static compounds, stabilizers, surfactants, organic processing assistants, cationic materials, colour • High acidity or alkalinity • Heat, foam • Toxic material, cleaning waste
Energy	• Extraction of fossil fuels - contamination from oil and gas wells and fracking • Hot cooling water

Table 5: Different industry sectors produce effluents with a wide range of contaminants. (Source: WWAP, 2017)

Two particularly concerning types of environmental toxins are heavy metals and endocrine disruptors. Heavy metals are basic metal elements such, as lead, mercury, cadmium and chromium. As elemental materials, they cannot be degraded or destroyed and also bioaccumulate in the body over time. Exposure to lead affects multiple body systems.

Young children are particularly vulnerable to the toxic effects of lead and can suffer profound and permanent brain and nervous system damage. An emerging threat from some contaminants is their potential impact to the human endocrine system. Some chemicals, including POPs and heavy metals, act as endocrine disruptors, interfering with the body's natural hormones. Even at very low levels of exposure, they may cause reproductive and other health problems, including infertility and early puberty, in humans and animals.

Discharge of effluent with a high biological carbon content (from, for example, pharmaceutical, textile, pulp and paper industries, as well as from sewage) results in a high biochemical oxygen demand (BOD) when discharged into water bodies. Microorganisms rapidly decompose the organic material and use up large quantities of oxygen in the process, which depletes the surrounding environment of oxygen and leads to hypoxic conditions (described above for fertilizer runoff). The lack of oxygen can lead to the death of aquatic fauna.

In developing regions, industrial waste products have commonly been discharged untreated into the nearest water body, as regulations that may have prohibited such dumping were absent, not enforced or overseen by corrupt authorities. More recently, however, increased societal concerns for a clean and healthy living environment have increased pressure in many regions for improved industrial waste management practices.

During recent decades, there have been stronger regulations for improving water quality and environmental protection. This has stimulated a range of technological innovations, which are increasingly adopted by industries, to reduce or eliminate discharge of water pollutants (UN, 2017). End-of-pipe solutions are available to manage existing effluent production, but more advanced solutions involve altering industrial processes to eliminate the source of pollutants. Broad implementation of global best practices within developing countries would significantly reduce industrial effluent discharge and improve water quality.

Existing chemical waste sites may be a long-term source of surface and groundwater contamination, unless the sites are remediated. A range of remediation techniques can be used, depending on the types of contaminants, their location in the ground or water and the resources available for treatment (U.S. EPA, 2002).

Bioremediation may be a cost-effective way to treat both organic and inorganic chemical contaminants on-site, and several microbial and fungal species have been shown effective at removing difficult contaminants such as heavy metals and endocrine disrupters (Pezzella, et al., 2017).

Removing chemical contaminants from polluted water is challenging, due in part to the wide range of pollutants, such as heavy metals discharged from mining, smelting and e-waste recycling industries and high organic loading released from pulp/paper, animal processing and pharmaceutical industries. The petroleum, petrochemical and transport industries are responsible for toxic compounds, such as hydrocarbons, polychlorinated biphenyls (PCBs), persistent organic pollutants (POPs), volatile organic compounds (VOCs) and chlorinated solvents.

Across this diversity of contaminants, there exists a range of technological processes to remove them from water (ITT, 2018). These include adsorption, filtration, electrochemical removal, chemical reaction, precipitation, bioremediation and others.

Regardless of the treatment method, there is the added challenge of disposing or containing the removed contaminants. Currently, there is no standard or recommended way to dispose of removed contaminants to eliminate re-exposure. Generally, the removal of many chemical contaminants from water is extremely challenging and costly, thus best practice is typically to increase safeguards to avoid or minimize their uncontrolled discharge to the environment.

8. Salty water is abundant in many places, but cannot be used directly

In regions that historically have had saline or brackish groundwater, as well as in coastal regions with access to sea water, salty water has long been present but has not typically been used as a water supply, except in some industrial applications.

Permanent human settlements in these regions have depended on reliable access to a separate source of freshwater. Thus, the presence of saline or brackish water has not been a problem per se, although it has limited the available options for water supply (Margat & Gun, 2013). Naturally occurring saline groundwater is particularly prevalent in Central Asia, Middle East, Australia and the southern part of South America (see **Exhibit 16**).

Presence of saline groundwater

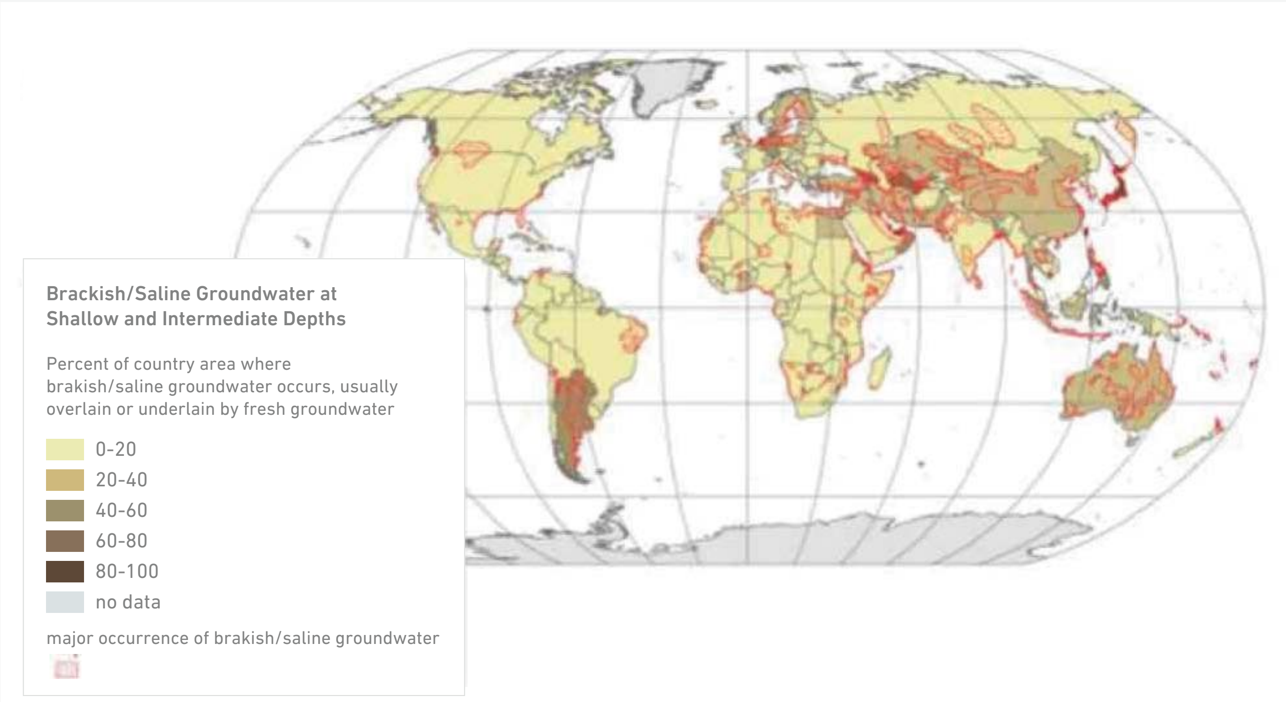


Exhibit 16: Groundwater in some regions contains salt. The worst affected regions include the Middle East, Central Asia and Australia. (Source: IGRAC, 2018)

More recently, some regions that historically had fresh groundwater supplies have suffered from salinization of their groundwater, or the intrusion of salty groundwater into freshwater aquifers. This may have a range of causes, including sea level rise, overdraft of freshwater aquifers, river basin closure and waterlogging of irrigated cropland.

In these regions, the salinization of previously fresh water sources can have a significant impact on social wellbeing and economic activity. The salinization of coastal aquifers is particularly acute in some parts of South Asia including the Sundarban region in coastal Bangladesh and eastern India (see **Exhibit 17**).

Groundwater salinization in Bangladesh

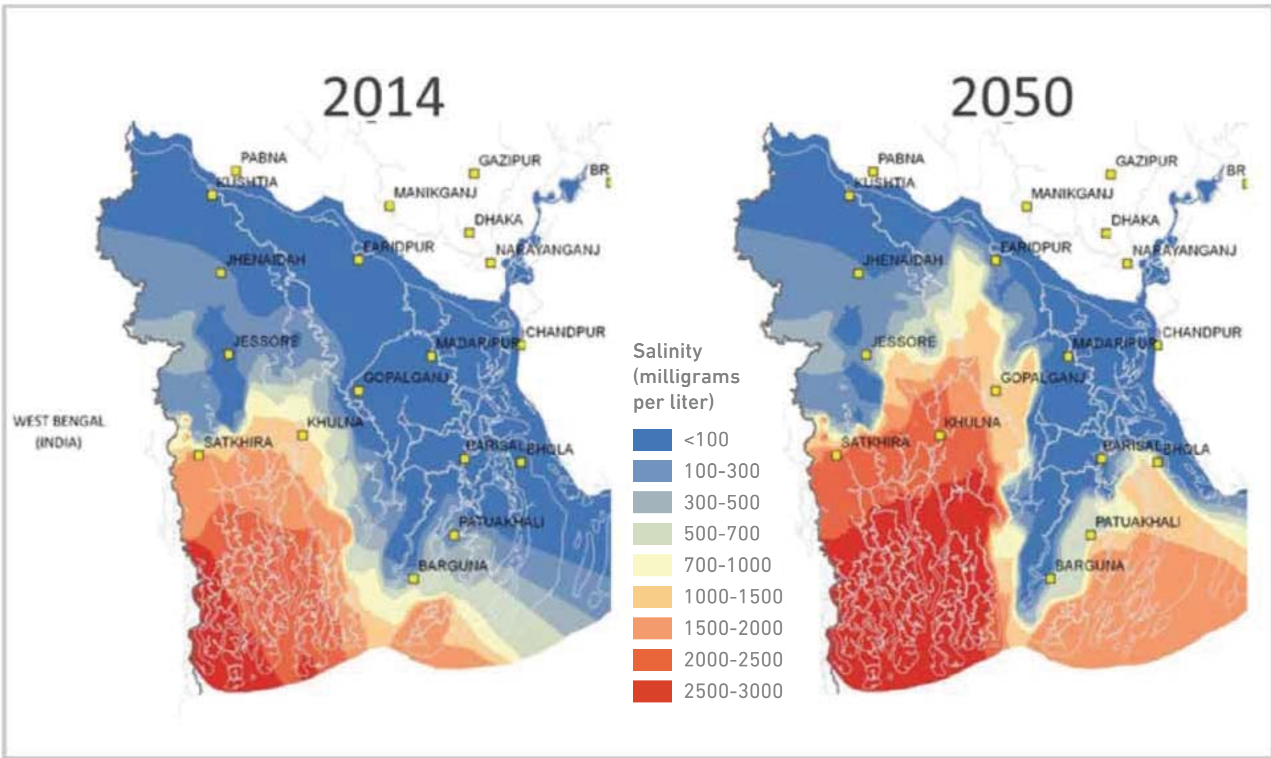


Exhibit 17: Groundwater in southern Bangladesh is expected to become increasingly saline by 2050, due to salinity intrusion from rising sea level. (Source: adapted from CSIRO, 2014)

Fresh groundwater aquifers are often surrounded by saltwater on one or more sides or underneath. Since freshwater is less dense than saline water, it tends to flow on top of the surrounding or underlying saline groundwater. Under natural conditions, the boundary between freshwater and saltwater maintains a stable equilibrium. Under some circumstances, the saltwater can move (or intrude) into the freshwater aquifer, making the water non-potable. When freshwater is pumped from an aquifer that is near saline groundwater, the boundary between saltwater and freshwater moves in response to the pumping. If this continues, unusable saline water will be pumped up from the well.

Freshwater aquifers are naturally recharged by rainwater, and the recharge rate can be manipulated by managed aquifer recharge. Thus, there is dynamic interplay between freshwater withdrawals, freshwater recharge and surrounding saline aquifers. Rising sea levels due to climate change are slowly increasing the gradient of saline water, although coastal aquifers are more vulnerable to groundwater extraction than to predicted sea-level rise (Ferguson & Gleeson, 2012).

Techniques are under development to manage saline groundwater intrusion. Actions, such as controlling the rate and depth of groundwater extractions and augmenting freshwater recharge by MAR, can reduce or eliminate undesired saline intrusion. Skimming wells can also be used to sustainably exploit fresh groundwater lenses that overlie native saline groundwater (Saeed & Ashraf, 2005). The freshwater lenses are renewed through deep percolation of rain and irrigation water. Skimming wells are designed and operated to minimize the mixing between overlying freshwater and underlying saline water.

Successful management of saline groundwater intrusion requires a deep understanding of aquifer dynamics and how they may be manipulated. The tools of groundwater mapping can provide the required knowledge of the hydrogeological landscape.

9. There is great potential for brackish water desalination

Desalination is the process of making potable water from saline water sources, such as sea water or brackish water. The salt content of water is typically measured in milligrams of total dissolved solids (TDS) per liter of water. The salinity of ocean water averages 35,000 milligram per liter globally, varying from about 32,000 to 38,000 milligram per liter. Water is generally considered potable when it contains TDS less than about 1,000 milligram per liter, though many potable water standards in Asia are stricter than this. The Indian standard specifies an acceptable limit of 500 milligram per liter, though in the absence of an alternative water source the permissible limit is 2000 milligram per liter (BIS, 2012).

Desalination is currently used in select regions of the world. There are more than 7,500 desalination facilities worldwide, more than half of which are located in the Middle East (Shatat & Riffat, 2014). Virtually all are powered by fossil fuels and are often integrated with, and use waste heat from, electricity generating stations. The world's largest desalination plant is located in Ras Al-Khair in Saudi Arabia, which produced more than a million cubic meters of fresh water per day in 2014. The southern Indian city of Chennai gets about a quarter of its domestic water from two desalination plants, each producing about 100,000 cubic meters per day, in operation since 2010 and 2013.

There are numerous desalination technologies, which can be divided into four major categories depending on the driving force of the process: thermal, pressure, electrical and chemical (Miller, 2003; Youssef, et al., 2014; Subramani & Jacangelo, 2015).

- Thermally driven systems use evaporation and condensation at different temperatures and pressures as the main process to separate salts from water. In these systems, heat transfer is used to either boil or freeze the feedwater to convert it to vapor or ice, so the salts are separated from the water. The most common thermal processes include the multi-stage flash process and the multi-effects distillation process (Shatat & Riffat, 2014). Other thermally activated systems include vapor compression distillation, humidification-dehumidification, solar distillation and freezing.

- Pressure-activated systems use a pressure gradient to force water through a permeable membrane, leaving salts behind. In recent decades, membrane technologies have matured and most new desalination installations use membranes. Of these, the reverse osmosis (RO) process is the most common; others include forward osmosis and nanofiltration.
- Electrically-activated systems take advantage of the charged nature of salt ions in solution, by using an electric field to remove ions from water. The most common configuration is electrodialysis (ED), which currently accounts for about 4 percent of global desalinated water production. An emerging technology is capacitive deionization.
- Chemically-activated desalination systems include ion-exchange desalination, liquid–liquid extraction and gas hydrate or other precipitation schemes. There are numerous alternate desalination processes that are technically possible but have economic or practical issues (Miller, 2003).

A major difference between the various processes is the source of energy, such as heat, pressure, electrical or chemical, that drives the desalination process (Rao, et al., 2016). Cost of the energy supply strongly affects the cost of desalination.

In general, thermal desalination uses large amounts of heat, reverse osmosis uses much smaller amounts of electricity and electrodialysis uses even less electricity but is limited to low-salinity feedwater (see **Exhibit 18**).

The overall cost of the various processes also varies and is heavily dependent on scale. Larger facilities are far less expensive per cubic meter of fresh water (see **Exhibit 19**).

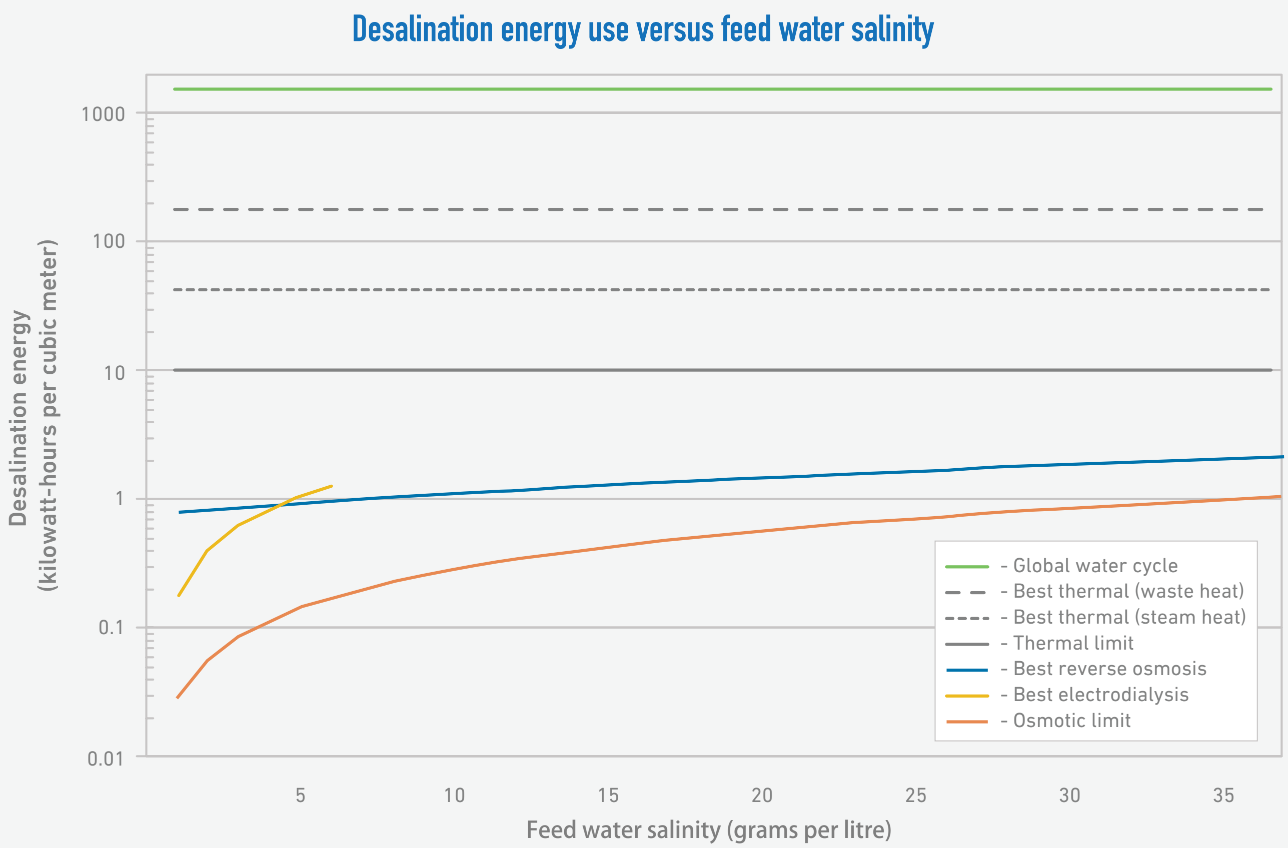


Exhibit 18: Energy use for desalination (kilowatt-hour per cubic meter of fresh water) as a function of feedwater salinity (grams TDS per liter of feedwater) for various desalination processes. Note vertical axis is logarithmic. (Source: ITT analysis based on Cerci, et al., 2003; Fritzmann, et al., 2007; Elimelech & Phillip, 2011; Shatat & Riffat, 2014)

Cost of desalination varies by process and scale

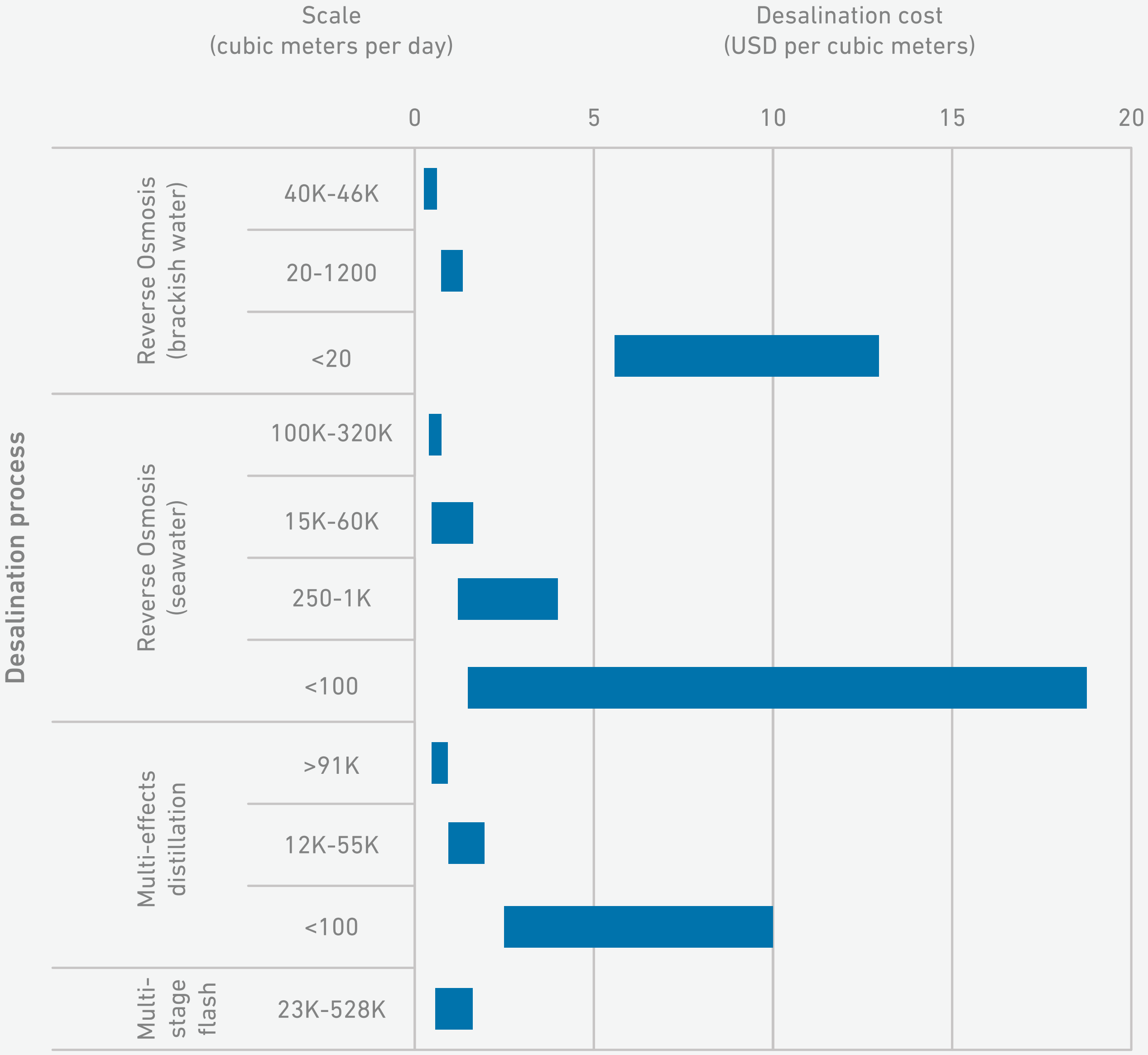


Exhibit 19: The levelized cost of current desalination processes (USD per cubic meter of fresh water) varies depending on the technology used and the scale of the process (cubic per day). The cost of energy inputs is also a significant variable. (Source: Shatat & Riffat, 2014)

Membrane-based seawater desalination technologies have benefited from numerous improvements during recent decades, including higher-permeability membranes, installation of energy recovery devices and the use of more efficient pumps. These technologies are approaching theoretical limits of energy efficiency (see **Exhibit 20**) and are already used at commercial scale for industrial and domestic use (Elimelech & Phillip, 2011).

Although minor incremental efficiency improvements may still be gained, it is unlikely that major technology breakthroughs will fundamentally alter the seawater desalination landscape. DOE (2017) found that adoption of current state-of-the-art practice would reduce total energy use by 20 percent from current typical level, and opportunities from additional R&D could reduce it by about half, before reaching a practical minimum level of energy use for seawater desalination.

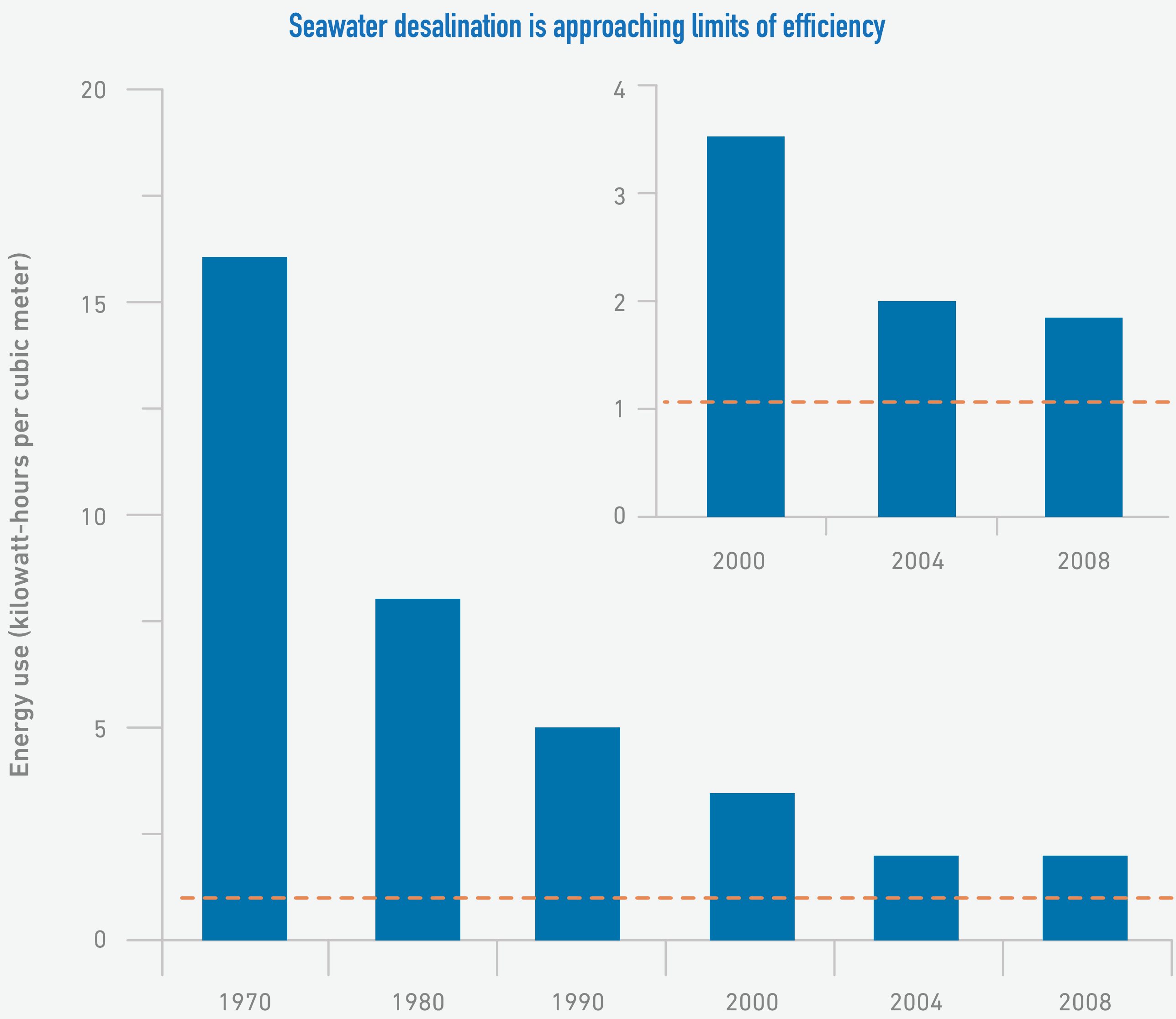


Exhibit 20: The energy requirement for seawater desalination using reverse osmosis has decreased during recent decades due to technology improvements. It is approaching theoretical limits of efficiency, shown by the dashed line. (Source: Elimelech & Phillip, 2011)

For brackish water, however, there are major opportunities for significant reductions in desalination cost and energy use through innovative electrochemical or other emerging techniques. The minimum theoretical energy requirement for desalination varies with the salinity of the feedwater—less energy is fundamentally needed to desalinate brackish water, compared to seawater.

Conventional thermal or pressure-based desalination techniques require similar energy inputs regardless of the feedwater salinity (although various configurations of brackish water reverse osmosis desalination are available to somewhat improve efficiency; see Li, 2012). Electrically-driven techniques, such as electrodialysis (ED) and capacitive deionization (CDI), are limited to low-salinity feedwater, but potentially cost less and require less energy than pressure or thermal techniques (see **Exhibit 18**). ED and CDI are highly efficient for desalinating feedwater on the dilute end of the brackish water range (0.6 to 4 grams per liter TDS).

ED and CDI technologies use less energy because they transport the (relatively few) dissolved salt ions out of the feedwater, rather than transporting the (plentiful) water molecules away from the salt as in thermal and pressure technologies (Suss, et al., 2015). The electrical current required for ED and CDI is proportional to the amount of salt removed (Knust, et al., 2014).

Electrically-driven desalination processes can achieve high water recovery and high brine concentrations. Electrical methods only remove ions from the water but leave organics and colloids in suspension, which is of concern for household water but less important for irrigation water. They require little or no feedwater pre-treatment, and membrane fouling can be prevented by reversing the electrode polarities. However, the selection and configuration of membranes is highly dependent on feedwater chemistry, thus must be adapted to local conditions of feedwater composition and concentration.

CDI is an important emerging technology that separates ions from water by using two highly porous electrodes, such as carbon aerogels, to capacitively adsorb ions thereby removing them from solution. Once the ionic capacity of the electrodes becomes saturated, the polarity is reversed to release the ions and the cycle is repeated. CDI is intrinsically a batch process that relies on polarity reversal, making it more difficult to implement in a continuous process.

Another challenge of CDI is a limited cycle life due to corrosion of the positively charged carbon electrode during operation. Activated carbon is the most commonly used electrode material. Electrode materials for CDI must have low electrical resistivity, high specific surface area and controllable pore size distribution. Numerous electrode materials, such as activated carbons, alumina and silica nanocomposites, carbon nanotubes, carbon nanofibers, carbon aerogel, graphene and mesoporous carbon, have been investigated. There is also potential for improved performance due to doping effects and blending of different materials (AlMarzooqi, et al., 2014).

There are additional opportunities to increase system efficiency and decrease delivered water costs for all desalination techniques, including for brackish and seawater. These include optimizing and standardizing the full desalination system, including feedwater input, pre-treatment, desalination, post-treatment and brine disposal.

There are also opportunities to make technological breakthroughs that minimize or eliminate membrane fouling, scaling and general maintenance, which would reduce breakdowns and allow small-scale systems to become more feasible. System characteristics should be tailored depending on scale and feedwater salinity. There should also be a focus on determining the appropriate unit scale for various applications like those for households, villages or cities, and developing appropriate business models to ensure economic sustainability.

The challenge of brine disposal must also be addressed. Brine is a hypersaline concentrate that remains after freshwater is separated from saline feedwater, and requires disposal. Brine disposal is costly and can potentially cause environmental damage. Jones, et al. (2019) estimated that more than 140 million cubic meters of brine is produced each day, from global desalination processes that produce 95 million cubic meters of freshwater.

Brine disposal cost is largely determined by volume. For a given volume of freshwater produced, the volume of brine produced is determined by the recovery ratio. Current reverse osmosis desalination processes, for example, have a recovery ration of about 50 percent, meaning that for each cubic meter of freshwater produced, 1 cubic meter of concentrated brine waste is created. Electrodialysis processes typically have higher recovery ratios, thus produce less brine waste by volume.

RO and other desalination technologies are already commercially available and in use for relatively high-value, low-volume requirements. These include drinking, cooking, washing and other domestic uses and industrial water uses. Agricultural water use for conventional irrigation typically requires much larger volumes and much lower costs than desalination can feasibly provide. Without a breakthrough that enables large scale, very low-cost technologies, desalination is unlikely to be used as a water supply for extensive agriculture, due to the relatively high cost of desalination and the large volumes of irrigation water needed (see **Exhibit 21**).

Desalination may be more suitable for high intensity cultivation of high value crops, using techniques like hydroponics or precision irrigation that have high water use efficiency. As additional efficiency gains are realized in large-scale brackish water desalination, these resources could enable greater use of desalinated water in agriculture. Kumar (2017) showed economic viability of desalinated water for irrigating high value fruits, vegetables and flowers in water scarce regions of India that also have brackish groundwater that can be treated, such as northern Gujarat, western Rajasthan and southwestern Punjab.

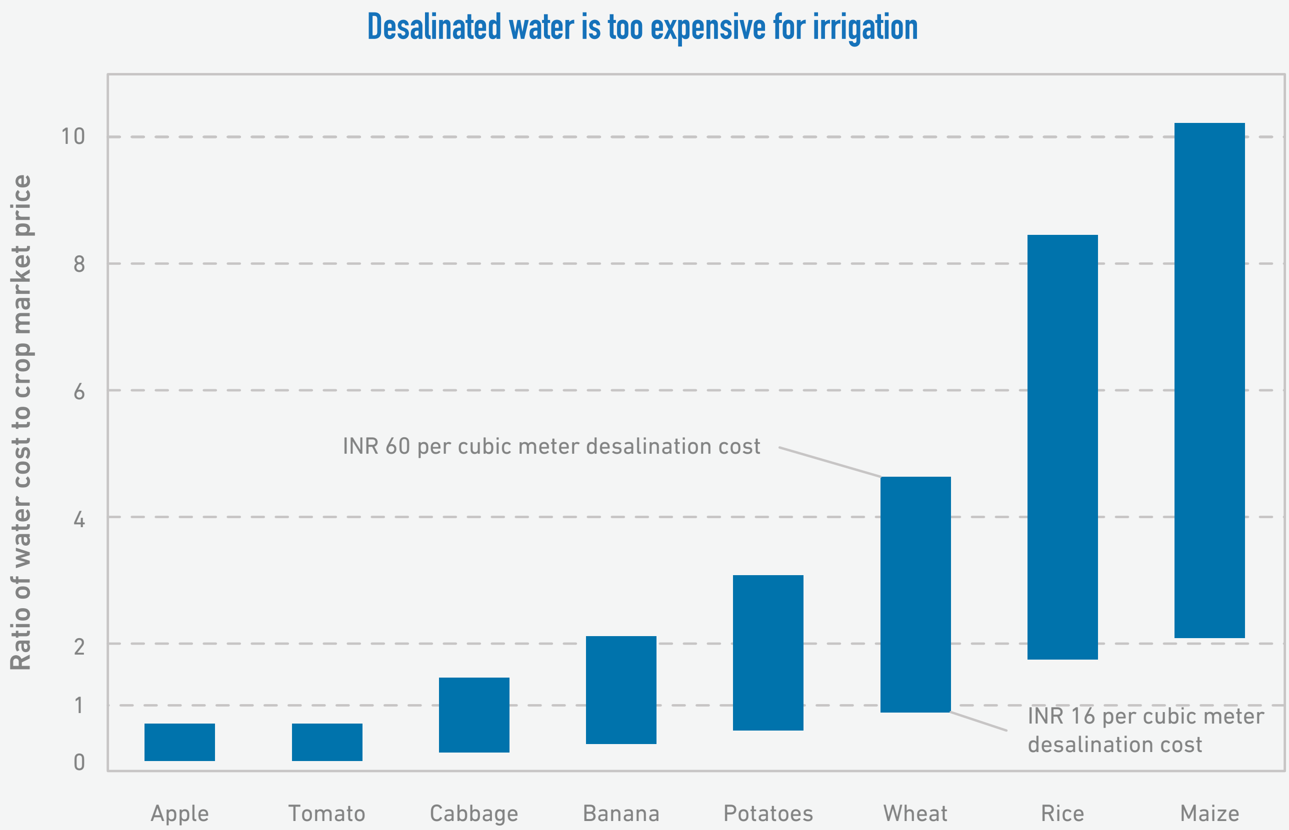


Exhibit 21: : If desalinated water were used for conventional crop irrigation, the water cost would exceed the current consumer price of all cereals and most fruits and vegetables. Efficiently using desalinated brackish water to grow high-value crops may be more viable. (Source: ITT analysis based on crop irrigation water requirements from Fishman, et al., 2015 and The Guardian, 2013; average consumer crop prices in India from USDA, 2017 and AgriXchange, 2017; low desalination cost (INR 16 per cubic meter) of large-scale brackish water RO from Shatat & Riffat, 2014; and typical desalination cost (INR 60 per cubic meter) representing current seawater RO in Chennai)

Though typically powered by grid electricity or fossil fuels, desalination can be performed using renewable energy. Solar stills are simple devices that combine an evaporator that exposes feedwater to sunlight and a condenser that converts the resulting vapor to liquid.

Numerous designs for solar stills have been proposed, but few have balanced the competing needs for affordability, durability and efficiency (El-Bialy, et al. 2016). A relevant metric when comparing direct solar desalination methods is the amount of fresh water produced per square meter of land area per day. Solar stills have a theoretical maximum efficiency of about 10 liters per square meters per day[1].

Actual solar stills typically produce 3 to 5 liters per square meters per day at efficiencies of less than 50 percent. Although ideas have been proposed to increase the efficiency of solar stills (e.g. Li, et al., 2016), their additional cost and complexity may preclude widespread adoption.

Another approach to solar desalination is to accept conventional efficiency levels of solar stills but aim for significantly reduced capital cost through innovative design and materials (e.g. Bhardwaj, et al., 2016).

Solar desalination may also be achieved by using electricity from a photovoltaic (PV) solar array to power a RO desalination unit. This could produce about 500 liters per day per square meters of land area[2] or 50 times the theoretical maximum output of a solar still.

If the feedwater is brackish, coupling PV power to electrodialysis desalination could produce even more fresh water per square meters of land area (Wright & Winter, 2014).

[1]Theoretical limit of solar still based on solar insolation in sunny location of ~6.5 kilowatt hours per square meters per day, and latent heat of water evaporation of 0.63 kilowatt hours per kilogram, resulting in maximum water evaporation of ~10 kilogram per square meters per day.
[2]RO desalination powered by PV electricity based on solar insolation in sunny location of ~6.5 kilowatt hours per square meters per day, PV solar-to-electricity conversion efficiency of 20 percent, and RO specific electricity use of 2.5 kilowatt hours per cubic meters, resulting in fresh water production of ~500 liters per square meters of PV panel per day.

KEY CHALLENGES

1. There is a large range of water contaminant types and growing scales of contaminant volumes

Water contaminants are often tasteless, odorless, colorless and difficult to identify.

They can be consumed without knowledge. Even if their presence is noted, they may be given little concern: “out of sight, out of mind”.

2. Effective large-scale human waste management is extremely challenging due to technical, economic and behavioral factors

In some regions there is little demand for improved sanitation. There remains strong cultural attraction to traditional sanitation methods, despite evidence of their deleterious health effects. There is also lack of sustainable sanitation infrastructure for growing urban areas, able to scale-up significantly to serve low-income populations, including both initial capital commitment and ongoing maintenance effort. Failure to scale faster than population growth rates leads to rising total contamination with fecal pathogens.

3. Water quality is impacted by climate change

Water pollution issues will increase due to reduced dilution of pollutants during droughts, disruption of treatment facilities during floods and increased loadings of sediment, nutrients and pollutants caused by heavy rainfall. Diminishing water availability during droughts leads to utilization of lower quality water sources.

4. There is a lack of regulatory clarity regarding water quality issues, a task that policymaker often see as low priority

Long-term structural opportunities for cleaner processes are typically overlooked in favor of short-term corrective measures with less overall potential.

SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

Clean water is essential for healthy living, but in many regions of the world the available water is contaminated and unsuitable for use. A diverse range of contaminants affect water quality, including human-caused pollutants like sewage and chemical toxins, as well as natural minerals like salt and arsenic.

Solutions to water quality problems will require tackling the sources of pollution, including human fecal waste, agricultural runoff and industrial effluent. They will also involve creating freshwater resources out of abundant yet under-appreciated liquids like seawater and wastewater.

Our analysis concludes that five technological breakthroughs can lead to significant improvement in water quality.

Breakthroughs:

1 2 3 4 5 6 7 8 9 10
11 12 13 14 15 16 17 18 19 20
21 22 23 24 25 26 27 28 29 30
31 32 33 34 35 36 37 38 39 40
41 42 43 44 45 46 47 48 49 50

1 A low-cost system for precision application of agricultural inputs, ideally combining water and fertilizer

In some regions like South Asia, the Green Revolution has brought unfortunate consequences including over-exploitation of groundwater resources and over-application of synthetic fertilizers. In other regions like sub-Saharan Africa, the Green Revolution has not arrived and there is under-utilization of groundwater resources and ongoing nutrient mining of soils. There is need for a low-cost, robust, scalable technology to precisely meter and distribute irrigation water and fertilizer to field crops.

This would allow farmers to apply the right amounts of water and nutrients (not too much or too little) at the right time to maximize economic returns and reduce nutrient loss. If made affordable, precision application systems for irrigation and fertilizers, calibrated to local crop type and soil conditions, could be a very effective way to increase agricultural yields, while also reducing negative impacts on the environment.

Enabling better management of the timing and formulation of irrigation and fertilization in cropping systems would ensure that water and nutrients are available where and when needed by the plant roots. Crop yields respond very well with initial inputs of fertilizer, but as additional nutrients are supplied the marginal yield increase becomes smaller.

Optimal results occur somewhere along that gradient, depending on the cost of fertilizer and seeds, land and selling price of harvested crops. For maximum returns, it is necessary to not just apply the right quantity of fertilizer, but to also apply it at the right time and place for optimal nutrient uptake by the plant. This would also protect watersheds and populations downstream from farm fields, by greatly reducing runoff.

The efficiency of using agricultural inputs, such as fertilizer is low in conventional farming. It is estimated that overall efficiency of applied fertilizers is about 50 percent for nitrogen, less than 10 percent for phosphorus and about 40 percent for potassium. The rest is wasted as runoff.

The mismatched timing between availability of nitrogen and crop need for nitrogen is likely the single greatest contributor to excess nitrogen loss in annual cropping systems. Ideally, nutrients should be applied in multiple small doses and when plant demand for them is greatest.

Current State

Development Stage: Engineering

Time to market (years)
<3 4-6 7-10 10+

Deployment: Challenging

Associated 50BT Chapters

Food Security
Global Change

SDG Alignment

Impact

Increased Access to Food (# of People)
<1M 10M+ 100M+ 1B+

New Income Generated (# of People)
<1M 10M+ 100M+ 1B+

Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

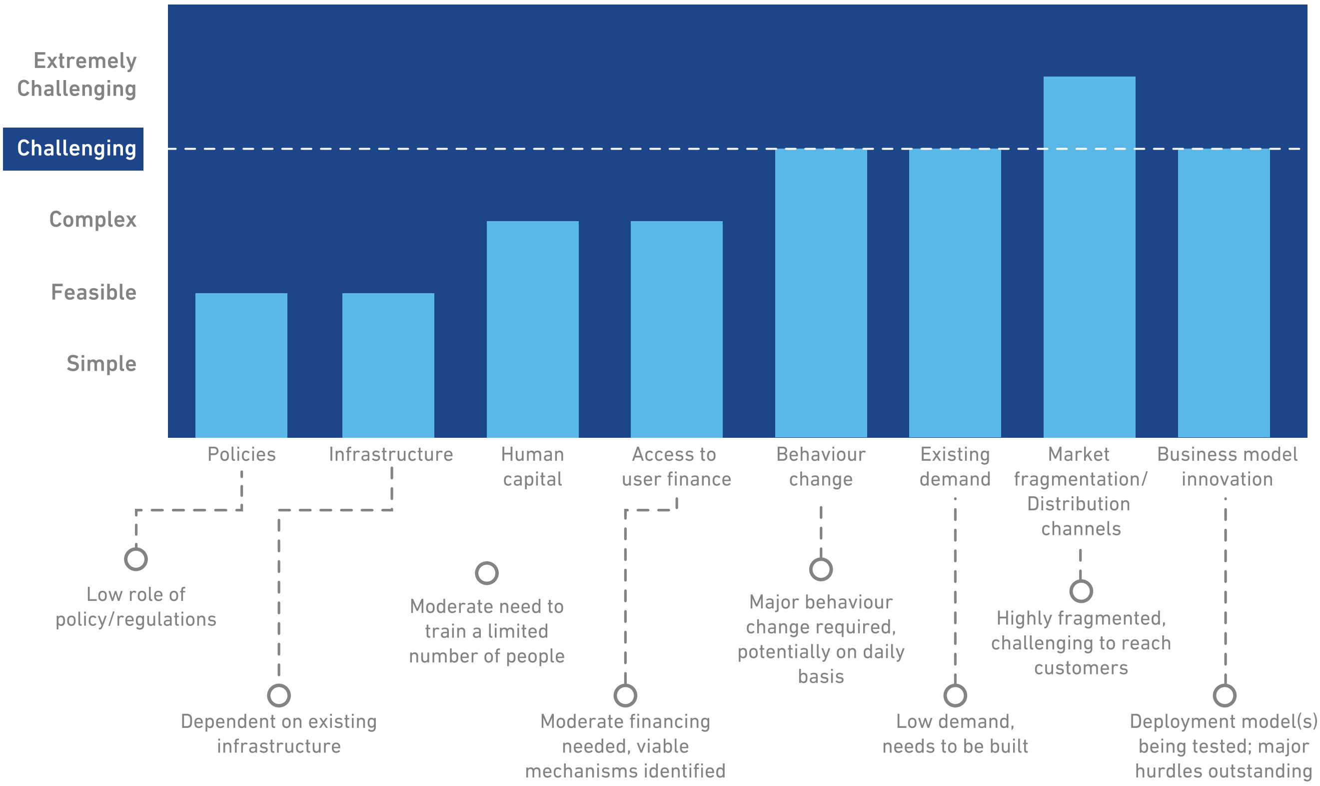
In principle, variations of existing programmable irrigation and fertigation systems used in industrialized countries can be adapted to the needs of smallholder farmers. Already, small-scale drip and sprinkler systems—along with other methods for increasing water usage efficiency—are beginning to emerge in markets like India. Cultivated area under drip irrigation in India has grown from 71 km^2 in 1992, to 2,460 km^2 in 1998, to 18,970 km^2 in 2010, up to 33,700 km^2 in 2015. The cost of such systems will continue to drop as scale of production increases.

This breakthrough would be strongly leveraged by three other breakthroughs, 5 Low-cost shallow groundwater drilling technologies, 6 Affordable solar-powered irrigation pumps, and 9 Low-cost soil nutrient analysis device. Overall, such devices would help farmers better predict crop nutrient requirements, better schedule irrigation and fertilizer applications, and avoid over-fertilization and nutrient runoff. If complemented with adjusted crop rotation patterns and additional biotic complexity, it could improve the plant community's ability to take up more of the available nutrients.

However, there is limited evidence to suggest that users—farmers or otherwise—will be interested in spending money on technologies to conserve water when the resource itself is available free of cost. The potential for saving fertilizer can prove to be a positive incentive, although the current demand for fertilizers is very low in sub-Saharan Africa.

It will face some deployment challenges that are common to the African smallholder farmer market, including structural barriers such as a fragmented market of farmers, limited access to finance for potential users, and lack of training to install, use and maintain the technology. The difficulty of deployment in this case would be CHALLENGING.

Breakthrough 1: Difficulty of deployment



2. A very low-cost scalable technique for desalinating brackish water

This breakthrough focuses on developing and enabling systems for very low-cost, high-efficiency desalination of brackish water resources. Households, industries and farms can utilize such systems to provide additional freshwater supplies for water-constrained regions. The introduction of very low-cost desalinated water could enable sustainable irrigation in vast regions of the world that contain brackish groundwater.

Desalination is increasingly used to provide household and industrial water in regions with scarce freshwater but abundant salt water. Most current desalination facilities are located in the Middle East, use seawater as feedwater and are powered by fossil fuels. The city of Chennai in southern Indian gets about a quarter of its municipal water from reverse osmosis seawater desalination plants.

Conventional desalination methods typically use seawater as feed. Seawater desalination technologies based on membranes, such as reverse osmosis, are approaching the thermodynamic limits of efficiency and have limited opportunity for further improvement. It is unlikely that major technology breakthroughs will fundamentally alter the seawater desalination landscape. Additionally, desalinated seawater is too expensive to use as irrigation water for crop production.

In contrast, there are large potential efficiency gains by using brackish water as feed. There are major opportunities for significant reductions in brackish water desalination cost and energy use through innovative electrochemical or other emerging techniques. The minimum theoretical energy requirement for desalination varies with the salinity of the feedwater—less energy is fundamentally needed to desalinate brackish water compared to seawater. Electromagnetic desalination processes such as electrodialysis (ED) and capacitive deionization (CDI) are limited to low-salinity feedwater, but potentially have much lower cost and energy than pressure or thermal techniques. They offer many advantages when used with brackish feedwater, such as high water recovery and high brine concentrations.

They also require little or no feedwater pre-treatment and membrane fouling can be prevented by reversing the electrode polarities. However, electromagnetic processes only remove ions from the water, leaving organics and colloids in suspension—this is a concern for household water, but less so for irrigation water. Furthermore, the selection and configuration of membranes is currently highly dependent on feedwater characteristics, thus must be adapted to local conditions of feedwater composition and concentration.

Current State

Development Stage: Engineering

Time to market (years): <3 | 4-6 | 7-10 | 10+

Deployment: Complex

Associated 50BT Chapters

Water Security

Food Security

SDG Alignment

2 ZERO HUNGER

6 CLEAN WATER AND SANITATION

Impact

Increased Access to Food (# of People): <1M | 10M+ | 100M+ | 1B+

New Income Generated (# of People): <1M | 10M+ | 100M+ | 1B+

Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

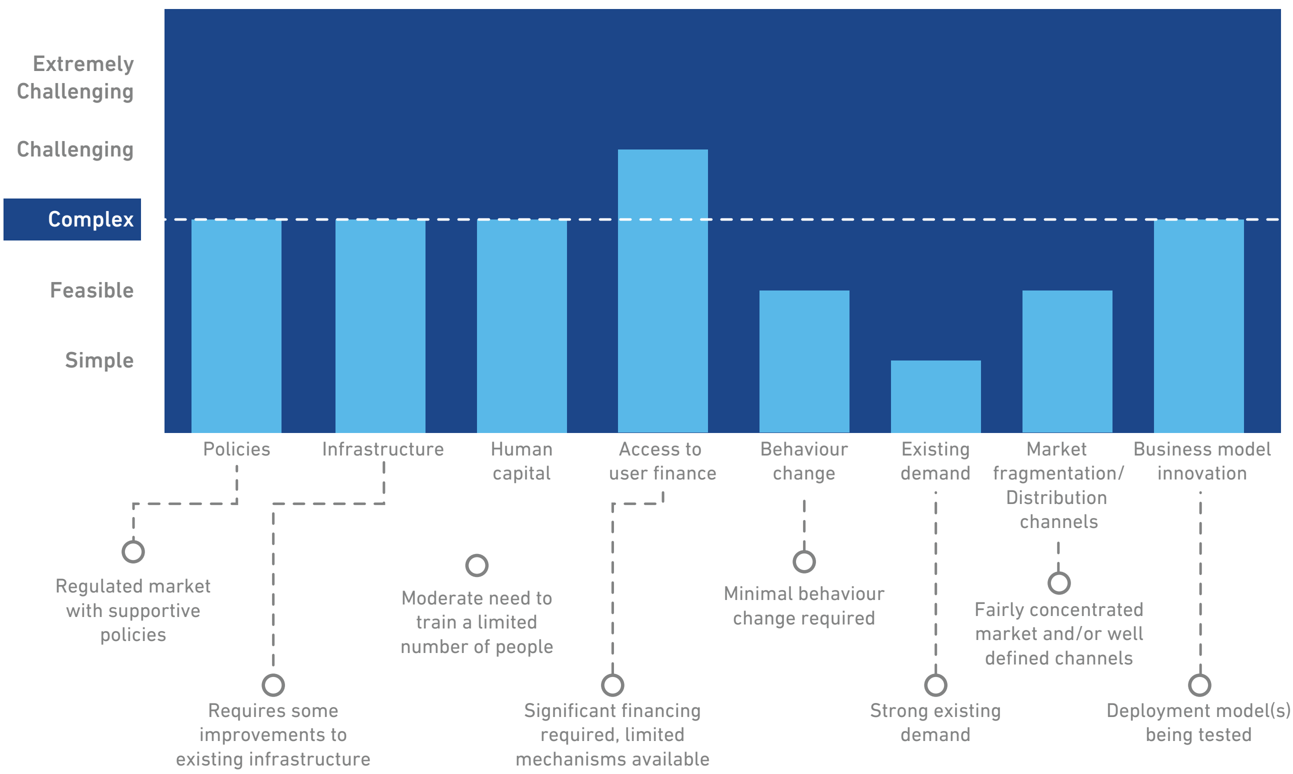
Concerted R&D efforts can overcome current obstacles to enable a major source of low-cost freshwater in regions with brackish resources. The appropriate unit scale of desalination facilities may vary depending on the application (such as household, irrigated farm, urban water utility). The salinity of the product water may also vary depending on the purity requirements of the end uses.

Costs can be further reduced by matching the salinity of the product water to the salinity thresholds for different uses; in other words, removing only enough salt to make the water viable for its intended use. Ideally, facilities will be powered by onsite renewable energy sources, such as photovoltaic solar arrays, to provide reliable and sustainable operation. Developing appropriate business models will be essential to ensure economic sustainability and continuing impact.

End-uses for the desalinated water will include drinking, cooking, washing and other domestic uses and industrial water uses. Efficient techniques for large-scale desalination of brackish water resources will also enable the use of desalinated water for production of agricultural crops using efficient irrigation techniques.

Substantial research and development work is required and we expect that it will take seven to ten years for this breakthrough to be ready. Deployment challenges include access to finance and policies regarding location and discharge streams. We rate the difficulty of deployment, COMPLEX.

Breakthrough 2: Difficulty of deployment



3 Network of low-cost distributed monitoring sensors to measure and map air and water quality

Discharge of pollutants into the air and water is an undesirable side effect of conventional industrialization and development processes. Because many environmental pollutants are invisible, tasteless and odorless, severe cases of contamination often go undetected and unremedied. Detection of environmental pollutants currently requires costly equipment and elaborate sampling protocols, and provides only isolated snapshots of individual places, times and contaminants. To fully understand and solve the problem of environmental pollution of air and water, a more fine-grained knowledge of exposure is required.

There is an urgent need for the development and widespread deployment of sensors that detect the levels of the most significant pollutants affecting the air and water, and transmit that information to a platform where it is validated and publicly displayed. Sensors will need to identify and measure a broad range of pollutants. Key air contaminants to be measured include particulate matter, ozone and carbon monoxide, while essential water contaminants include E. coli, salinity and arsenic. Though challenging, there is an important and growing need to measure diverse chemical toxins from sources including industry, vehicles and agriculture.

Required technological innovations include integrated sensors for the most significant contaminants that are inexpensive enough for mass deployment, as well as a platform for data collection, validation, analysis and dissemination. The sensors may be hard-wired and provide continuous monitoring of particular locations, or may be portable to conduct mobile geolocated assessments of contamination.

Fixed sensors would likely form the basis of a sensor network, transmitting (continuous or periodic) data to a mapping platform to show changes in quality parameters over time. Issues of sensor performance degradation over time will need to be addressed, to enable robust long-term monitoring. A successful sensor technology will likely not test separately for each individual contaminant, but would scan a sample of air or water and determine quickly and inexpensively its multiple constituents.

For maximum effectiveness, this sensor technology would be integrated with a web-based platform to allow collection and comparison of environmental pollution risks over time and place.

Current State

Development Stage: Engineering

Time to market (years)

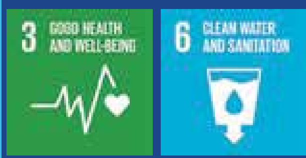
<3 4-6 7-10 10+

Deployment: Complex

Associated 50BT Chapters

Food Security Global Change

SDG Alignment



Impact

Lives Saved (# of People/Year)

<1M 10M+ 100M+ 1B+

Health Improved (# of People)

<1M 10M+ 100M+ 1B+

Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- Emerging markets potential; requires derisking (sustainable)
- **Non-commercial (unprofitable)**

The linking of improved sensor technology with mobile communications technology would lead to a system for real-time, spatially-explicit, multi-agent exposure monitoring that would create an unprecedented understanding of global air and water pollution, and pathways toward their reduction. Once identified, areas of high risk could be assessed in more detail, and critically contaminated locations in need of remediation can be flagged.

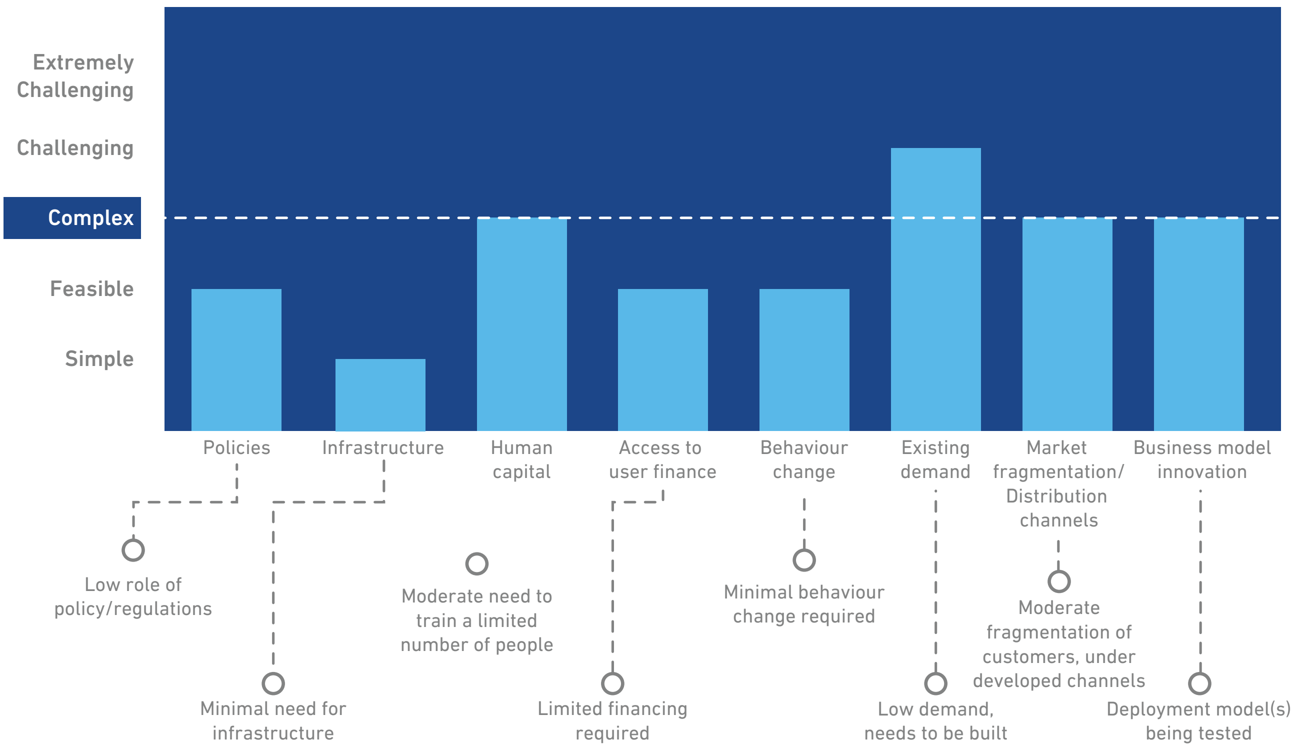
Portable sensing by trained staff using mobile devices with disposable one-time sensors could also be useful to increase the spatial density of measurements. Another approach to mobile sensing is community-based air and water quality monitoring, using low-cost portable sensors connected to smartphones that communicate results to the network.

This approach may face issues with data reliability due to incorrect sampling techniques or fraud, so would require additional validation. The initial cost of the hardware should be modest (less than $500), perhaps taking the form of a plug-in sensor that leverages the computing power of an existing mobile device. Cost of consumables should be low (less than $1 per test), allowing ubiquitous monitoring even in remote sites of low- and middle-income countries.

Progress is being made rapidly in the field of environmental monitoring, though there appears to be little focused effort towards the integrated technology we envision here. A basic form of air quality mapping using near real-time data from a global network of sensors can be found at http://aqicn.org/map/world/.

If sufficient resources were allocated to allow the necessary research and development efforts, we expect that it will take seven to ten years for this breakthrough to be ready for use. A significant deployment challenge is the lack of consumer demand for environmental monitoring. Therefore, deployment is likely to be COMPLEX.

Breakthrough 3: Difficulty of deployment



4 Sustainable, affordable, household-level fecal waste management system

A large share of the population in rural and peri-urban areas of many low-income countries lacks access to household toilets, and is habituated to open defecation. Many others have access to toilets, but of substandard type and capable of contaminating groundwater. This poses serious health risks in the form of diarrheal and other diseases. An effective household sanitation system must provide an initial hygienic separation of the fecal waste, as well as prevent opportunities for secondary exposure to the fecal pathogens such as surface and groundwater contamination. Ultimately, the fecal waste must be made harmless and definitively disposed of.

In rural and many peri-urban areas, the most appropriate sanitation system employs household-level collection and full on-site treatment of waste materials. Household-level sanitation is quite appropriate in rural areas, where extensive sewage networks would be prohibitively expensive due to low population density.

Household sanitation is also widely used in some higher density places such as peri-urban areas, where sewer networks have not reached. A wide range of on-site sanitation technologies have been developed, including pit latrines (single and twin pits), pour-flush pit toilets (with septic tanks, and single and twin leach pits), vermicomposting toilets, dry composting toilets, and anaerobic baffled reactor toilets.

However, existing on-site sanitation methods fall short is some regards. In some cases they do not safely contain fecal waste, instead letting it leak into groundwater aquifers. In other cases, the waste is safely contained in storage only temporarily, but eventually becomes full and must be emptied and can then cause broad contamination.

Despite our long experience accumulated with sanitation practices, there is a large gap for a sustainable, affordable, decentralized, on-site household sanitation solution for low-income households. Of the existing household sanitation technologies, vermicomposting toilets appear to provide relatively high performance at low cost, largely due to enhanced decomposition of fecal matter by earthworms, leading to less waste build-up and less frequent emptying and thus lower maintenance costs.

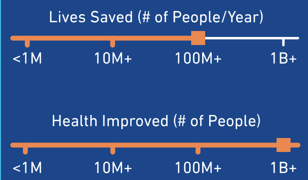
Current State

Associated 50BT Chapters

Water Security
Global Health
Gender Equity

SDG Alignment

Impact



Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

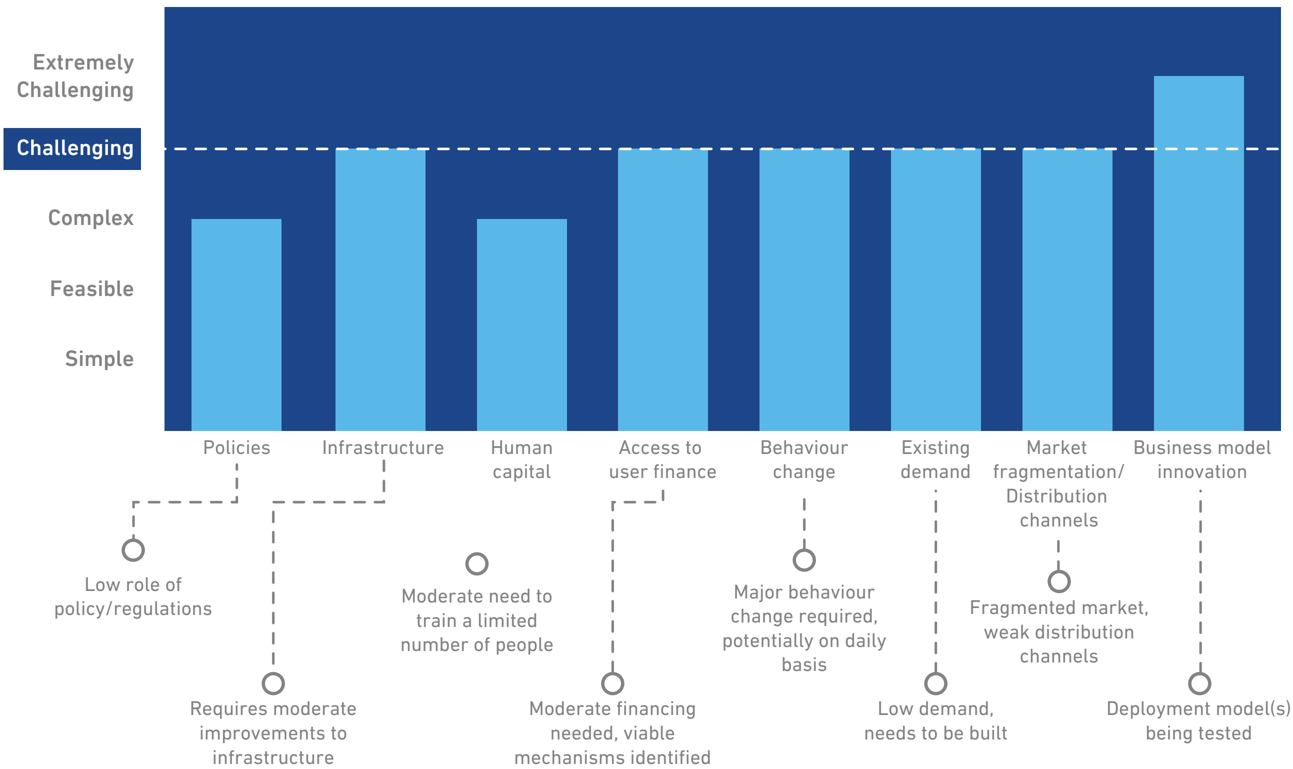
The development of improved on-site household sanitation systems should be viewed as a long-term solution to rural sanitation (and possibly peri-urban sanitation) rather than an interim fix, and should be given a high priority in resource allocation. Sanitation facilities that are merely waste storage repositories, such as pit latrines, must be coupled with mechanisms for regular emptying of fecal sludge and transporting it to appropriate sites for processing or safe disposal. Facilities that include on-site treatment, such as vermi-filtration, generate smaller quantities of residue that must be disposed of.

One potentially useful path may involve additives that facilitate the breakdown of fecal sludge, reducing the need to empty latrines. Researchers are currently developing and testing several options, including addition of higher organisms, microorganisms and hydrolytic enzymes.

In the longer term, opportunities could include use of fermenting organisms, development of new enzymes or facilitation of the current microorganisms involved in digestion. Regardless of the specific path, each step of the sanitation service chain is important to achieve effective waste management, from toilet siting and construction, to final treatment and disposal of waste.

Effective sanitation is challenging where there is no piped water or sewerage, as household toilets must be low-cost, have an effective method to control odor, a system for processing and disposing of waste, and occupy minimal space. Significant experience has been gained on technical aspects of sanitation, but we lack full understanding of the important socio-cultural aspects. Initial technologies are already on the market, but the difficulty of deployment is CHALLENGING.

Breakthrough 4: Difficulty of deployment



5 Medium to large-scale sewage treatment process with recovery of water (and ideally nutrients and energy)

This imperative calls for the development and deployment of novel sewage treatment facilities that are net sources, rather than sinks, of resources. Primarily this applies to water resources, for treating and reusing the wastewater collected in sewer systems. Systems should enable reuse of the treated water for secondary purposes including industrial, recreational and agricultural applications. A secondary focus is on energy resources, where sewage treatment facilities could operate with net zero energy inputs, and could even have the capability to produce energy for societal use. The recovery of nutrient resources from sewage, such as phosphorus or nitrogen, may also be a goal. Integrated sewage treatment can be viewed as a way to harvest clean, renewable sources of water, energy or nutrients while disposing of a waste product.

There is a great need for a low-cost, sustainable and scalable sewage management process for deployment in fast-growing cities in developing regions. In India, for example, less than 38 percent of the sewage that is generated is treated before being discharged into water bodies. The amount of resulting sewage in the environment is contributing to the country's health problems, including diarrheal outbreaks among children and lifelong stunting and wasting.

The massive organic and nutrient loading also has adverse environmental effects and leads to the destruction of ecological productivity of water bodies. Simultaneously, many growing cities have difficulty meeting the water needs of households and industries, due to physical constraints to water supply manifest as closed river basins and depleting groundwater stocks.

The quantities of wastewater generated in major cities are enormous, thus reusing this water for other purposes is a major lever for enhancing water security. For example, if 80 percent of the wastewater collected by urban sewage networks in India were reused, an additional water resource of 18 cubic kilometers per year would be obtained (ITT, 2018). What is lacking is an effective and affordable sewage treatment method that can rapidly scale up in developing regions.

Conventional wastewater treatment methods are a major resource sink, and should not be held as models for scalable sanitation methods for fast-growing cities in low-income countries. In the United States, for example, about 1.3 percent of all electricity is used for sewage treatment. This is a wasted opportunity, because raw sewage contains about six times more chemical energy than the amount of electrical energy required to treat it.

The most appropriate method of treatment for wastewater will depend largely on the intended use of the recycled wastewater and the scale of the treatment facility. Major reuse applications include agriculture (food and non-food crops), industry, and groundwater recharge, for which increasing effluent quality is required, respectively. For agricultural purposes, nutrient removal (or partial nitrogen removal) can be left out of the treatment process, whereas reuse in industrial applications or groundwater recharge requires nutrient and solids removal.

Current State

Development Stage: In-Market Small Scale

Deployment: Challenging

Associated 50BT Chapters

Water Security
Global Health
Gender Equity

SDG Alignment

3 Good Health and Well-Being
6 Clean Water and Sanitation
14 Life Below Water

Impact

Lives Saved (# of People/Year)
<1M 10M+ 100M+ 1B+

Health Improved (# of People)
<1M 10M+ 100M+ 1B+

Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

Groundwater recharge applications may also require removal of micro-pollutants as well as organic carbon. In terms of costs, the higher the quality of treated effluent, the higher the total capital and operational costs are. Generally, larger treatment plants have an increased efficiency, which lowers the lifecycle costs and environmental impacts per cubic meter of treated water.

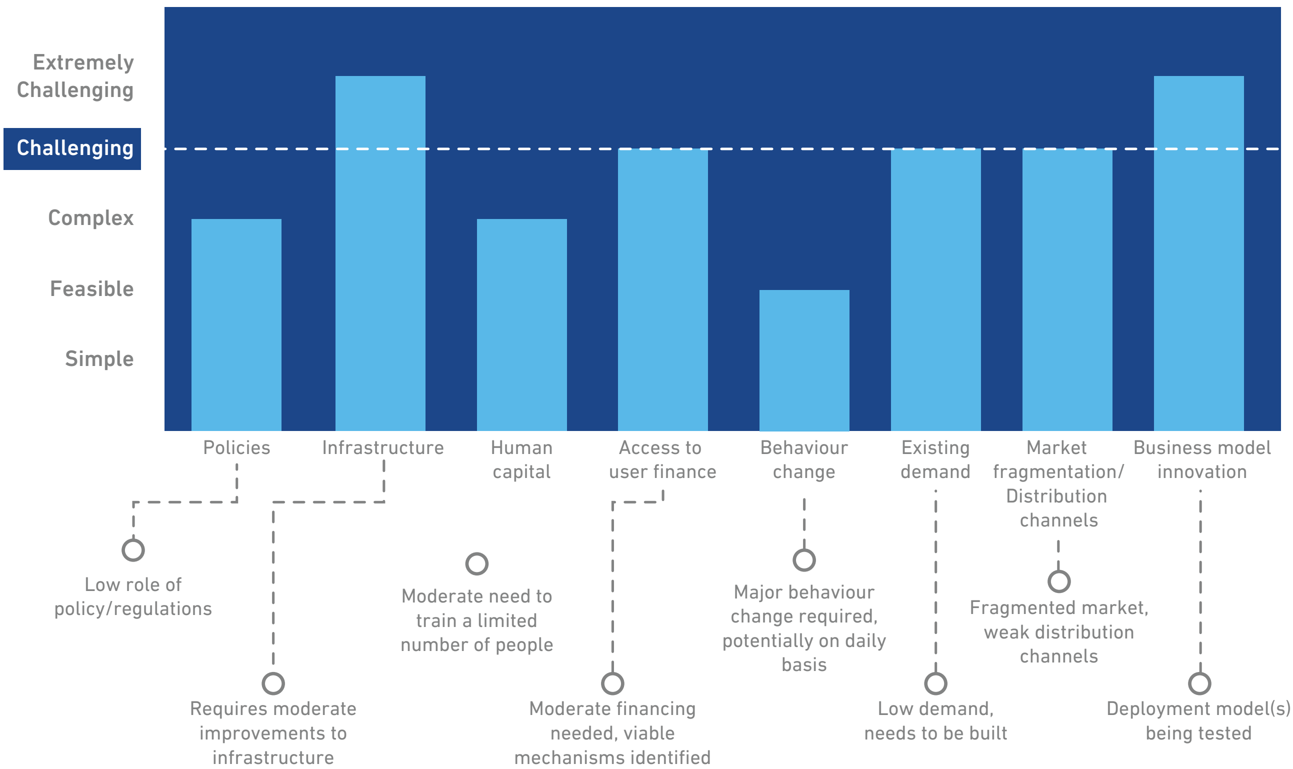
Novel sewage treatment methods followed by wastewater reuse is a potentially important lever for enhancing water security. Reusing wastewater brings two important benefits: less pollution entering water bodies, and less need for freshwater withdrawals. However, in the areas where it is currently practiced, wastewater reuse is typically considered as a temporary solution for acute needs, instead of implemented as a long-term solution to improve water security.

Important criteria for successful treatment technologies include the extent of land area required, the economic resources needed for capital and O&M, and the quality requirements for the reused water. Land area requirements, in particular, may be an impediment to scale-up of some technologies. Different technology solutions may be appropriate for different settings as the scale increases from household to neighborhood and metropolitan level.

There are many challenges to sanitation infrastructure deployment, and business models should not expect to extract high-value content from sewage. Sanitation systems tend to have fairly high up-front costs and require skilled labor to install and maintain. Distribution channels are also poorly defined. In addition, significant public investment is likely to be still required.

Some promising technologies have entered the market, and others should become market-ready in the coming years. Given the lack of proven models and the growing scale of the urban sanitation problem, the level of difficulty for deployment is CHALLENGING.

Breakthrough 5: Difficulty of deployment



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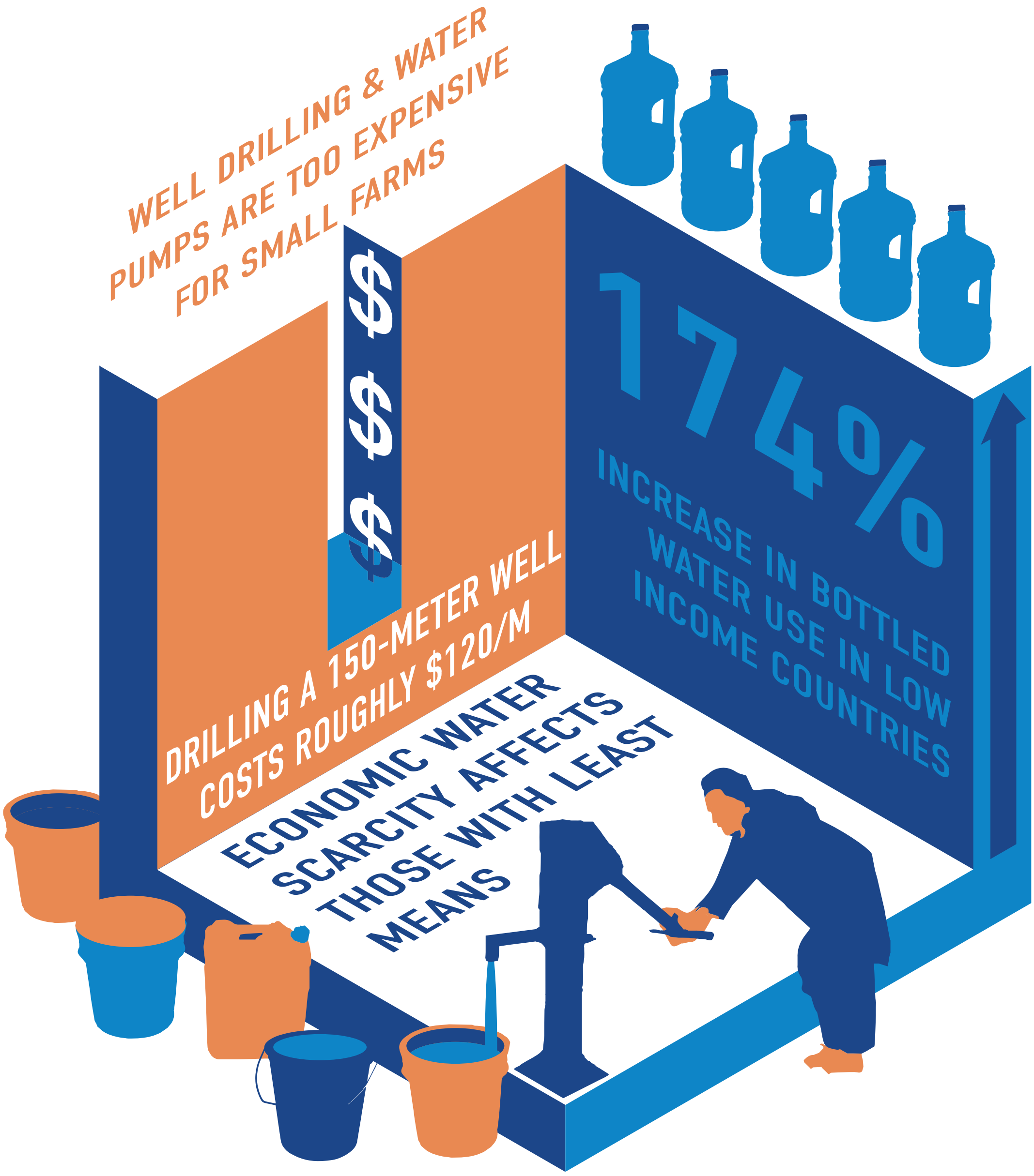


ECONOMIC WATER SCARCITY

INTRODUCTION

Much of sub-Saharan Africa and parts of South Asia face economic water scarcity.

These are areas where the population cannot access water, even though it is physically available in abundance. Economic water scarcity affects poor urban households, who cannot afford to buy clean water on the market. It affects poor rural households, who cannot invest in borewells and pumps to access local groundwater. It also affects entire communities and countries that lack the necessary infrastructure, like dams, canals, treatment facilities, pumps and distribution systems to provide water for all.

In fast-growing, water-stressed cities in low-income countries, reliable daily access to clean household water is a growing challenge. Where urban water utilities fail to deliver the precious liquid, poor families must resort to desperate measure to obtain it, either walking for long distances to public water points, paying inflated prices for private water supplies, or risking disease by using available polluted waters.

Rural economic water scarcity is especially prevalent in sub-Saharan Africa, where the vast majority of smallholder farmers do not have access to irrigation water.

While only 3.4 percent of farmland in Sub-Saharan Africa is irrigated, the region possesses abundant renewable groundwater that is untapped because farmers lack the knowledge and capital to access it. Not surprisingly then, agricultural yields in the region are a fraction of that in other parts of the world, and food insecurity remains problematic on the African continent.

Despite these challenges, four technology breakthroughs can substantially reduce the burden of economic water scarcity:

- Breakthrough 1. A low-cost system for precision application of agricultural inputs, ideally combining water and fertilizer
- Breakthrough 2. A very low-cost scalable technique for desalinating brackish water
- Breakthrough 6. Low-cost drilling technologies for shallow groundwater, which reduce the cost to less than $100 per farmer
- Breakthrough 7. Affordable (less than $50), lightweight, energy-efficient, solar-powered irrigation pumps

Economic water scarcity occurs where water is physically available locally to meet human demands, but access to that water is limited due to the lack of human, institutional or financial capital. Some places contain abundant water resources, but poorer segments of the local populations face water scarcity because they cannot access it. This occurs in both urban and rural areas, and involves drinking, household and irrigation water.

CORE FACTS AND ANALYSIS

1. Poor households in both rural and urban areas lack access to clean water

There is a strong relationship between socioeconomic status and access to adequate household water. Wealthier households tend to have greater access to cleaner water supplies, such as improved wells, piped water and public stand posts, while poorer households tend to access their water from local surface water sources and unimproved wells.

Exhibit 1 shows this distinction across African households, broken down by socioeconomic quintiles (World Bank, 2010).

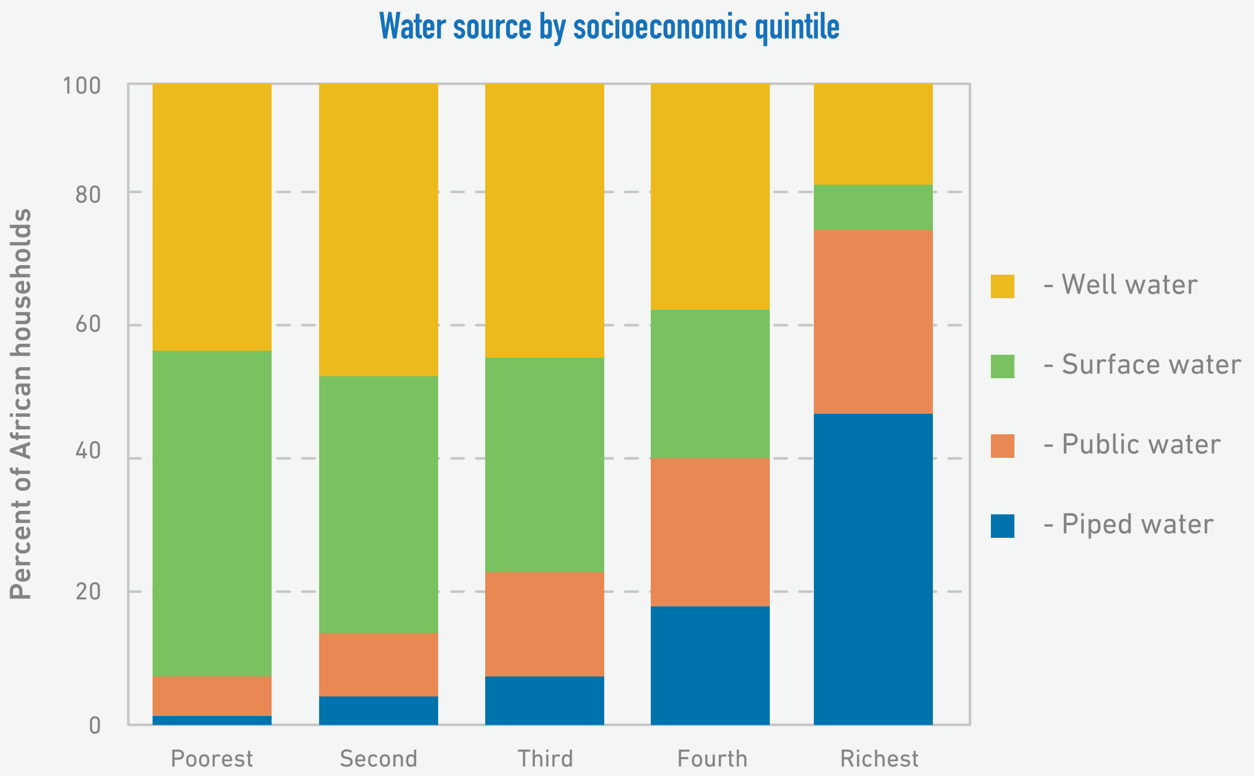


Exhibit 1: Wealthier households in Africa have greater access to municipal water supply (piped water and public stand posts), while poorer households are more likely to access their water from local surface and well water source. (Source: data from World Bank, 2010 on household water sources for socioeconomic quintiles of African population)

Globally, India has the largest number of rural people without access to clean drinking water, totaling more than 63 million people in 2015. During the same year, there were 13.6 million and 11.6 million people living without access to clean drinking water in Bangladesh and Pakistan, respectively (WaterAid, 2017).

Exhibit 2 depicts the relationship between income and access to improved water sources in rural Bangladesh and Pakistan: poorer families have lower access to safe water supplies.

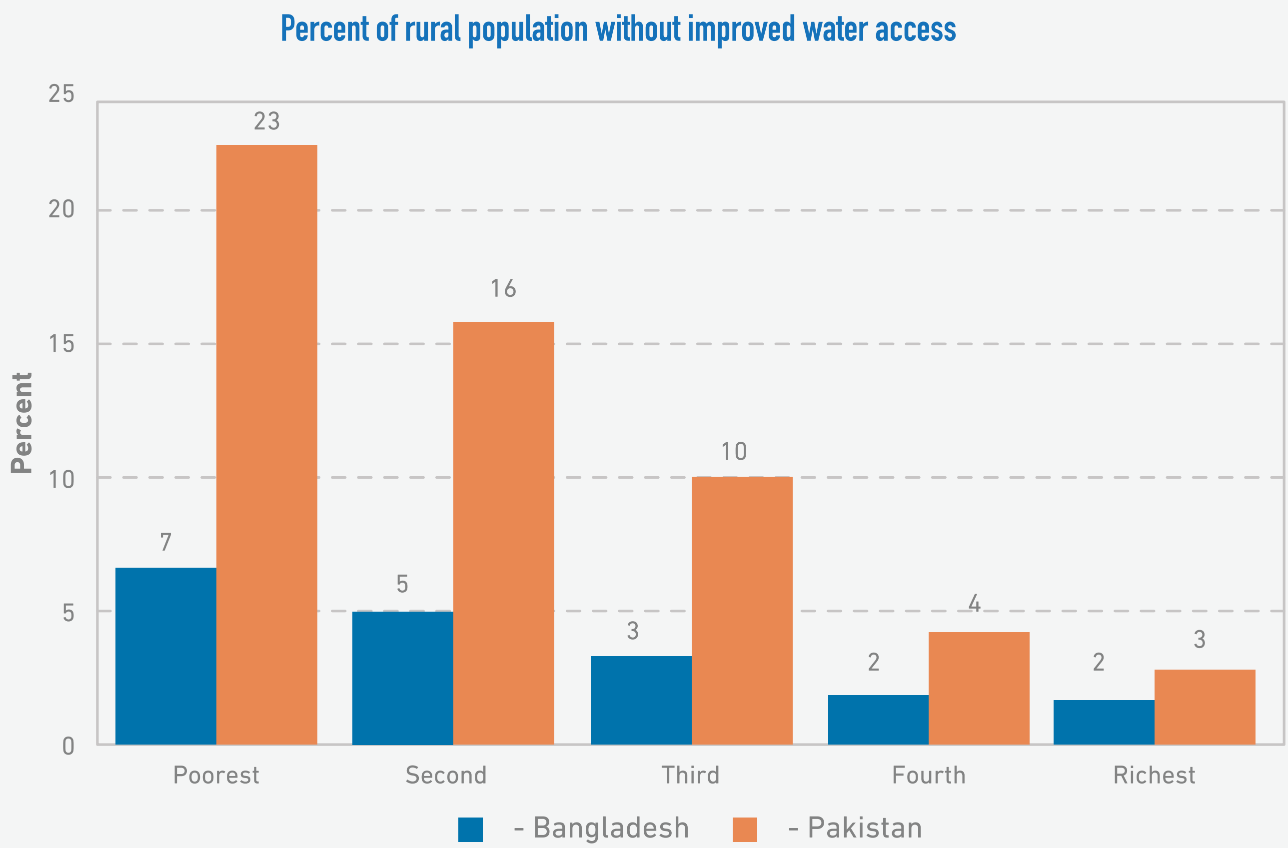


Exhibit 2: Poor rural populations tend to have less access to improved household water sources. (Source: data from JMP, 2017 on household water sources for socioeconomic quintiles of rural populations of Pakistan and Bangladesh)

Rural populations are at a greater disadvantage in gaining access to drinking water due to their remote locations, weak infrastructure and lack of public funds. Furthermore, a lack of awareness often prevents people from knowing which sources of water are safe to drink from and the health implications of consuming contaminated water. Without adequate economic resources, people facing these issues cannot afford to attend school, purchase clean drinking water or dig wells.

Analysis of household water use in a rural semi-arid village in Nigeria showed strong seasonal variation as well, ranging from 45 liters per capita per day in the rainy season to a meager 26 liters per capita per day in the dry season (Nyong & Kanaroglou, 1999). Climate change exacerbates these issues since the poorest people bear the brunt of extreme weather events. Many of the world's least developed countries are extremely vulnerable to climate change, yet least prepared to adapt to the changes (ND-GAIN, 2017).

While traditionally considered a problem of rural communities, there is also a strong urban component of economic water scarcity. Aggregated per capita urban water supply statistics mask the inequity between citizens, with the poorest residents barely securing water for subsistence, while the wealthiest residents enjoy abundant water supply (see **Exhibit 3**).

Gleick (1996) recommended a minimum water requirement of 50 liters per person per day to meet basic domestic needs of drinking, cooking, bathing and sanitation. WHO (2003) suggested that access to 50 liters per person per day would result in low level of health concern, while access to 100 liters per person per day would result in very low level of health concern.

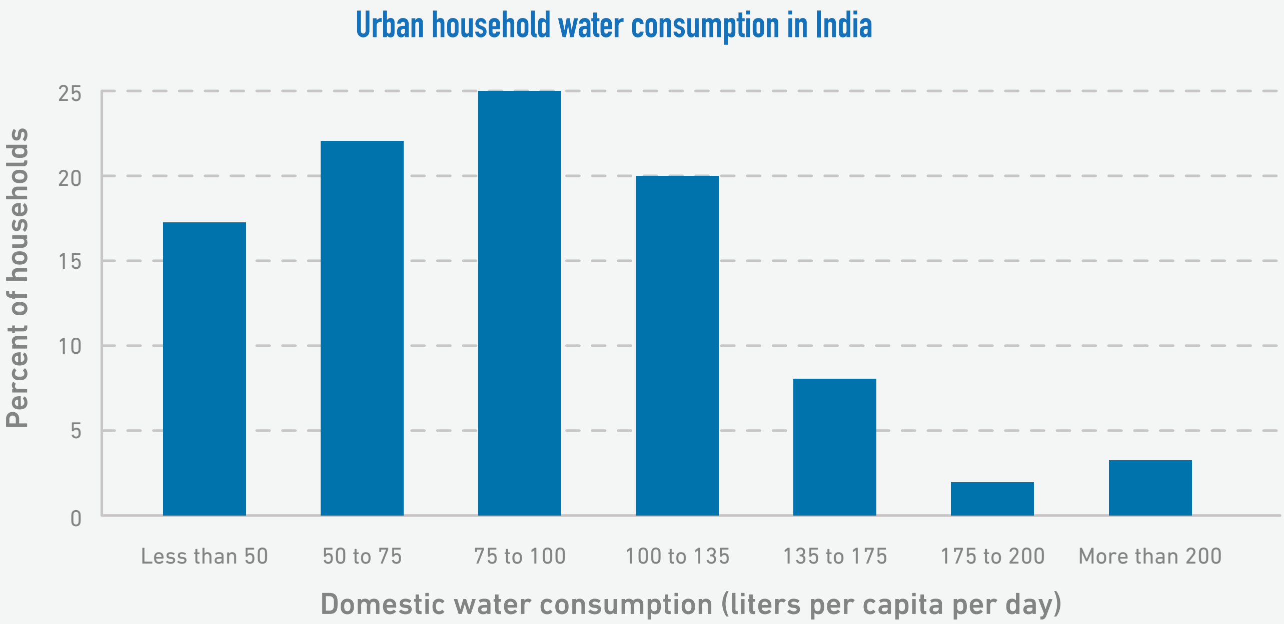


Exhibit 3: Daily water use in urban Indian households varies widely, with 17 percent of households using less than 50 liters per capita, while 14 percent of households use more than 135 liters per capita. The average household water consumption is 92 liters per capita per day. (Source: data from Shaban & Sharma, 2007, based on survey of 7 Indian cities)

Poor households may apply a hierarchy of water needs (similar in concept to Maslow's hierarchy of needs) and prioritize available water for essential uses (see **Exhibit 4**).

Often living in informal settlements without connections to municipal water supply, poor urban households end up paying elevated retail prices for essential water delivery from private service providers, or risk disease by using contaminated local water sources.

Hierarchy of household water needs

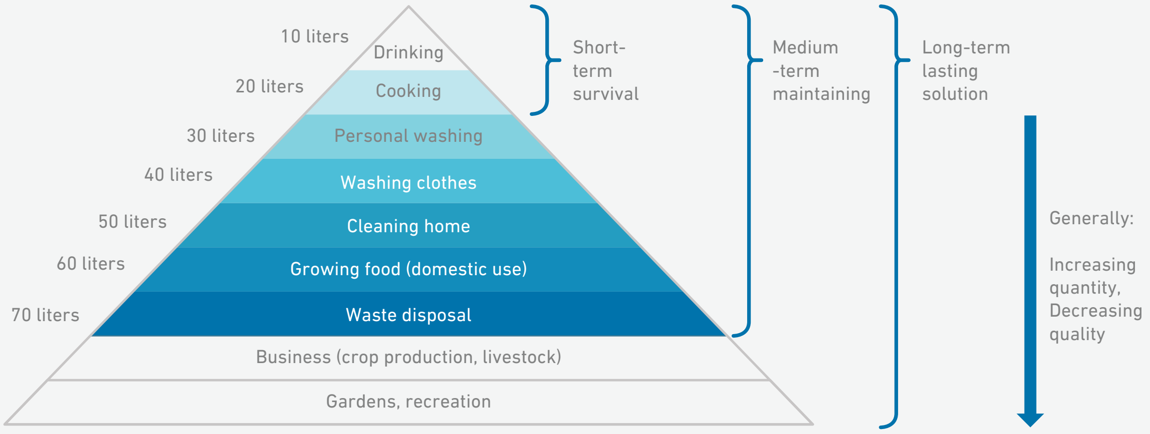


Exhibit 4: Households require access to sufficient water for numerous uses in a hierarchy of water needs. (Source: WHO, 2013)

Private markets for drinking water are expanding in cities, serving the communities living in slums as well as the wealthier classes. Expensive bottled water is increasingly used in developing countries, due to the inadequate quantity and quality of piped water supply (see **Exhibit 5**).

Since 2004, consumption of bottled water in low- and medium- income countries has increased by 174 percent, compared to 26 percent in high-income countries (Cohen & Ray, 2018).

Use of bottled water is increasing rapidly in low- and middle-income countries

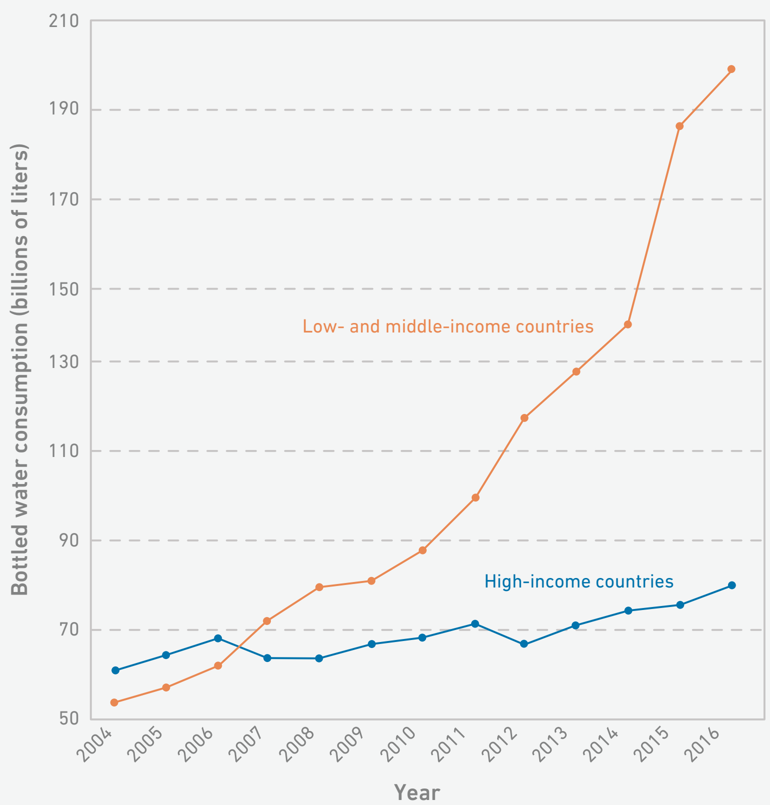


Exhibit 5: Trends of bottled water consumption show that bottled water is increasingly used in low- and medium-income countries. (Source: Cohen & Ray, 2018)

2. Many poor farmers, particularly in sub-Saharan Africa, lack access to water for irrigation

Irrigation offers several critical benefits for smallholder farmers including increased crop yields, the possibility of cultivation during dry seasons and droughts and the opportunity to grow high value, high nutrition crops. Since the Green Revolution, intensified agricultural practices in many developing regions have led to greater adoption of irrigation.

In South Asia, for example, the share of farmland that is irrigated increased from 24 percent in 1973 to 46 percent in 2013 (**Exhibit 6**). Sub-Saharan Africa has lagged far behind, however, where only 3.4 percent of farmland is irrigated (FAO, 2016). Where irrigation is used, both groundwater and surface water resources are utilized (**Exhibit 7**). Groundwater is more commonly used in South Asia and North America, while surface water is used more in other regions.

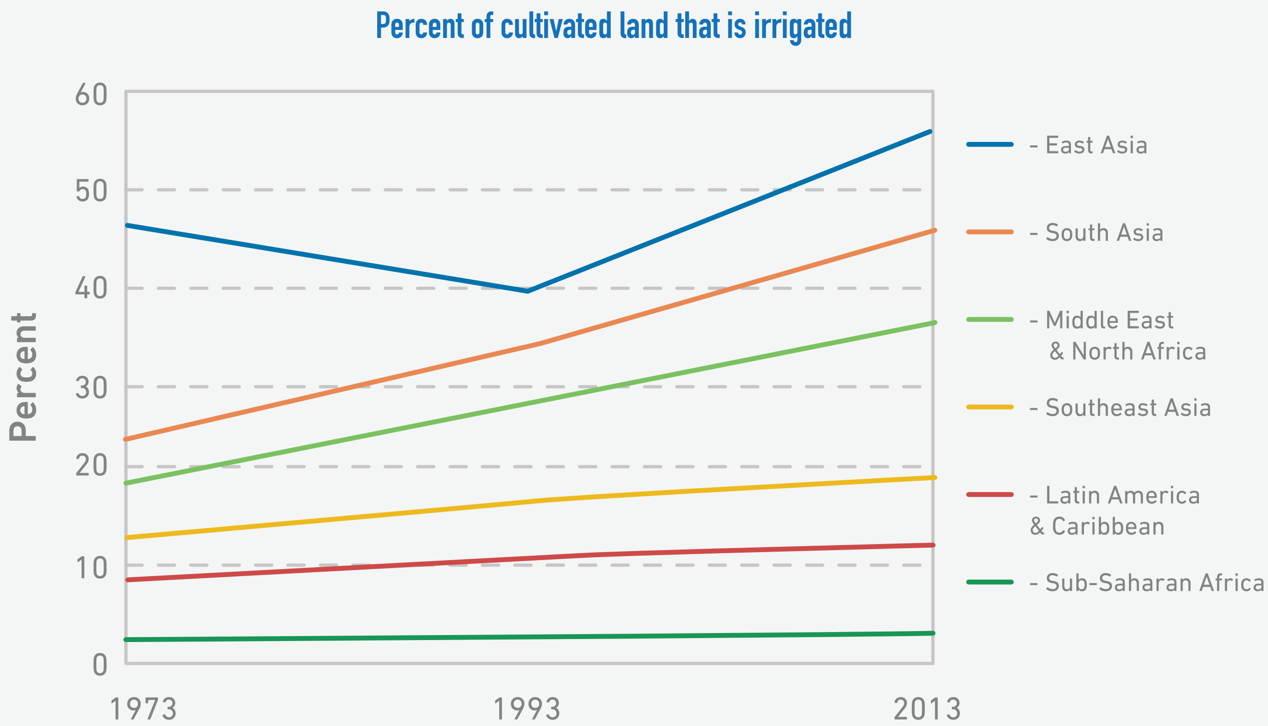


Exhibit 6: The percentage of cultivated land that is irrigated is increasing in all regions. About half of farmland in South Asia and East Asia is now irrigated.[1] Very little farmland in sub-Saharan Africa is irrigated. (Source: FAO, 2016)

[1]The decrease in East Asian irrigation percentage between 1973 and 1993 was due to a strong increase in non-irrigated cultivated land during that period. The area of irrigated land in East Asia also increased during that period, but at a slower rate.

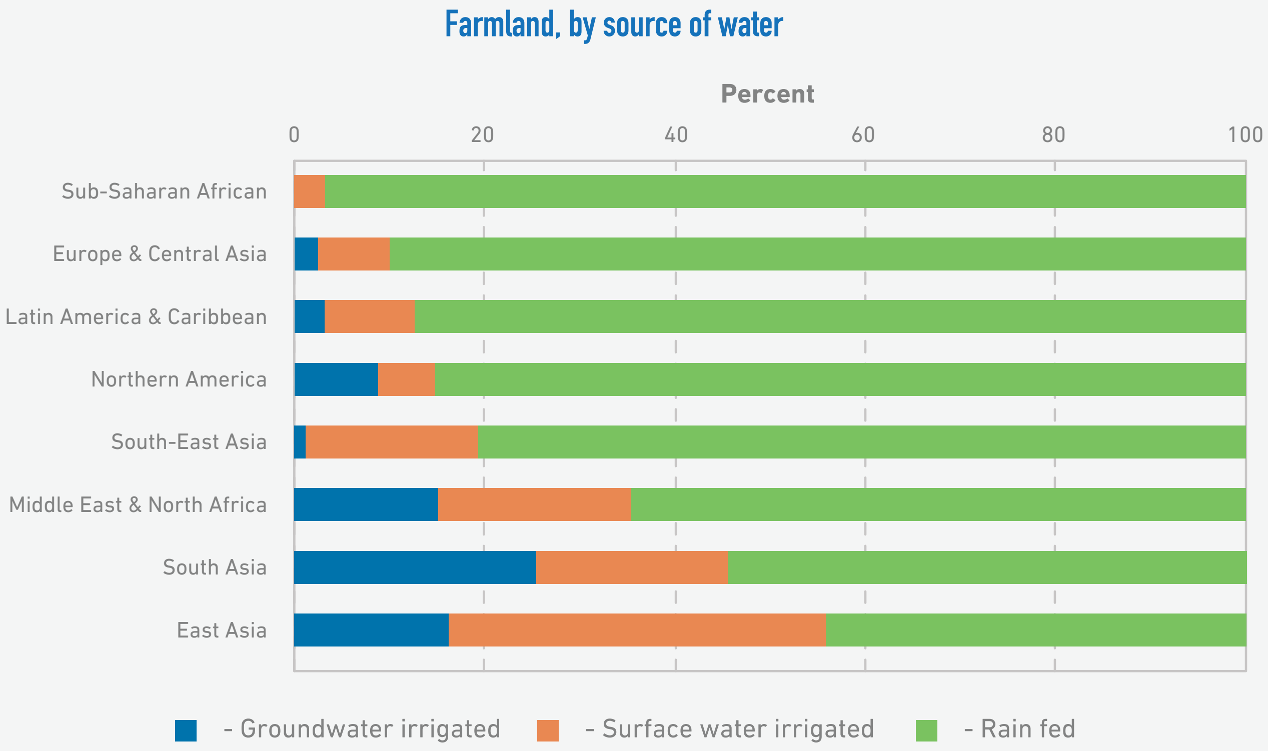


Exhibit 7: Most of the world's agricultural land is rain-fed and not irrigated. Groundwater is used more for irrigation in South Asia and North America, while surface water is used more in other regions. (Source: FAO, 2016)

Most smallholder farmers in Africa have traditionally relied on rainfall as the sole source of farm water, and continue to do so. Irrigation technologies remain largely out of their economic means.

As a result, cereal production closely follows the amount of rainfall in any given year (**Exhibit 8**) (McIntyre, et al., 2009; Molden, 2007).

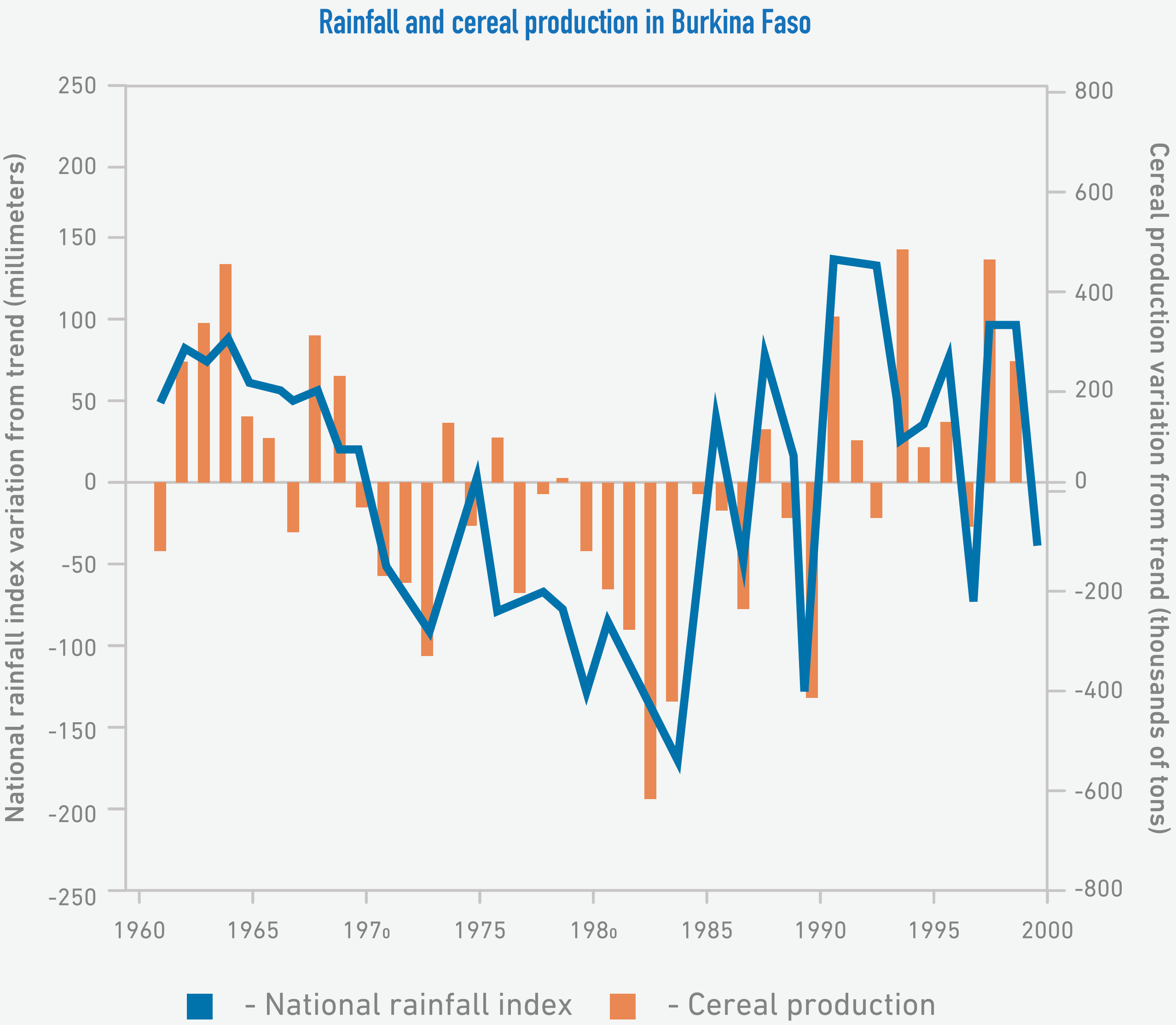


Exhibit 8: Cereal production in Africa is closely linked to rainfall, as shown in this study from Burkina Faso. (Faurès, et al., 2007)

It is important to note that South Asia and sub-Saharan Africa face different challenges with regard to irrigation. Much of South Asia[2] and Central Asia is struggling with major long-term physical water scarcity, which is strongly exacerbated by water withdrawals for irrigation (illustrated in **Exhibit 9**, and detailed above in the section on physical water scarcity).

Farmers in Sub-Saharan Africa, on the other hand, face little physical water scarcity (see **Exhibit 9**), but instead suffer from inadequate access to available water.

[2]With the exception of Bangladesh and Indian states, such as Orissa and Bihar, which were not deeply involved in the Green Revolution.

Irrigation water stress

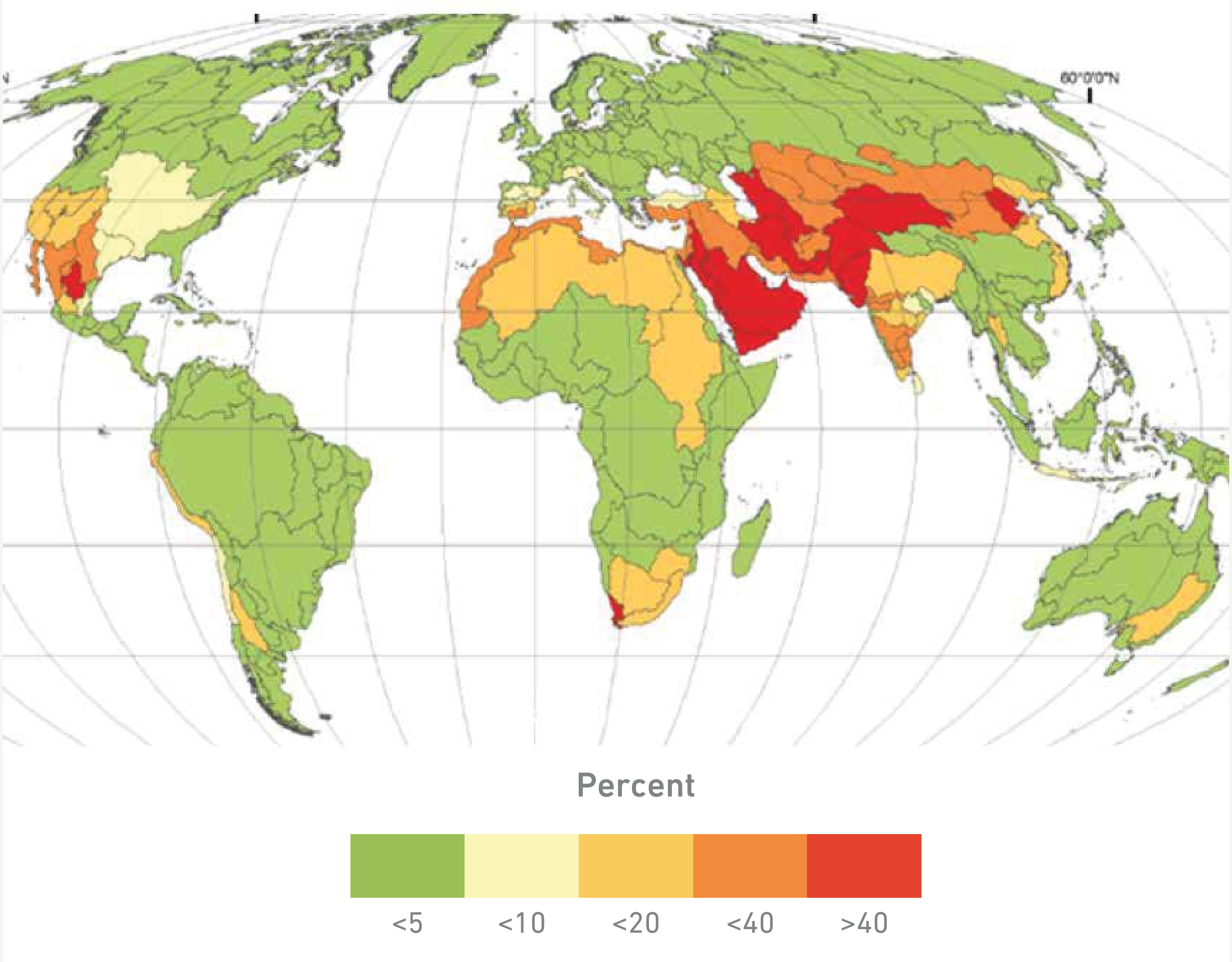


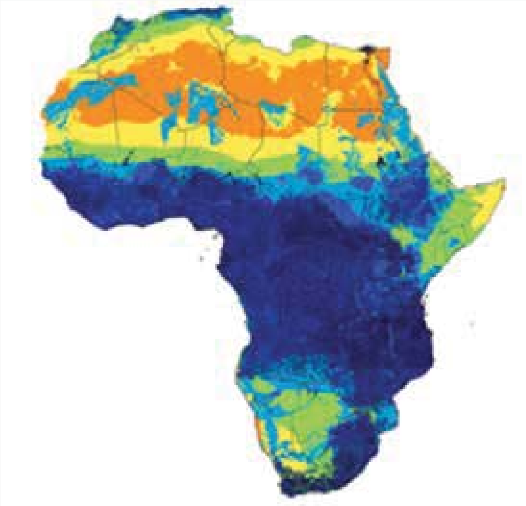
Exhibit 9: The Middle East and Central Asian regions face the highest water stress due to irrigation, while sub-Saharan Africa faces very little irrigation water stress. The map shows the irrigation water stress by major river basins, calculated as the incremental evaporation caused by irrigation as a percentage of total generated groundwater and surface water resources. (Source: Hoogeveen, et al., 2015)

Exhibit 10 shows hydrological maps of Africa, according to which there is abundant shallow groundwater (at a depth of 7 meters or above) through much of sub-Saharan Africa (MacDonald, et al., 2012).

In Ethiopia, for example, it is estimated that roughly 1.9 million hectares of arable land can be irrigated using household-level irrigation systems, which is five times the total area currently irrigated (ATA, 2013).

Despite the availability of groundwater, most African smallholder farmers do not have the economic wherewithal to access the water because pumps and other irrigation equipment are too expensive. As such, sub-Saharan Africa is considered to be a region of economic water scarcity (FAO, 2012).

Characteristics of groundwater in Africa

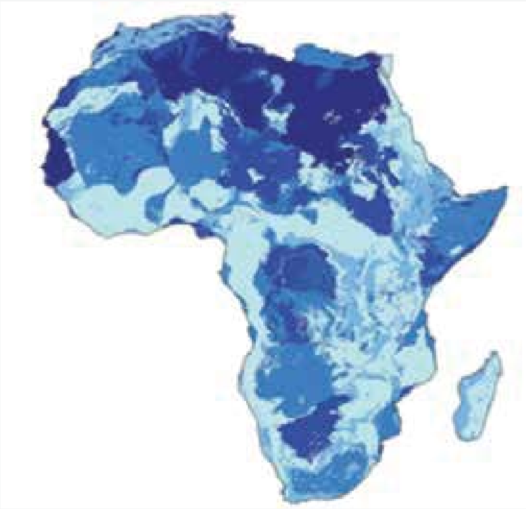


Estimated depth to groundwater (meters below ground level)

- 0-7
- 7-25
- 25-50
- 50-100
- 100-250
- >250

Aquifer productivity (liters per second)

- Very High: >20
- High: 5-20
- Moderate: 1-5
- Low-Moderate: 0.1-0.5
- Low: 0.1-0.5
- Very Low: <0.1



Groundwater storage (water depth in meters)

- 0
- <1
- 1-10
- 10-25
- 25-50
- >50

Exhibit 10: Groundwater is available at relatively shallow depths throughout much of sub-Saharan Africa (top). The aquifers vary widely in terms of productivity (middle) and storage volume (bottom). (Source: MacDonald, et al., 2012)

Economic water scarcity for agricultural irrigation is most common in Sub-Saharan Africa, among communities using low-yielding and highly-variable subsistence rain-fed farming methods, despite abundant shallow groundwater. The lack of irrigation is a critical constraint to increasing agricultural productivity for smallholder farmers in sub-Saharan Africa. With proper irrigation, farmers can increase crop yields, produce more consistent harvest, diversify their portfolio toward higher income crops and increase the total number of harvests in a given year.

Generally, there is a lack of demand for irrigation among smallholder farmers in sub-Saharan Africa, where only 3.4 percent of farmland is irrigated. Irrigation is a relatively new practice in much of sub-Saharan Africa, and few farmers have witnessed the tangible economic benefits they can derive from the practice. Most farmers in the region are subsistence farmers, and are understandably wary of investing their scarce resources into expensive, and seemingly unproven, irrigation systems.

As a result, they have been less willing to change traditional practices and still depend on rainfall as the primary source water for their crops.

Interventions in the water sector have varying opportunities to alleviate economic water scarcity among farmers, depending on climate, crops, geology and existing level of economic development. Within Africa, the greatest opportunities are in semi-arid regions where potential agricultural production is relatively high and where water is sufficient in absolute physical terms but is a limiting factor because of seasonal and interannual variability and lack of water control (see **Exhibit 11**). These regions are priority areas for expanding food production through interventions in irrigation, rain-fed agriculture, rainfall harvesting and conservation of soil moisture.

Potential impact of water sector interventions on poverty reduction

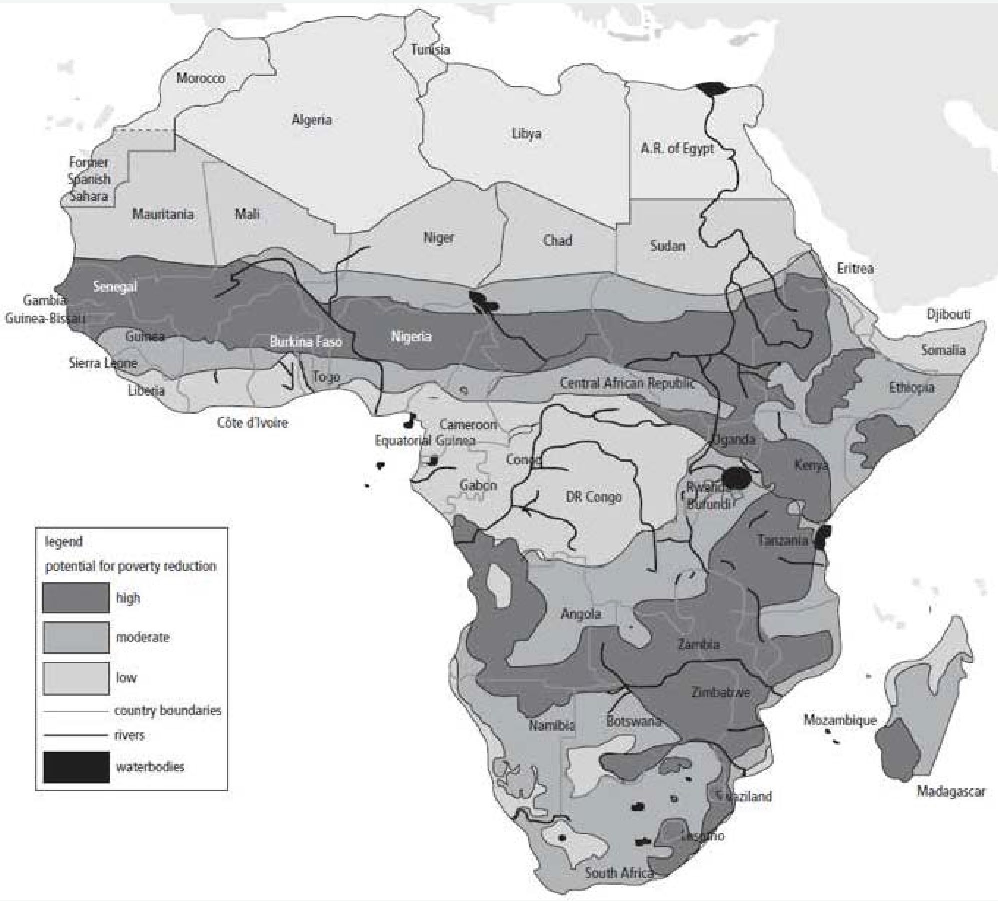


Exhibit 11: Water sector interventions have the greatest opportunity for poverty reduction in semi-arid regions of Africa that have high agricultural potential but are limited in production due to significant seasonal and interannual variability in water supply. (Source: FAO, 2008)

In South Asia, households and farmers commonly experience physical water scarcity. However, in specific regions, there is abundant unutilized groundwater that could be sustainably drawn for household consumption and increasing agricultural production and economic prosperity. **Exhibit 12** shows an index of economic water scarcity for Indian farmers, combining metrics of unirrigated farmland, smallholder farms and unutilized groundwater (ITT, 2018).

In general, Northeastern Indian states suffer most from economic water scarcity for irrigation. An estimated 80 million farmers in India, cultivating roughly 30 million smallholder farms, are affected by economic water scarcity (ITT estimates based on data from the Indian Ministry of Agriculture, 2015).

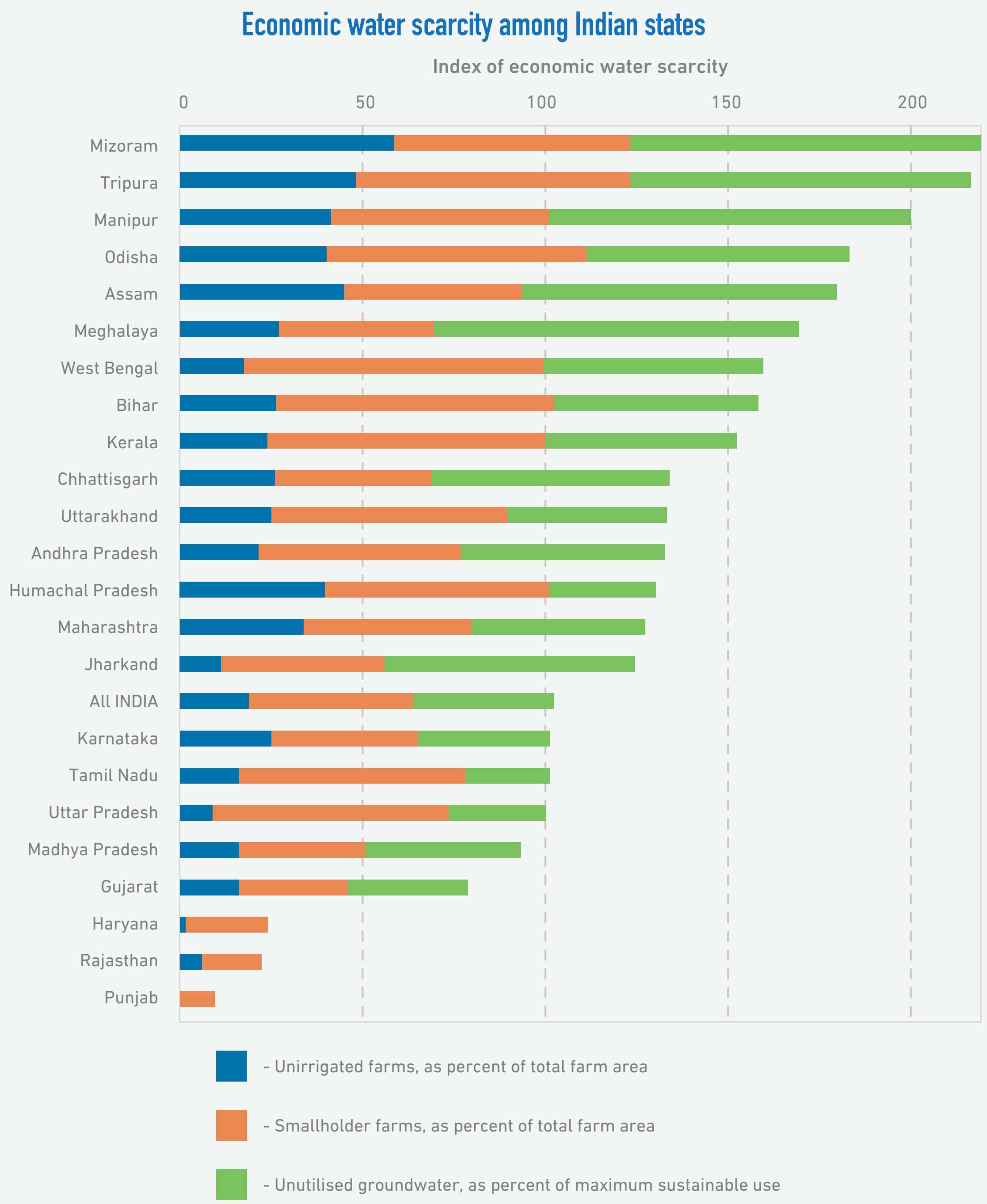


Exhibit 12: Rural economic water scarcity in Indian states is estimated with an index combining unirrigated farmland, smallholder farms and unutilized groundwater. Economic water scarcity is most prevalent in Northeast India. (Source: ITT, 2018)

Eliminating economic water scarcity will require broader socio-economic interventions, though appropriate technologies for low-cost well drilling and water pumping can make important contributions.

There are numerous reasons why many farmers do not have access to irrigation systems: there is limited awareness of irrigation value; digging wells and drilling boreholes is prohibitively expensive; diesel and electric pumps are currently too expensive and supply of diesel and electricity is both sparse and expensive; even most manual pumps are too expensive, in addition to being very strenuous to use (especially for women).

3. Well drilling is too expensive for smallholder farmers

Groundwater well drilling played a major role in the Green Revolution, and is an important part of water supply development in South Asia. Millions of borewells have been drilled in South Asia since the 1960s, and many locals have developed strong expertise in siting and drilling wells, as well as in producing and maintaining drilling equipment. This expertise is currently lacking in most parts of sub-Saharan Africa, as well as in parts of South Asia not affected by the Green Revolution. A variety of drilling technologies are available, depending on soil characteristics and required depth (see **Table 1**).

Geological conditions		Percussion drilling	Hand-auger drilling	Jetting	Sludging	Rotary percussion drilling	Rotary drilling with flush	Air lift reverse circulation
Gravel	Unconsolidated formations	✓?	✗	✗		✓?	✗	✓
Sand		✓?	✓	✓	✓	✓?	✓	✓
Silt		✓?	✓	✓	✓	✓?	✓	✓
Clay		✓ slow	✓	?	✓	✓ slow	✓	✓
Sand with pebbles or boulders		✓?	✗	✗	✗	✓?	✗	?
Shale	Low to medium -strength formations	✓	✗	✗	✗	✓ slow	✓	✗
Sandstone		✓	✗	✗	✗	✓	✓	✗
Limestone	Medium to high-strength formations	✓ slow	✗	✗	✗	✓	✓ slow	✗
Igneous (granite, basalt)		✓ slow	✗	✗	✗	✓	✗	✗
Metamorphic (slate, gneiss)		✓ v slow	✗	✗	✗	✓	✗	✗
Rocks with fractures or voids		✓	✗	✗	✗	✓	?	✗
Above water table		✓	✓	?	✗	✓	✓	✓
Below water table		✓	✗	✓	✓	✓	✓	✓

✓ - Suitable drilling method ✓? - Danger of hole collapsing ? - Possible problems ✗ - Inappropriate method of drilling

Table 1: Various well drilling technologies have been developed, which can create borewells in different geological conditions. (Source: adapted from WEDC, 1994)

The difficulty and cost of digging wells is a direct function of the water table depth.

- When groundwater is available at depths less than 4 meters, manual digging or drilling is adequate. Shallow hand-dug wells are inexpensive, with the primary cost being a farmer's time.
- When water is between 4 and 7 meters deep, hand-dug wells can still be used but require a robust lining of brick or concrete, for example. Shallow borewells can be made with a human-powered drill, especially in soft soils. In Kenya, drilling a 7 meter well in soft soils costs about $300 to $400 (Kickstart, 2013).
- For water tables of 7 to 20 meters, wells become more expensive and the risk of hitting rock increases as the well goes deeper. More sophisticated equipment like motorized percussion drills are often used. Borewells of this depth cost roughly $1,000 in Kenya.
- Deeper wells much greater than 20 meters are typically dug using truck-mounted mechanized drilling machine, which can cost more than $10,000. Innovative semi-mechanized techniques, however, could reduce the cost of drilling deeper wells.

Numerous manual drilling techniques have also been developed, which can produce borewells more economically and in locations that don't have access to mechanical drilling rigs (see **Exhibit 13**). These manual techniques often involve community participation as drilling labor. Manual techniques are, however, typically slow and limited in the geological strata they can drill.

Manual well drilling techniques

Exhibit 13: Numerous techniques have been developed for manual well drilling. (Source: adapted from RWSN, 2009)

Mechanized drilling of deeper wells is typically unaffordable for subsistence farmers. This type of drilling is typically conducted with portable diesel-powered rigs, such as percussion and rotary percussion methods.

Powered mechanical rigs are expensive (>$100,000) and have limited mobility to reach remote areas. They are able to effectively drill through most geological features and are relatively quick to create a well. The cost of drilling is largely driven by capital equipment, fuel and labor.

A case study in Ethiopia analyzed a 150-meter deep borewell (Rural Water Supply Network, 2006) costing $18,000 (**Exhibit 14**), and found that the cost per meter is roughly $120, with about 75 percent of this cost being expense for capital equipment, fuel, and labor.

High competition in emerging economies like India has historically pushed down the overall costs of drilling a well. Such competition does not yet exist in Africa, hence the cost of equipment is generally higher.

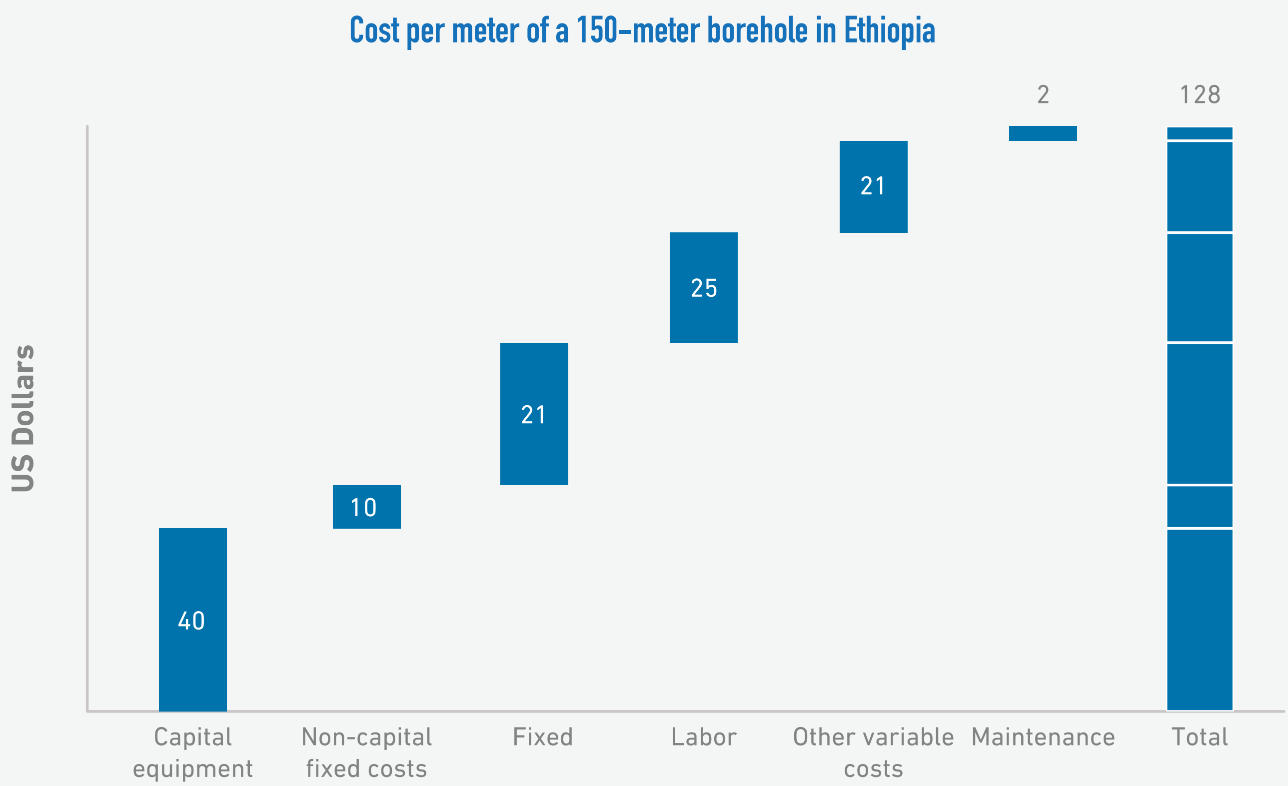


Exhibit 14: Mechanized drilling of a 150-meter borewell costs roughly $120 per meter. About 75 percent of this is expense for capital equipment, fuel and labor. (Source: Rural Water Supply Network, 2006)

Current well drilling technologies suffer from high cost, limited portability, slow drilling rate and/or limited geologic suitability. To expand groundwater opportunities to rural populations facing economic water scarcity, a drilling technology is needed that combines the speed and capability of powered equipment with the portability and low cost of manual techniques.

Such a technology like the innovative air-lift reverse circulation drill recently introduced in India by ITT, could enable more accessible borewells in regions (sub-Saharan Africa and northeastern India, for instance) suffering from economic water scarcity (**Exhibit 15**).

Exhibit 15: The air-lift reverse circulation drill is an example of a drilling technology that combines hand-operated portability with mechanized productivity. (Photo source: Sai Madhavi Antharam)

4. Water pumps are expensive to buy and operate

There is a broad range of water pumping technology, which can be categorized in various ways. One important distinction is based on pumping depth: shallow or deep. The divide occurs at a depth of about 10 meters, which is the longest column of water that can be drawn up a pipe. Shallow pumps are located at the surface, and pull water up from the well. Beyond 10 meters of depth, deep well pumps must be used.

These pumps are inserted into a well, and push the water up to the surface. Some form of power must be transferred from the surface down to operate the pump. This transfer takes the form of reciprocating metal rods in most handpumps, rotating shafts in line shaft pumps and electrical current in submersible electric pumps.

Another important pump distinction is based on the source of motive power: human muscles or externally powered. Manual-powered pumps are commonly used to lift water from boreholes and shallow wells for household use in rural areas. Technologies for shallow and deep handpumps were significantly advanced during the International Drinking Water Decade, 1981 to 1990.

Robust community-scale pumps, such as the India Mark III and the Afridev, were designed and widely deployed, with attention not only to technical efficiency but also user ergonomics and practical maintenance. While marginal improvements may be made to handpump technology, no radical innovations are expected.

Rather, water providers can make improvements by increasing coverage and ensuring timely maintenance and repairs.

Another advancement in manual pumping is the treadle pump, developed in Bangladesh during the 1970s and 1980s. This low-cost shallow pump is actuated by strong leg muscles, and pumps sufficient water for irrigating smallholder farms.

Treadle suction pumps that cost between $30 and $150 can draw water from up to a depth of 7 meters and can irrigate 0.25 hectares per 4 hours of labor (Kickstart, 2013; ATA, 2013). These pumps are easy to service as the entire pumping mechanism is above the surface.

In recent years treadle pumps have achieved some adoption in a few regions: IDE has sold 1.4 million treadle pumps in South Asia since 1985, and Kickstart sells about 25,000 pumps each year in East Africa. A portion of the Kickstart pumps are bought by NGOs, who then handle distribution to farmers (Kickstart, 2013; ATA, 2013).

Despite some success, treadle pumps are still relatively expensive for smallholder farmers and labor-intensive, especially for women.

Most irrigation pumps are powered by an external energy source, usually grid electricity or diesel fuel. Electrical pump sets are common in much of India, while diesel-powered pump sets are more common in Pakistan, Bangladesh and eastern India (see **Exhibit 16**).

A study of efficiency of electrical pump sets in Haryana found an average efficiency of 24 percent (World Bank, 2001), while other studies of South Asia suggest average pump efficiencies of about 30 percent (Singh, 2009; Kaur, et al., 2016). These efficiency levels are much lower than typical pump set efficiencies of greater than 50 percent in industrialized countries, and well below the practical efficiency limit of about 85 percent.

Efficiencies can be increased by matching the size of pumps and motors to their tasks, as most pump sets in South Asia are oversized. Renovation of existing pump sets may gain efficiency by replacing foot valves and suction and delivery piping to reduce frictional losses.

Currently, however, generous subsidies on pumping electricity discourage the adoption of more efficient pumping techniques or more rational irrigation water use (Singh, 2012).

Irrigation pumps in South Asia

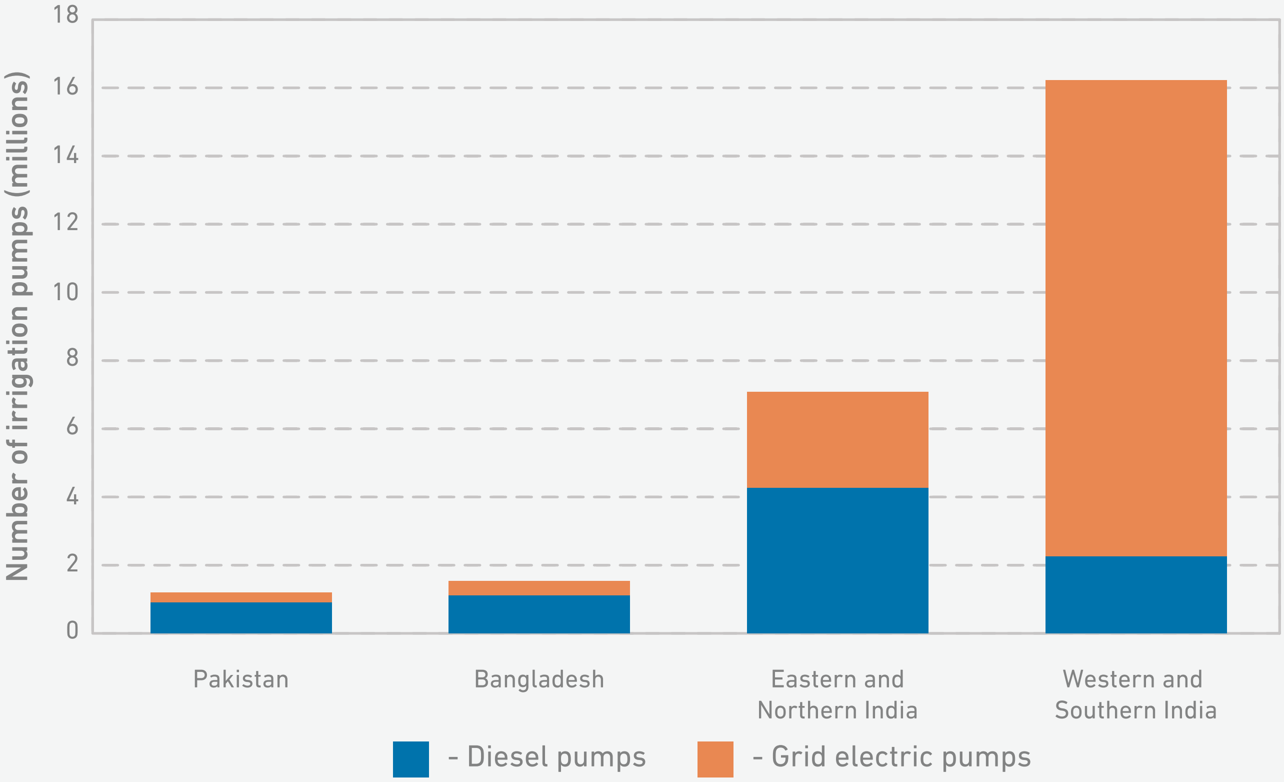


Exhibit 16: In South Asia, diesel powered irrigation pumps are most common in Pakistan, Bangladesh and eastern and northern India.[3] Grid electric powered irrigation pumps are most common in western and southern India.[4] (Source: ITT, 2018)

[3]TEastern and northern India is here defined as Assam, West Bengal, Bihar, Odisha, Jharkhand, Uttar Pradesh and Uttarakhand states.
[4]Western and southern India is here defined as Andhra Pradesh, Gujarat, Haryana, Karnataka, Kerala, Madhya Pradesh, Maharashtra, Punjab, Rajasthan and Tamil Nadu states.

Diesel powered pumps are more often used where grid electricity is not available, such as parts of sub-Saharan Africa and South Asia. In markets such as Kenya, motorized pumps that can irrigate 3 hectares are becoming available for $150 to $200 (Kickstart, 2013; ATA, 2013). However, the cost of diesel—roughly $120 per hectare per year in East Africa—necessary to run these pumps, increases the overall operating cost for farmers.

The pumps have also been prone to damage after a few years of use. The low demand for irrigation systems in sub-Saharan Africa has made it less attractive for the private sector to enter markets with suppliers and after-sale-service providers. There are few private sector suppliers and after-sale-service operators in sub-Saharan Africa. This further weakens the broader ecosystem for irrigation equipment. Without sufficient industry competition, equipment prices in sub-Saharan Africa are higher than in countries like India.

Solar powered electric pump sets, which use photovoltaic (PV) arrays to convert sunlight to electricity that then power submersible or surface-mounted electric pumps (GIZ, 2013), are currently under development. The number of PV pumps, and the land area they irrigate, is still small globally. Roughly 15,000 solar irrigation pumps have been installed in India, mainly in the states of Punjab, Rajasthan and Haryana (KPMG, 2014). The technology nevertheless has the potential to significantly scale up in future, as part of a long-term transition toward renewable energy sources.

Direct solar pumping can be quite efficient, as all harvested power is used for pumping and there is no need for batteries and associated losses. Modern positive displacement pumps have efficiencies of up to 70 percent (GIZ, 2013). There is also potential for solar pumping to be integrated into village-level solar-powered mini-grid systems.

Such integration may bring advantages to the farmer (e.g. the high capital cost of PV system is spread across many users) as well as to the mini-grid utility (e.g. having flexible and reliable pumping loads). However, the economic value of pumped irrigation water, expressed as willingness to pay by mini-grid users, is likely to be much less than that of competing uses of limited electrical power by households and industry.

There are significant barriers to the scale-up of PV-powered irrigation pumps including the high upfront cost of PV systems, which are typically 10 times that of conventional pumps (KPMG, 2014). This cost difference is diminishing over time as PV system costs decline.

Other challenges include the present lack of maintenance skills and services, low awareness of PV pumps among farmers and the risk of theft (Bassi, 2018). Furthermore, since there is zero marginal cost for additional water pumping, there is a risk of unrestrained aquifer depletion if the technology is scaled up in the absence of rational water allocation systems.

Despite the very low operating costs of PV irrigation pumps, the high capital cost leads to long economic payback times, unless substantial subsidies (approximately 80 percent) are offered by government (KPMG, 2014). Economic payback periods for solar pumping systems in South Asia range from zero to 14 years on subsidized prices, and from six to 25 years on non-subsidized prices (FAO, 2018).

Experience in the India states of Bihar (GIZ, 2013) and Rajasthan (Kishore, et al., 2014) shows that wealthier farmers are better positioned to take advantage of subsidies on PV pumps, suggesting that the existing technology is more suitable for economic development of commercial farmers, rather than alleviation of economic water scarcity among poor subsistence farmers.

KEY CHALLENGES

1. Economic water scarcity affects, by definition, those with the least economic means

Extreme economic inequity means that the poorest of the poor have very little purchasing power. The number of extreme poor (defined as living on less than $1.90, based on 2011 purchasing power parity) is decreasing for the world as a whole, but continues to rise in sub-Saharan Africa (**Exhibit 17**).

Most potential solutions involve costs (both capital and operational) that are unaffordable to these households not firmly engaged in the market economy.

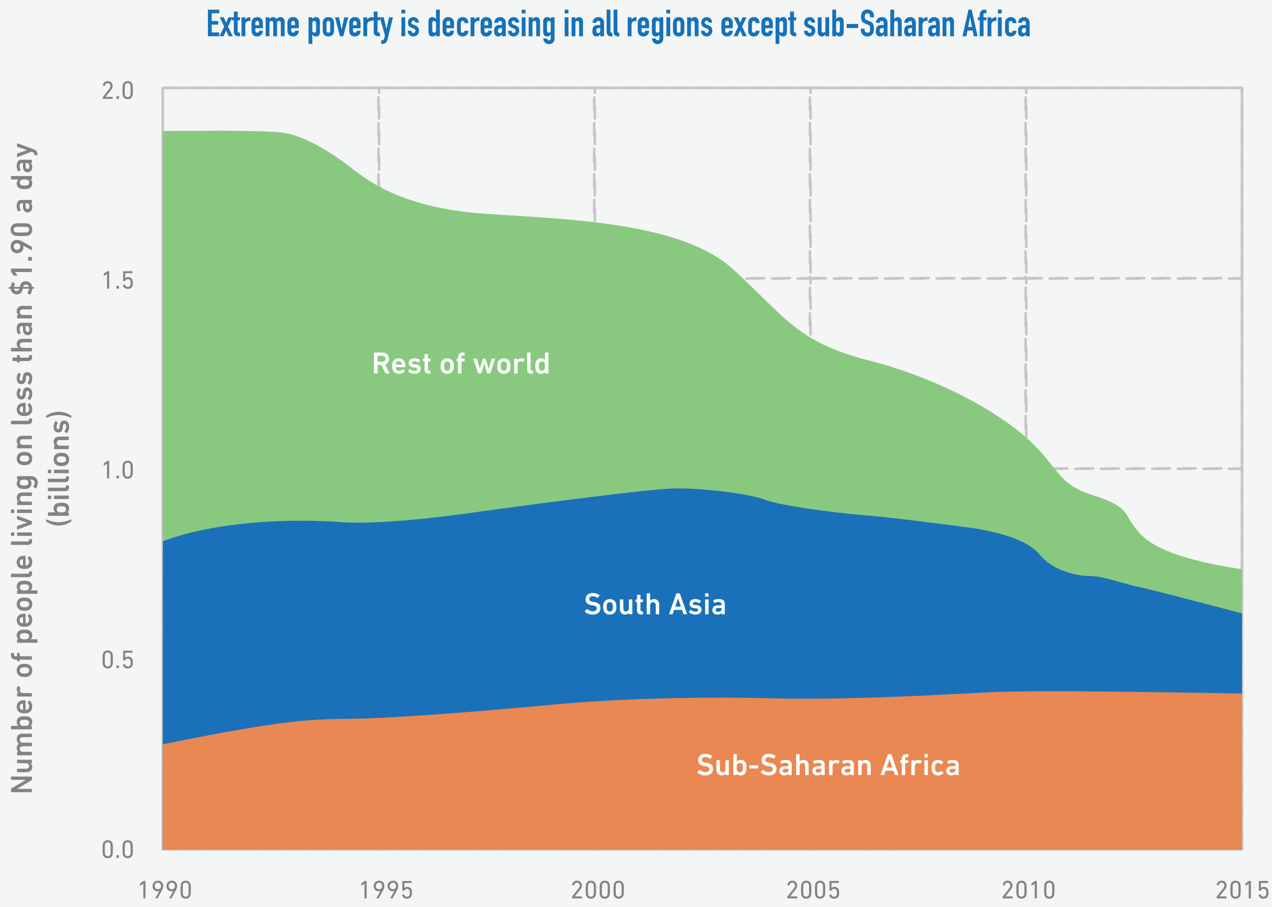


Exhibit 17: The number of extremely poor people, who live on less than $1.90 (2011 PPP), is decreasing in most regions of the world. In sub-Saharan Africa, however, the absolute number of extremely poor people continues to rise. (Source: World Bank, 2018; data on South Asia for 2015 is provisional)

2. Poor smallholder farmers in areas with abundant groundwater cannot afford the costs of drilling wells and operating pumps

Current well drilling methods are either too complex and mechanized, or too slow and labor intensive. Water pumps, and the energy to operate them, are beyond the reach of smallholder farmers, considering capital and O&M costs.

3. Expanding surface water irrigation requires centralized coordination and budgeting

Social means to achieve consensus on potential large-scale initiatives often remain elusive. In the absence of collective action, decentralized decisions are limited to the distributed resources available, such as groundwater.

SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

Economic water scarcity is more of a social challenge than a technological one. It occurs where water is locally available, but cannot be accessed due to lack of human, institutional or financial capital. It occurs in both urban and rural areas, and involves drinking, household and irrigation water.

While primary solutions to economic water scarcity will require innovations in social and economic justice, our analysis concludes that four technological breakthroughs can also contribute to significantly reducing the economic water scarcity that households and smallholder farms experience.

Breakthroughs:

1 2 3 4 5 6 7 8 9 10
11 12 13 14 15 16 17 18 19 20
21 22 23 24 25 26 27 28 29 30
31 32 33 34 35 36 37 38 39 40
41 42 43 44 45 46 47 48 49 50

1 A low-cost system for precision application of agricultural inputs, ideally combining water and fertilizer

In some regions like South Asia, the Green Revolution has brought unfortunate consequences including over-exploitation of groundwater resources and over-application of synthetic fertilizers. In other regions like sub-Saharan Africa, the Green Revolution has not arrived and there is under-utilization of groundwater resources and ongoing nutrient mining of soils. There is need for a low-cost, robust, scalable technology to precisely meter and distribute irrigation water and fertilizer to field crops.

This would allow farmers to apply the right amounts of water and nutrients (not too much or too little) at the right time to maximize economic returns and reduce nutrient loss. If made affordable, precision application systems for irrigation and fertilizers, calibrated to local crop type and soil conditions, could be a very effective way to increase agricultural yields, while also reducing negative impacts on the environment.

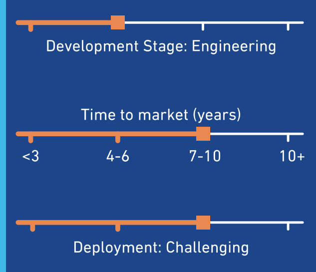
Enabling better management of the timing and formulation of irrigation and fertilization in cropping systems would ensure that water and nutrients are available where and when needed by the plant roots. Crop yields respond very well with initial inputs of fertilizer, but as additional nutrients are supplied the marginal yield increase becomes smaller.

Optimal results occur somewhere along that gradient, depending on the cost of fertilizer and seeds, land and selling price of harvested crops. For maximum returns, it is necessary to not just apply the right quantity of fertilizer, but to also apply it at the right time and place for optimal nutrient uptake by the plant. This would also protect watersheds and populations downstream from farm fields, by greatly reducing runoff.

The efficiency of using agricultural inputs, such as fertilizer is low in conventional farming. It is estimated that overall efficiency of applied fertilizers is about 50 percent for nitrogen, less than 10 percent for phosphorus and about 40 percent for potassium. The rest is wasted as runoff.

The mismatched timing between availability of nitrogen and crop need for nitrogen is likely the single greatest contributor to excess nitrogen loss in annual cropping systems. Ideally, nutrients should be applied in multiple small doses and when plant demand for them is greatest.

Current State

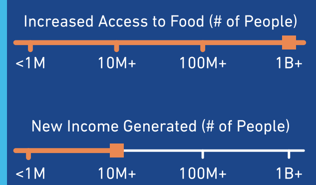


Associated 50BT Chapters

Food Security Global Change

SDG Alignment

Impact



Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

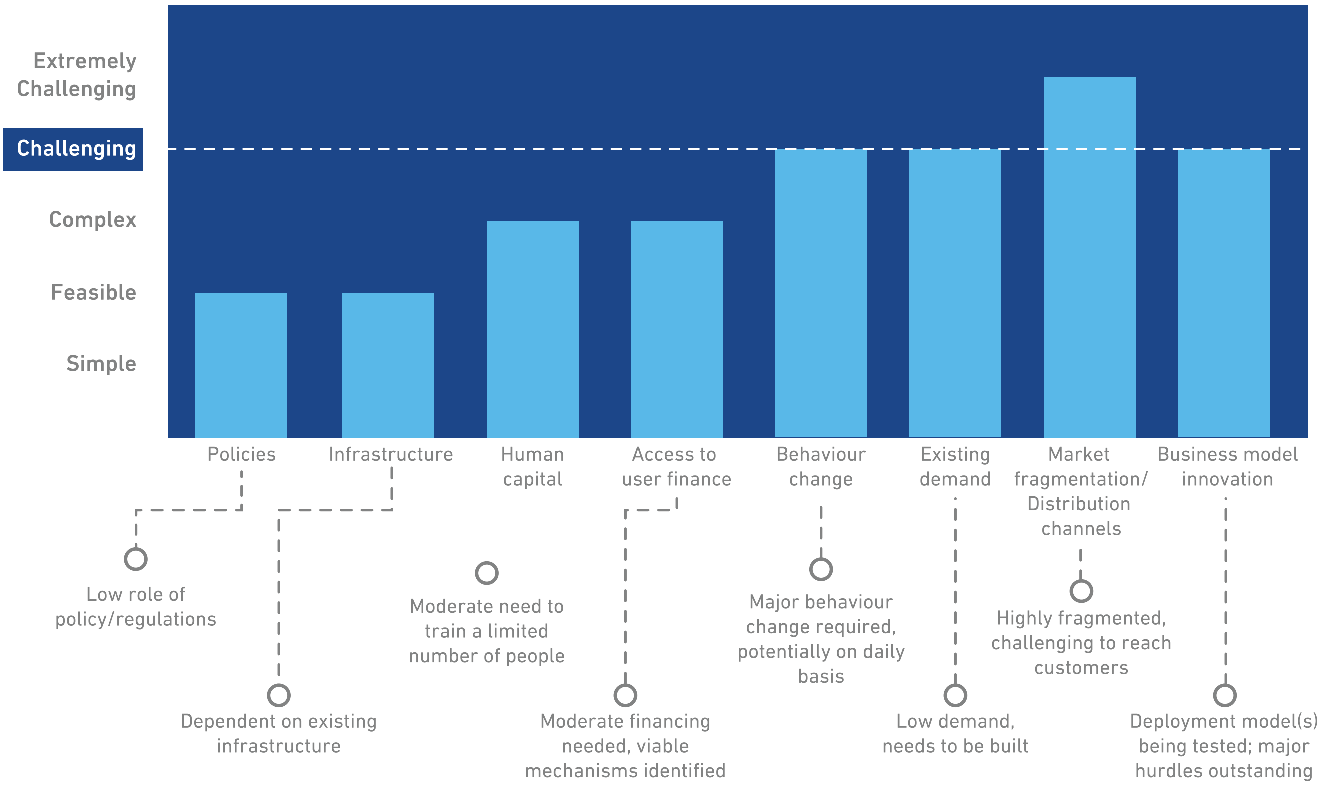
In principle, variations of existing programmable irrigation and fertigation systems used in industrialized countries can be adapted to the needs of smallholder farmers. Already, small-scale drip and sprinkler systems—along with other methods for increasing water usage efficiency—are beginning to emerge in markets like India. Cultivated area under drip irrigation in India has grown from 71 km^2 in 1992, to 2,460 km^2 in 1998, to 18,970 km^2 in 2010, up to 33,700 km^2 in 2015. The cost of such systems will continue to drop as scale of production increases.

This breakthrough would be strongly leveraged by three other breakthroughs, 5 Low-cost shallow groundwater drilling technologies, 6 Affordable solar-powered irrigation pumps, and 9 Low-cost soil nutrient analysis device. Overall, such devices would help farmers better predict crop nutrient requirements, better schedule irrigation and fertilizer applications, and avoid over-fertilization and nutrient runoff. If complemented with adjusted crop rotation patterns and additional biotic complexity, it could improve the plant community's ability to take up more of the available nutrients.

However, there is limited evidence to suggest that users—farmers or otherwise—will be interested in spending money on technologies to conserve water when the resource itself is available free of cost. The potential for saving fertilizer can prove to be a positive incentive, although the current demand for fertilizers is very low in sub-Saharan Africa.

It will face some deployment challenges that are common to the African smallholder farmer market, including structural barriers such as a fragmented market of farmers, limited access to finance for potential users, and lack of training to install, use and maintain the technology. The difficulty of deployment in this case would be CHALLENGING.

Breakthrough 1: Difficulty of deployment



2. A very low-cost scalable technique for desalinating brackish water

This breakthrough focuses on developing and enabling systems for very low-cost, high-efficiency desalination of brackish water resources. Households, industries and farms can utilize such systems to provide additional freshwater supplies for water-constrained regions. The introduction of very low-cost desalinated water could enable sustainable irrigation in vast regions of the world that contain brackish groundwater.

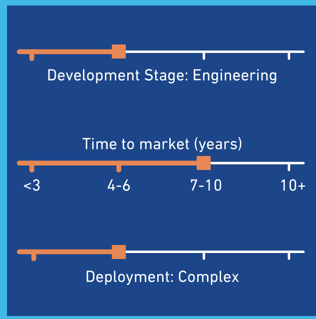
Desalination is increasingly used to provide household and industrial water in regions with scarce freshwater but abundant salt water. Most current desalination facilities are located in the Middle East, use seawater as feedwater and are powered by fossil fuels. The city of Chennai in southern Indian gets about a quarter of its municipal water from reverse osmosis seawater desalination plants.

Conventional desalination methods typically use seawater as feed. Seawater desalination technologies based on membranes, such as reverse osmosis, are approaching the thermodynamic limits of efficiency and have limited opportunity for further improvement. It is unlikely that major technology breakthroughs will fundamentally alter the seawater desalination landscape. Additionally, desalinated seawater is too expensive to use as irrigation water for crop production.

In contrast, there are large potential efficiency gains by using brackish water as feed. There are major opportunities for significant reductions in brackish water desalination cost and energy use through innovative electrochemical or other emerging techniques. The minimum theoretical energy requirement for desalination varies with the salinity of the feedwater—less energy is fundamentally needed to desalinate brackish water compared to seawater. Electromagnetic desalination processes such as electrodialysis (ED) and capacitive deionization (CDI) are limited to low-salinity feedwater, but potentially have much lower cost and energy than pressure or thermal techniques. They offer many advantages when used with brackish feedwater, such as high water recovery and high brine concentrations.

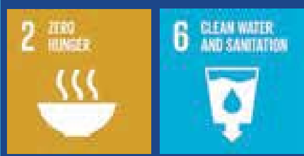
They also require little or no feedwater pre-treatment and membrane fouling can be prevented by reversing the electrode polarities. However, electromagnetic processes only remove ions from the water, leaving organics and colloids in suspension—this is a concern for household water, but less so for irrigation water. Furthermore, the selection and configuration of membranes is currently highly dependent on feedwater characteristics, thus must be adapted to local conditions of feedwater composition and concentration.

Current State

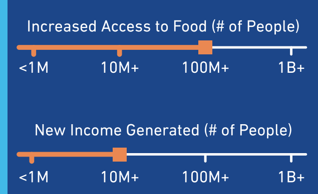


Associated 50BT Chapters

SDG Alignment



Impact



Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

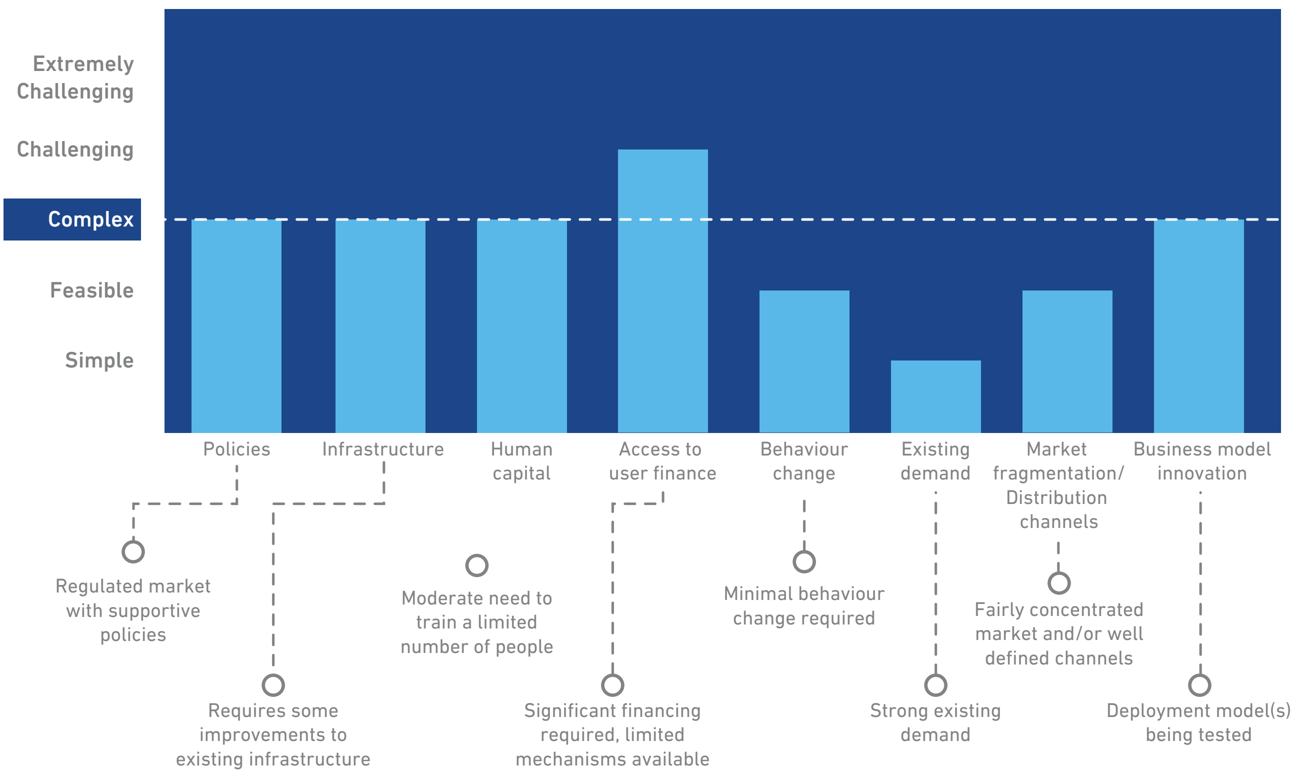
Concerted R&D efforts can overcome current obstacles to enable a major source of low-cost freshwater in regions with brackish resources. The appropriate unit scale of desalination facilities may vary depending on the application (such as household, irrigated farm, urban water utility). The salinity of the product water may also vary depending on the purity requirements of the end uses.

Costs can be further reduced by matching the salinity of the product water to the salinity thresholds for different uses; in other words, removing only enough salt to make the water viable for its intended use. Ideally, facilities will be powered by onsite renewable energy sources, such as photovoltaic solar arrays, to provide reliable and sustainable operation. Developing appropriate business models will be essential to ensure economic sustainability and continuing impact.

End-uses for the desalinated water will include drinking, cooking, washing and other domestic uses and industrial water uses. Efficient techniques for large-scale desalination of brackish water resources will also enable the use of desalinated water for production of agricultural crops using efficient irrigation techniques.

Substantial research and development work is required and we expect that it will take seven to ten years for this breakthrough to be ready. Deployment challenges include access to finance and policies regarding location and discharge streams. We rate the difficulty of deployment, COMPLEX.

Breakthrough 2: Difficulty of deployment



6 Low cost drilling technologies for shallow groundwater, which reduce the cost to less than $100 per farmer

Less than 5 percent of farmland in sub-Saharan Africa is irrigated, despite the presence of extensive, renewable, shallow (less than 10 meters) groundwater. An important reason for this lack of irrigation is the relatively high cost of well drilling in the region.

Mechanized drilling of wells is typically unaffordable for subsistence farmers. This type of drilling is typically conducted with portable diesel-powered rigs, such as percussion and rotary percussion methods. Powered mechanical rigs are expensive (more than $100,000) and have limited mobility to reach remote areas. High competition in emerging economies like India has historically pushed down the overall costs of drilling a well. Such competition does not yet exist in Africa, hence the cost of well drilling is generally higher.

Manual drilling techniques have been developed that can produce borewells more economically and in locations that don't have access to mechanical drilling rigs. These manual techniques often involve community participation as drilling labor. Manual techniques are, however, typically slow and limited in the geological strata they can drill.

Most current well drilling technologies suffer from high cost, limited portability, slow drilling rate or limited geologic suitability. To expand groundwater opportunities to rural populations facing economic water scarcity, a drilling technology is needed that combines the speed and capability of powered equipment with the portability and low cost of manual techniques. It should be comprised of lightweight, easily transportable components, yet powered by a portable mechanized source.

An affordable method to reach shallow groundwater will enable widespread irrigation in sub-Saharan Africa, providing smallholder farmers with increased crop yields, the possibility of cultivation during dry seasons and droughts and the opportunity to grow high value, high nutrition crops.

While shallow groundwater resources are rechargeable by rain and thus sustainable under moderate use, there is a risk of water over-extraction and aquifer depletion. This has occurred, for example, in parts of South Asia that practice intensive Green Revolution agriculture. Any low-cost drilling solution will have to be accompanied by some form of community-level metering and monitoring to ensure sustainability of available water.

Current State

Development Stage: In-Market Small Scale

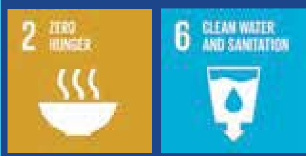
Deployment: Challenging

Associated 50BT Chapters

Water Security

Food Security

SDG Alignment



Impact

Increased Access to Food (# of People)

<1M 10M+ 100M+ 1B+

New Income Generated (# of People)

<1M 10M+ 100M+ 1B+

Commercial Attractiveness

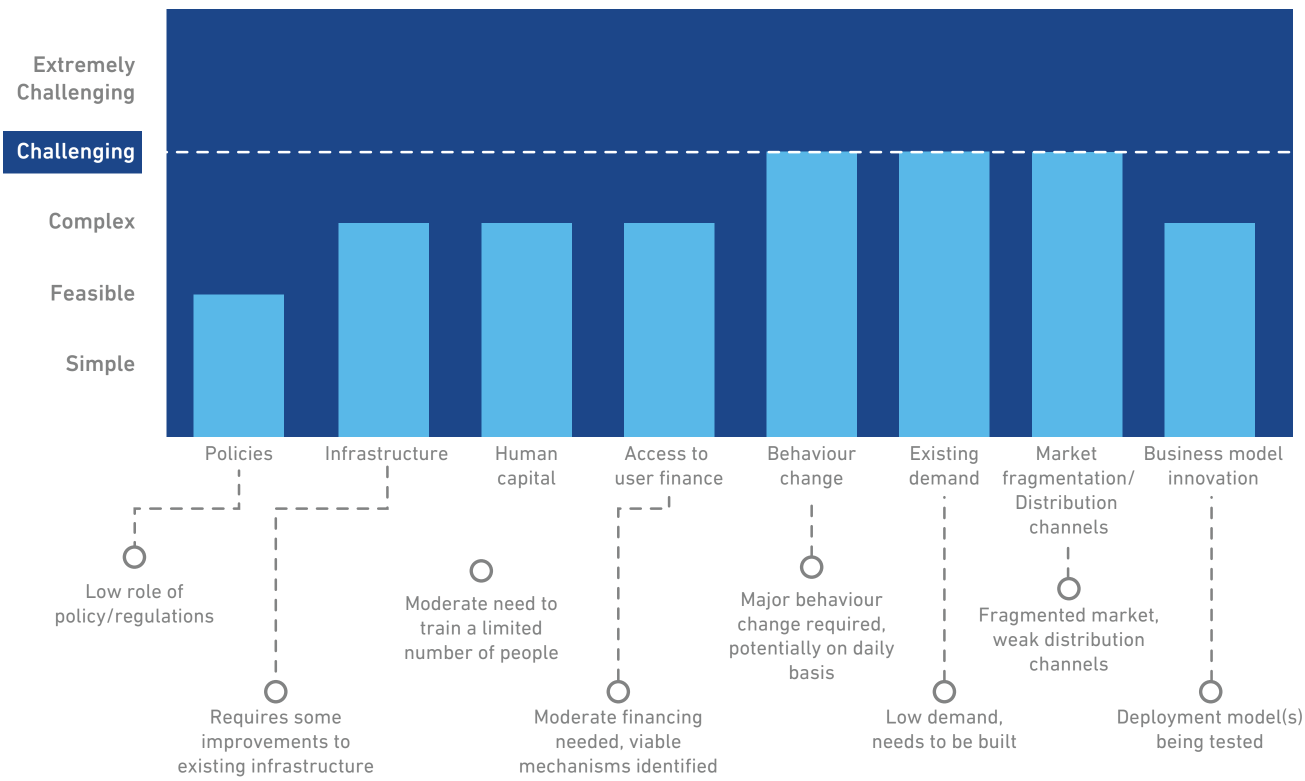
- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

Currently, there is extremely low demand among African smallholder farmers for irrigation. Depending on the cost of the technology that is developed, farmers may require financing to pay for construction and usage of wells (even for community-level wells).

Such a technology will also have to overcome many of the typical challenges faced by products and services in this market: fragmentation and the lack of an ecosystem of suppliers and after-sale-service providers.

However, based on the agricultural development experience in South Asia and what can be seen in areas of Africa that have access to irrigation services, there is reason to believe that appreciation of the benefits of irrigation can become apparent within a short period of time. Hence, we believe such a technology is four to six years from becoming market-ready. Overall, we believe deployment will be CHALLENGING.

Breakthrough 6: Difficulty of deployment



7 Affordable (less than $50), lightweight, energy-efficient, solar-powered irrigation pumps

Irrigation is one of the most significant levers for increasing on-farm yield. However, currently available manual irrigation pumps (for example, treadle pumps) are quite strenuous to use and often not suited to the needs of women farmers. Motorized pumps available on the market are even more expensive, and the cost hurdle is compounded by the recurring cost of diesel fuel. In remote areas, the paucity of distribution networks for diesel is an additional constraint.

A solar powered pump that costs under $50, and pumps enough water for a typical smallholder farm, could dramatically increase access to irrigation. Direct-drive photovoltaic solar pumping can be quite efficient, as all harvested power is used for pumping and there is no need for batteries and associated losses.

Modern positive displacement pumps have efficiencies of up to 70 percent. Nevertheless, a significant barrier to the scale-up of PV-powered irrigation pumps is the high upfront cost of PV systems, which are typically 10 times that of conventional pumps. Despite the very low operating costs of solar irrigation pumps, the high capital cost leads to untenably-long economic payback times. Strongly reducing cost, while ensuring reliable service, is thus essential.

Considering the effort being dedicated to this problem and the pace with which this market is developing, it is likely that low-cost market-ready pumps will become available within the next two to three years. A number of organizations are developing solar pumps, a small number of which are already being used in India and other developing regions.

The biggest hurdle appears to be throughput: the more the volume of water pumped, the larger and more expensive the solar panel needs to be.

Current State

Development Stage: Engineering

Time to market (years): <5 | 5-7 | 7-10 | 10+

Deployment: Complex

Associated 50BT Chapters

Water Security

Food Security

SDG Alignment

2 ZERO HUNGER

6 CLEAN WATER AND SANITATION

Impact

Increased Access to Food (# of People): <1M | 10M+ | 100M+ | 1B+

New Income Generated (# of People): <1M | 10M+ | 100M+ | 1B+

Commercial Attractiveness

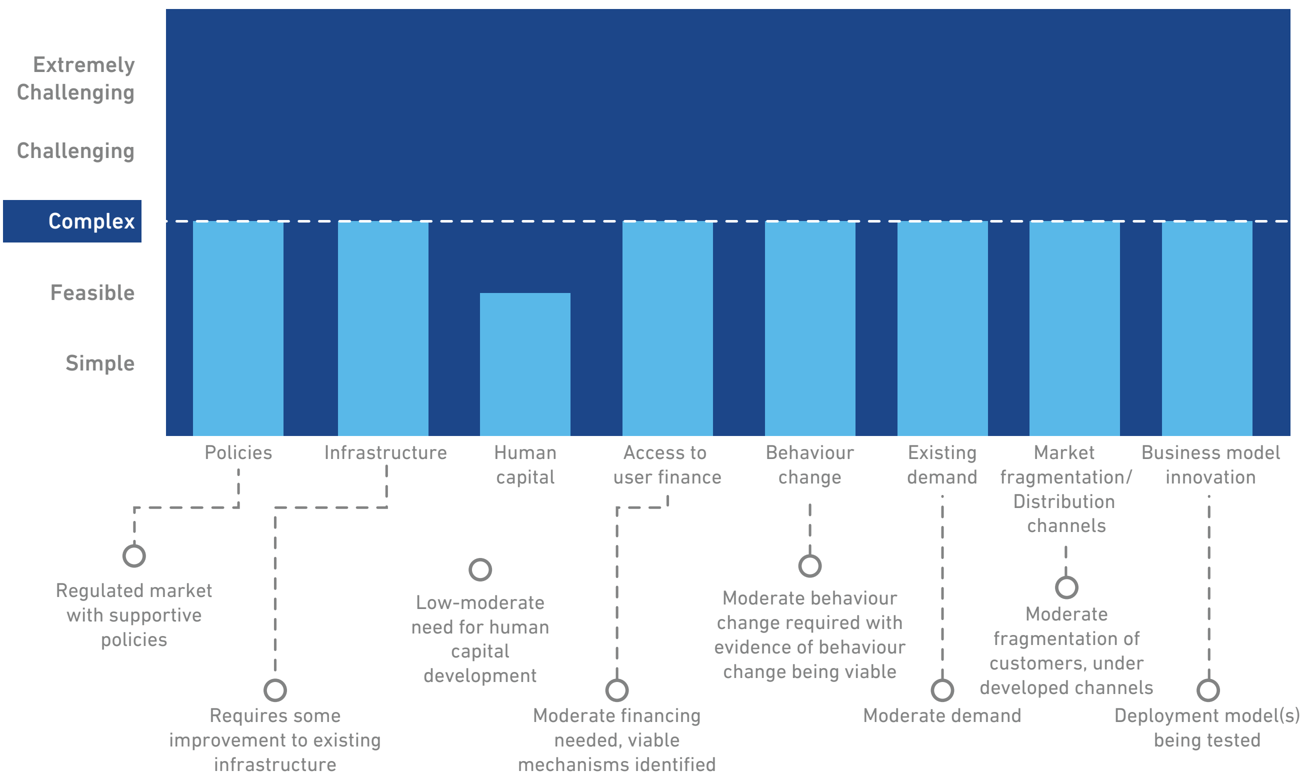
- Attractive for industrialized markets (high profits)
- **Attractive for emerging markets (lower profits)**
- Emerging markets potential; requires derisking (sustainable)
- Non-commercial (unprofitable)

However, even if solar pumps become available, there are a number of deployment hurdles: the majority of African farmers are still extremely poor, live in remote areas and are accustomed to rain-fed farming.

Considerable effort will be required for creating demand and providing financing and training. A critical lesson from the decades of agricultural development in South Asia is that water can easily be overused and groundwater easily depleted.

Since there is zero marginal cost for solar water pumping, there is a risk of unrestrained aquifer depletion if the technology is scaled up in the absence of rational water allocation systems. Enforcing any such system will be very challenging. Hence, we believe that deployment will be COMPLEX.

Breakthrough 7: Difficulty of deployment



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FOOD SECURITY AND AGRICULTURE

OVERVIEW

Food insecurity is one of the most significant problems faced by the global poor. More than 820 million people—constituting about 11 percent of the world's population—do not have enough food to live a healthy life (FAO, 2018). This happens in spite of the fact that most developing countries, especially in sub-Saharan Africa and South Asia, have large agrarian populations.

Over 60 percent of the people in sub-Saharan Africa live in rural areas, more than half of whom live below the poverty line; in South Asia too, over 60 percent of the population is rural, with one-third living below the poverty line.

About 50 percent of the total population in these regions is either employed in agriculture, or dependent on local agriculture as the primary source of food (**Exhibit 1**) (World Bank, 2018). Most farmers in these regions are smallholders, typical working plots of land one hectare or smaller in size. Most smallholder farmers, especially in sub-Saharan Africa, are subsistence farmers—their main source of food is what they grow.

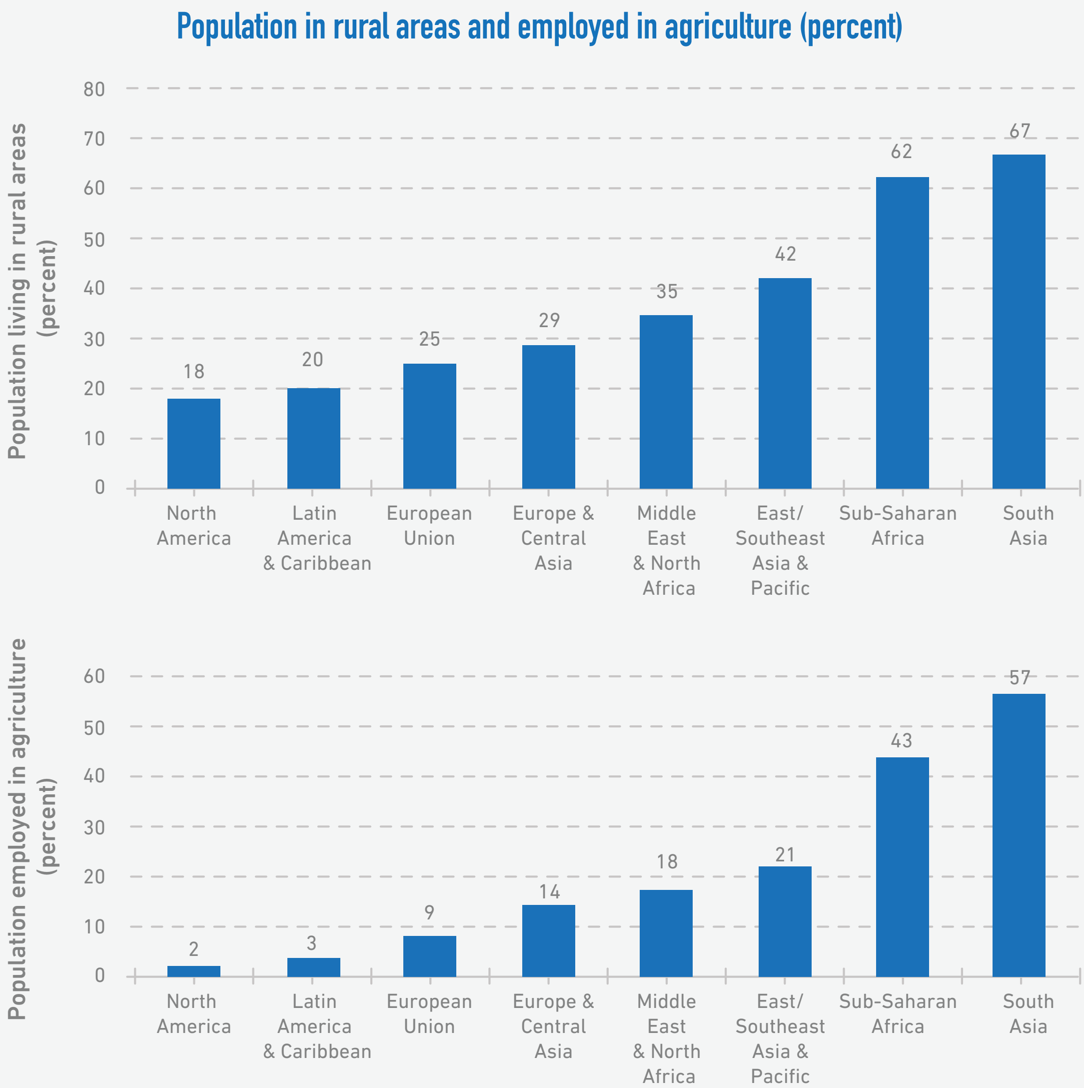

Exhibit 1: Most people in sub-Saharan Africa and South Asia live in rural areas. In addition, the majority of the labor force in these regions works in agriculture. (Source: World Bank, 2018; year 2016 data for Living in rural areas, year 2017 data for Employed in agriculture)

Despite the significance of local agriculture as the primary economic base and source of food, agricultural yields lag well behind those in other parts of the world, particularly in sub-Saharan Africa, and to a lesser extent in South Asia (**Exhibit 2**).

As a result, most countries in sub-Saharan Africa and South Asia are net importers of food (**Exhibit 3**). For example, about 30 percent of cereals consumed in sub-Saharan Africa are imported (FAO, 2014). In many developing countries, the cost of food comprises a very large part of total household expenditures (**Exhibit 4**).

In some sub-Saharan African countries, such as Nigeria and Kenya, more than half of all household expenditures are devoted to food (USDA, 2018). In industrialized countries, by contrast, food costs are a much smaller percentage of total expenses; households in the United States and United Kingdom spend less than ten percent of household budgets on food.

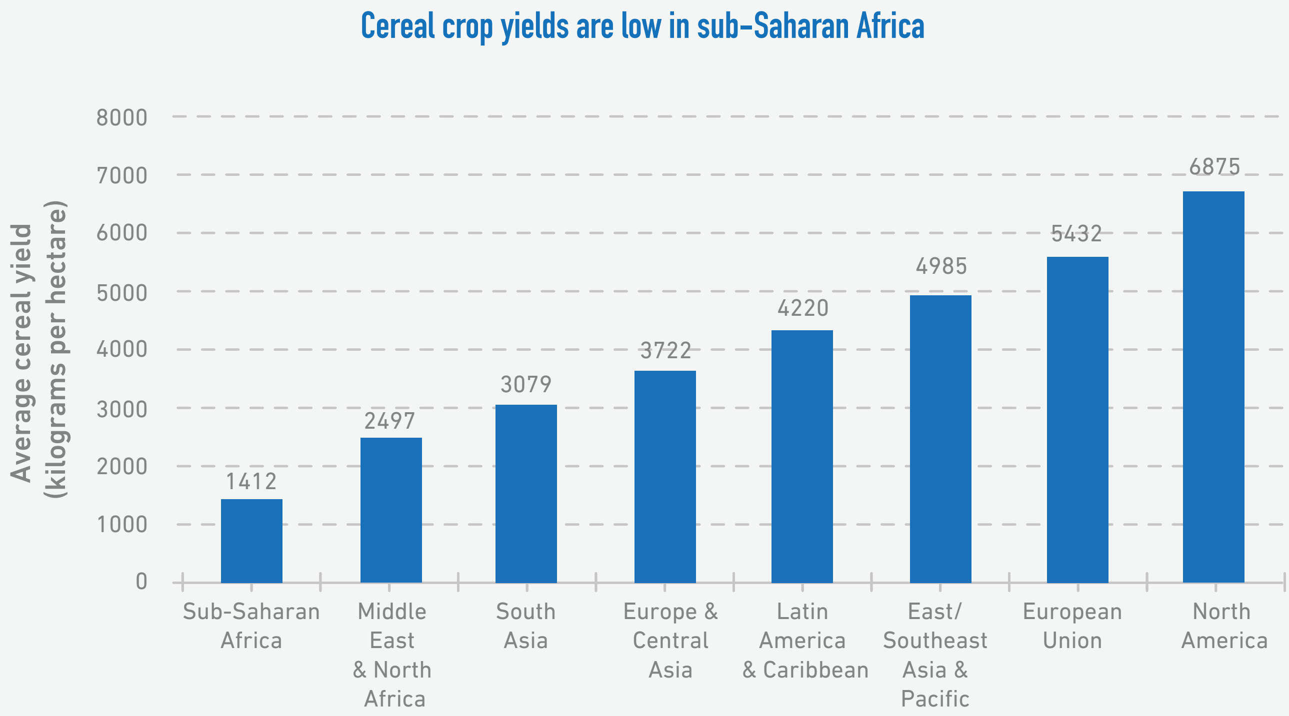

Exhibit 2: Cereal crop yield in sub-Saharan Africa is less than half that of South Asia, and a fraction of that in other parts of the world. Yields for other agricultural commodities—cash crops, horticulture and livestock—also lag significantly behind. (Source: data from World Bank, 2018, average of years 2013 to 2016)

Percentage of net food imports in domestic food supply, measured in total calories

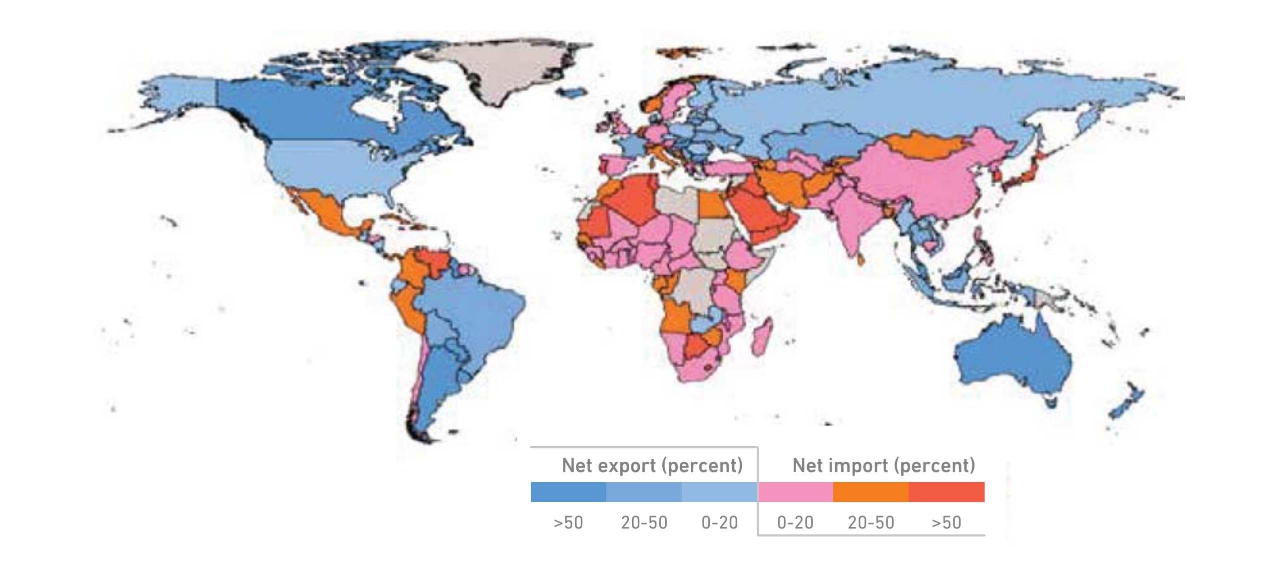

Exhibit 3: Most sub-Saharan African countries, and many Asian countries, are net importers of food calories. (Source: year 2011 data from FAO, 2017)

Food expenses, as percent of total consumer expenses

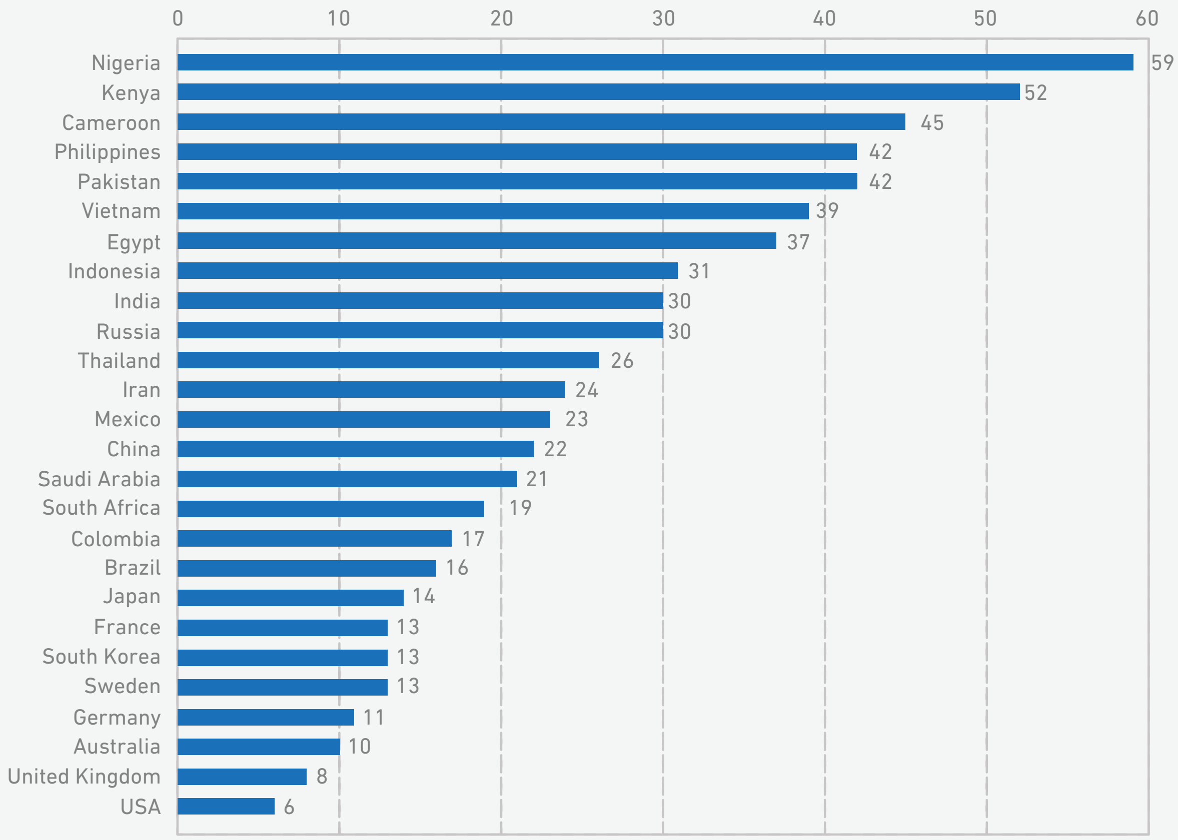

Exhibit 4: Food comprises a very large part of total household expenditures, in many developing countries. In contrast, in industrialized countries food costs are a much smaller percentage of total expenses. (Source: year 2016 data from USDA, 2018)

In both sub-Saharan Africa and South Asia, poverty and undernourishment are considerably higher than in the rest of the world. These interrelated factors have made agriculture and its role in alleviating poverty, and improving food security and health, a primary focus of international development.

Considering both the rates and absolute extent of undernourishment, sub-Saharan Africa and South Asia are the regions of greatest concern (FAO, 2018). About 23 percent of the population in sub-Saharan Africa is undernourished, and that percentage has risen in recent years after many years of gradual decline (**Exhibit 5**).

In South Asia, the rate of undernourishment continues to decline, currently standing at about 15 percent. Globally, the total number of undernourished people has increased in recent years, after years of steady decline (**Exhibit 6**).

This is primarily a result of growing undernourishment in sub-Saharan Africa, where both population numbers and undernourishment rates are rising. In sub-Saharan Africa, about 236 million people face undernourishment, of which more than half live in East Africa. South Asia is home to the greatest absolute number of undernourished people (280 million), though their numbers are slowly decreasing.

Undernourishment rate by region, since 2005

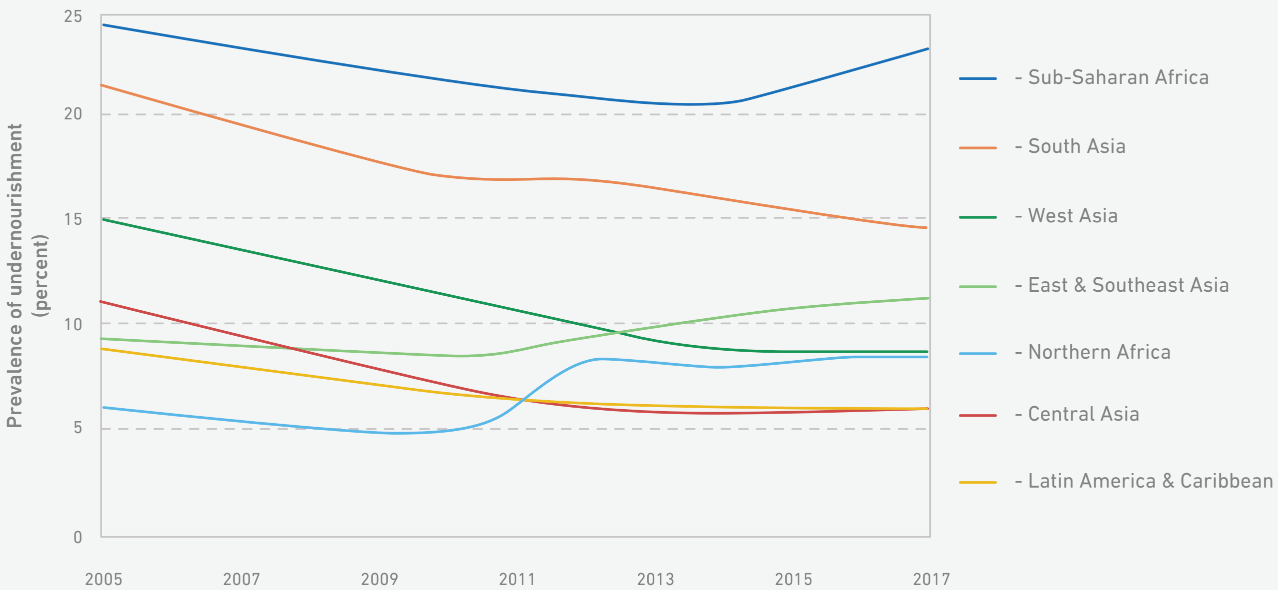

Exhibit 5: About 23 percent of the population in sub-Saharan Africa is undernourished, meaning they lack regular access to enough dietary energy for a healthy, active life. The undernourished percentage in sub-Saharan Africa has risen in recent years, after many years of steady decline. In South Asia, the undernourished population is about 15 percent and continues to decline. (Source: FAO, 2018)

Number of undernourished people, since 2005

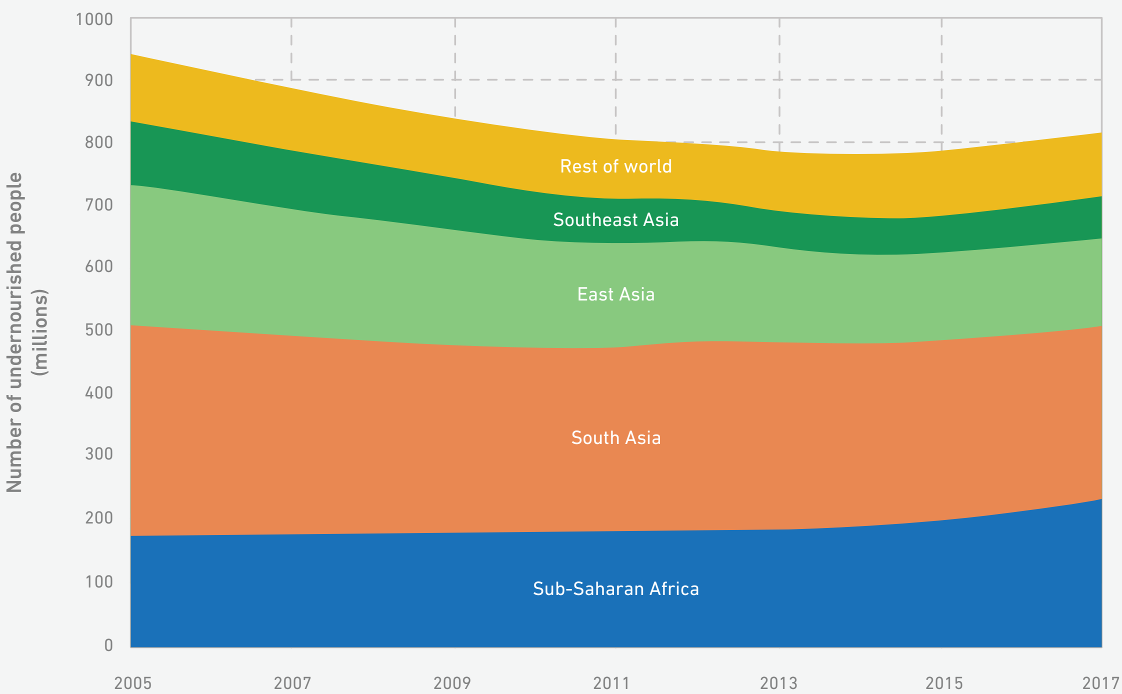

Exhibit 6: After years of steady decline, the global number of undernourished people has increased in recent years. The greatest numbers of undernourished people live in South Asia, though their numbers are slowly decreasing. The next largest group of undernourished people lives in sub-Saharan Africa, and their numbers are increasing. (Source: FAO, 2018)

The Green Revolution has led to a dramatic increase in food production in South Asia, while sub-Saharan Africa has lagged behind

The Green Revolution that started in the 1950s is considered by some to be among the most successful large-scale programs to help alleviate poverty and improve food security in the history of international development (Spielman & Pandya-Lorch, 2009) (Hazell, 2009).

Norman Borlaug, the biologist who developed the high-yield seed varieties that launched the Green Revolution, was awarded the Nobel Peace Prize in 1970. By combining improved seed varieties with intensive use of irrigation and fertilizers, strengthening local institutions and a range of major policy reforms, numerous countries were able to make substantial gains in food production.

Nevertheless, increased levels of pollution from pesticide and fertilizer run-off have accompanied the productivity gains enjoyed in many regions. Furthermore, there are concerns about the long-term sustainability of high yielding agriculture due to emerging issues such as groundwater depletion and soil erosion.

South Asian countries, in aggregate, have tripled their cereal yields since 1960 (**Exhibit 7**). During the same period, sub-Saharan Africa— which was not a part of those Green Revolution efforts— achieved little in the way of increased agricultural productivity (World Bank, 2018).

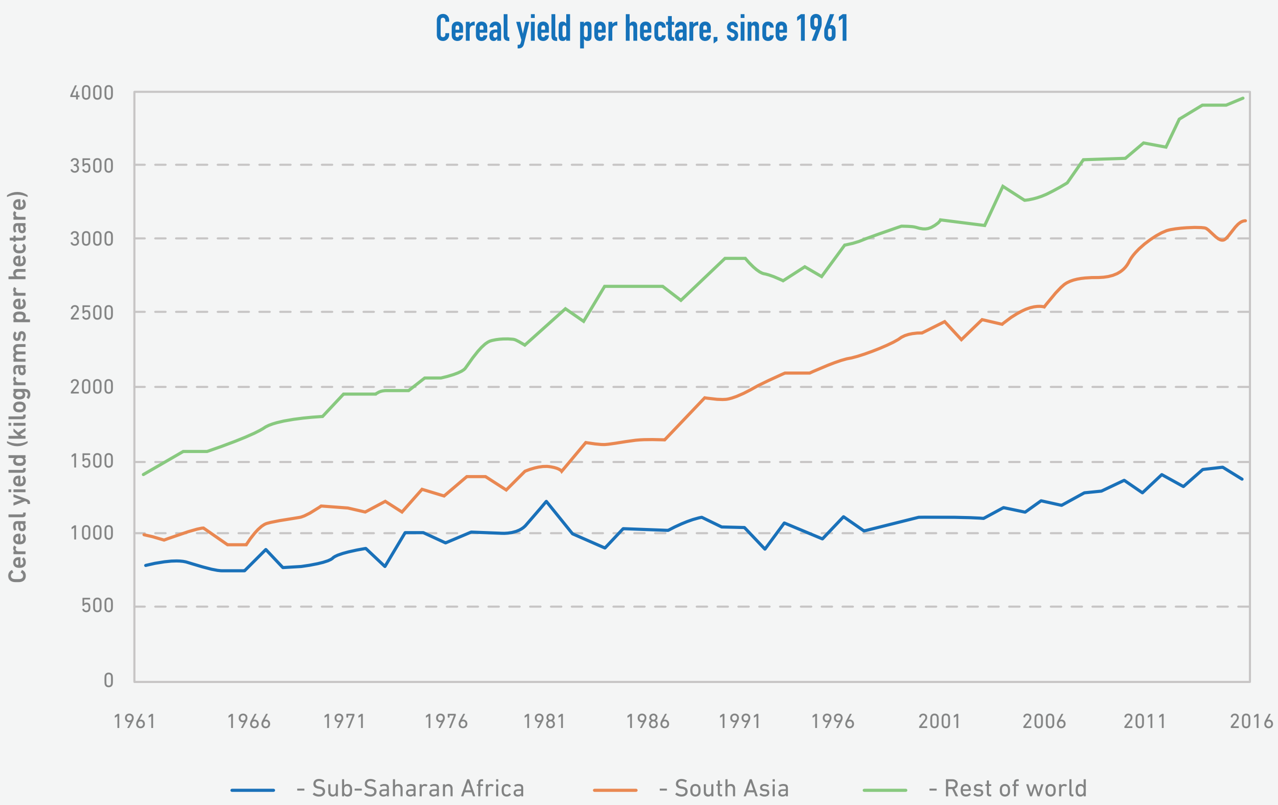

Exhibit 7: The Green Revolution led to dramatic increases in agricultural productivity in South Asia to the extent that South Asia is approaching agricultural self-sufficiency. On the other hand, sub-Saharan Africa continues to lag far behind the world average. (Source: World Bank, 2018)

Another telling measure of the Green Revolution's impact is the role agricultural intensification has played on the amount of land used for food production. As **Exhibit 8** shows, the yield of cereals in South Asia increased by 160 percent between 1961 and 2009, with only a small increase in cultivated land area.

During the same time, there was only a 50 percent increase in per hectare cereal yield in sub-Saharan Africa, and farmers have had to increase the amount of land for cultivation by 140 percent (VFRC, 2012).

Cereal production, yield and land usage in South Asia and sub-Saharan Africa, 1961 to 2009

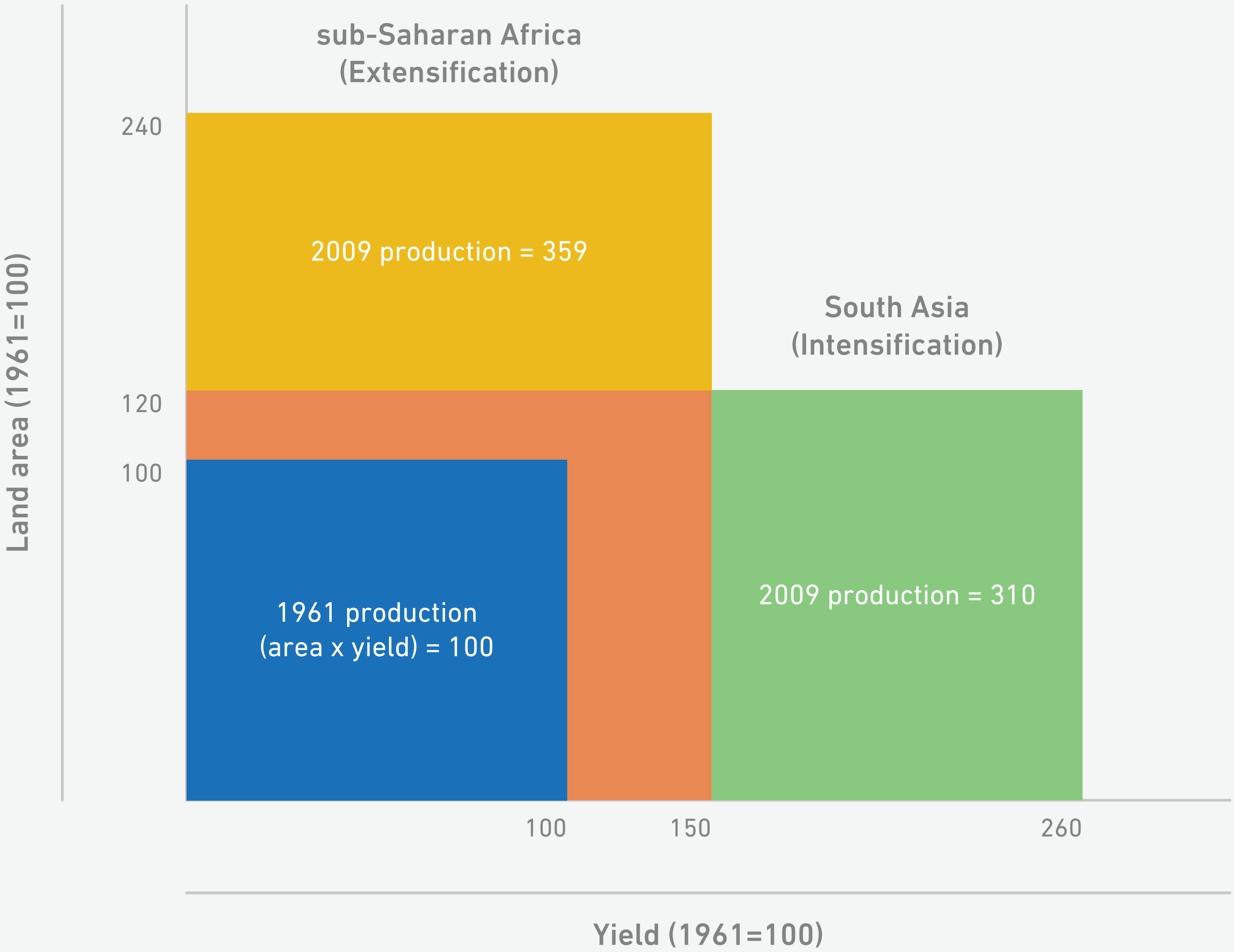

Exhibit 8: In South Asian countries agricultural yield increased dramatically over the past few decades due to intensified agricultural practices. Compared with 1961, per hectare cereal yield in South Asia has increased by 160 percent, leading to a total output increase of 210 percent, with only a 20 percent increase in cultivated land. During the same period in sub-Saharan Africa, there was a 140 percent increase in cultivated land and only a 50 percent increase in per hectare yield, for a total increase in output of 259 percent. (Source: VFRC, 2012)

Prevalent forms of agriculture have a significant environmental footprint

As described in detail in the Agricultural Sustainability section, virtually all forms of agriculture practiced in both industrialized and developing countries cause significant primary environmental damage, for example due to wildland clearance and soil erosion.

In addition, the intensified agricultural practices that arose from the Green Revolution have several specific negative environmental impacts. One important impact is water overuse, particularly in South Asia where more than 90 percent of water withdrawals are used for agriculture (World Bank, 2017).

Overuse, together with population growth, has led to a 65 percent reduction in the supply of renewable water since the early 1960s, on a per capita basis (FAO, 2014); as a consequence, much of South Asia is now facing severe water scarcity. In contrast, much of sub-Saharan Africa has abundant unutilized renewable groundwater.

Another effect of current intensive agriculture is the runoff of excess fertilizer nutrients into waterways, which causes overgrowths of algae that lead to dead zones when the algae decay and the oxygen in the water depletes. More than 400 marine dead zones resulting from nutrient runoff are reported worldwide, having approximately doubled each decade since the introduction of synthetic fertilizers in the 1960s (Diaz & Rosenberg, 2008).

Large algal blooms and hypoxia characterize the Arabian Sea, due to massive organic and nutrient loads entering the sea from India and Pakistan (Gomes, et al., 2014). Nutrient runoff also causes blooms of cyanobacteria (also known as blue-green algae), which can produce toxic compounds that are hazardous to humans and animals.

Mass blooms of toxic cyanobacteria occur regularly in water subject to nutrient runoff, with the timing and duration of the bloom season varying by location. Sub-Saharan Africa does not suffer greatly from water dead zones, due to their limited use of chemical fertilizers.

A sizable amount of food is lost or wasted because smallholder farmers do not have appropriate storage facilities or access to markets

Most African smallholder farmers lack access to ready markets for their produce. As a result of this and other factors, a large number of grain producers store their own grains, as food for their families until the next harvest. The storage facilities they use—typically made with easily available local material, like mud and straw—do not offer adequate protection from moisture, excess heat, rodents or pests, and a substantial portion of the grains are spoiled (**Exhibit 9**).

Another equally pressing problem is the lack of adequate refrigeration, because of which perishable products like fruits, vegetables, dairy and meat, cannot be preserved for long.

Agricultural losses in sub-Saharan Africa across the value chain, for different types of crops

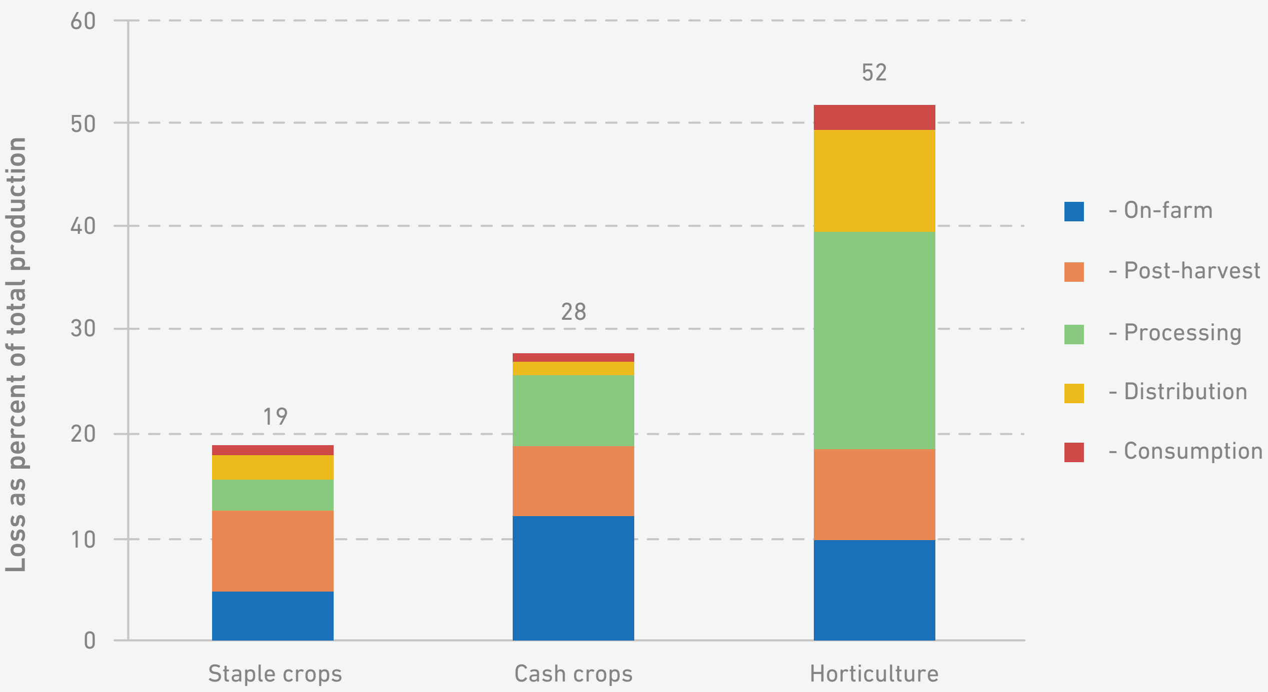

Exhibit 9: Due to a lack of appropriate technologies for handling, storing and transporting, smallholder farmers in sub-Saharan Africa lose a substantial portion of their produce, even before the food is ready to be consumed. (Source: FAO, 2011a)

A dearth of local food processing facilities to convert raw produce to consumable foods (such as, cocoa beans to chocolate, milk to packaged cream or cheese, or raw cashew nuts to consumable cashews) means that the bulk of high value produce is processed outside the region. While this is especially true for export commodities (like cocoa), there are also many food products imported into the region (like fruit juices, chocolate and cheese) made from raw produce that is locally available.

Exhibit 10 is an illustrative example of the gap between overall production and available processing facilities for cashew nuts. The lack of processing facilities deprives the local economy of agribusiness jobs, and smallholder farmers of higher prices for what they produce (African Cashew Alliance, 2010). This also drives up the costs of food and agricultural products, making them unaffordable for low-income populations.

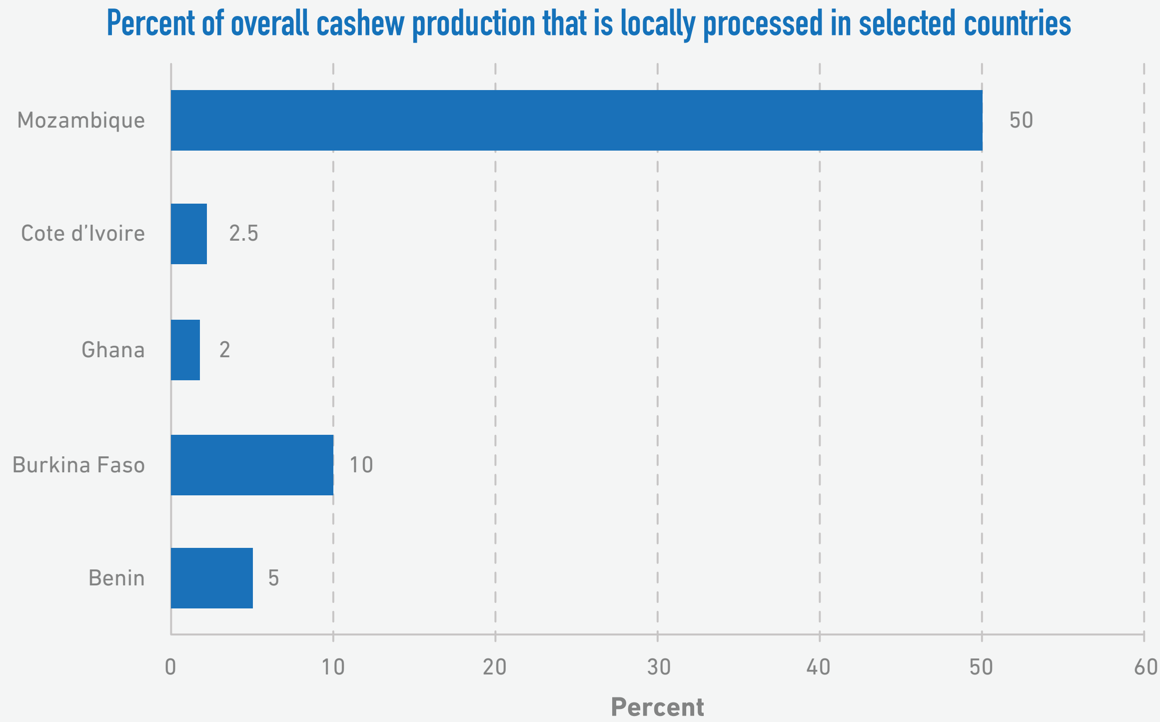

Exhibit 10: Cashews have to be processed before they are consumed. The dearth of cashew processing factories means that most of the cashews grown in Africa are shipped elsewhere for processing. (Source: African Cashew Alliance, 2010)

Women perform a significant portion of agricultural labor

Agriculture constitutes the single most significant type of economic activity, and accounts for about 40 percent of effort, by South Asian and sub-Saharan African women (**Exhibit 11**). Women perform the majority of agricultural labor in many countries in these regions (**Exhibit 12**) (World Bank, 2015, 2018).

Still, as our Gender Equity chapter discusses, most farm implements are not engineered for use by women—taking into account their size, weight, strength, traditional clothing and other constraints.

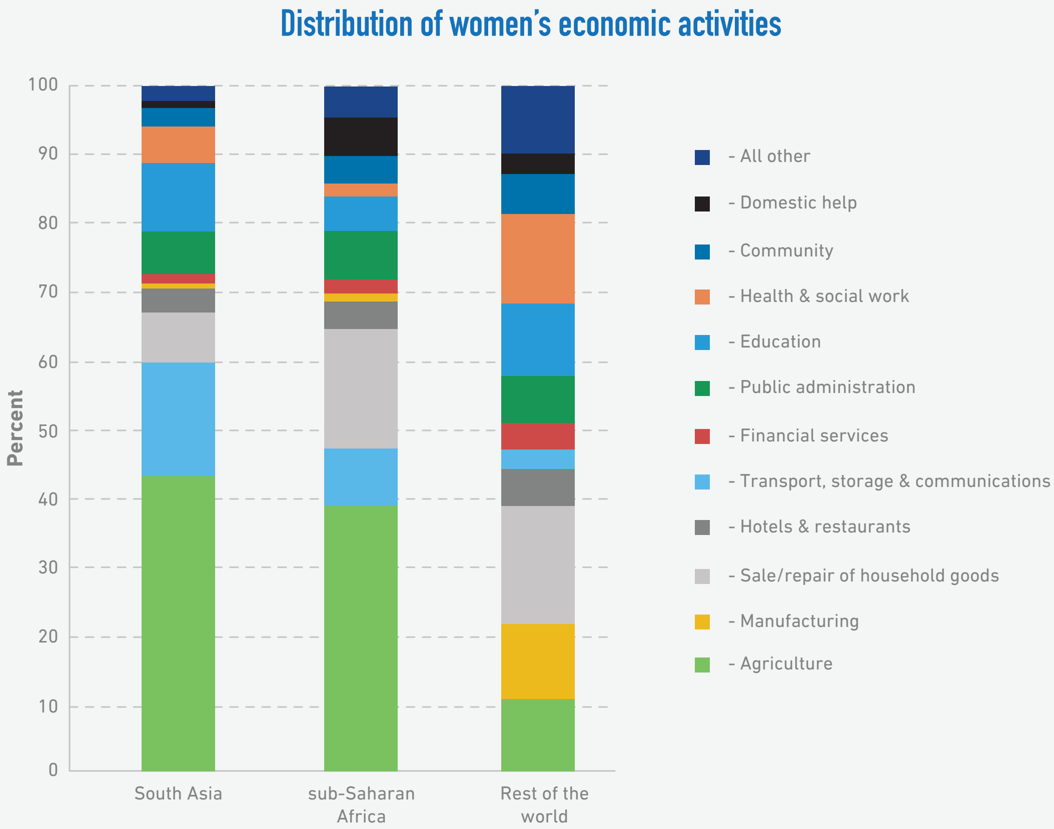

Exhibit 11: In South Asia and sub-Saharan Africa, agriculture constitutes the single largest type of economic activity performed by women. (Source: FAO, 2011b)

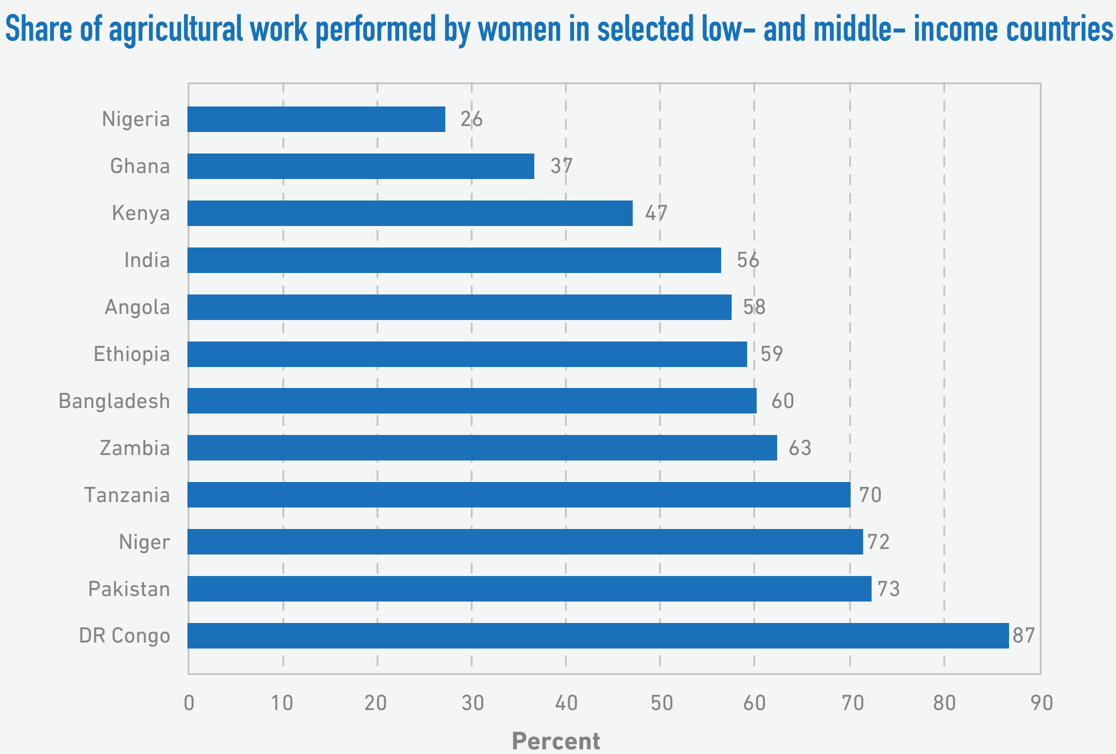

Exhibit 12: Women contribute to a substantial portion of total agricultural labor, ranging from 26 percent in Nigeria, to 87 percent in DR Congo. (Source: year 2017 data from World Bank, 2018)

RECENT TRENDS IN AGRICULTURAL DEVELOPMENT

As we examine the role of various interventions in improving food security, the following recent trends in agricultural development are important to consider.

There is a growing emphasis on the long-term sustainability of agriculture

There has always been ongoing tension between economic development and environmental sustainability, in both industrialized and developing countries.

Until recently, most developing countries (including emerging middle-income countries like China) had taken the posture that climate change and other forms of environmental damage are problems caused primarily by industrialized countries.

However, there has been a marked turnaround in attitudes in recent years, and developing countries are beginning to recognize the steps they can take to reduce the environmental impact of their actions. Sustainable agronomy is now a core component of the global agricultural development agenda (WRI, 2018).

The need for agriculture to produce more food without causing environmental harm, and even to make positive contributions to natural and social capital, has resulted in sustainable intensification practices such as crop rotations, integrated pest management, soil- and water-conserving tillage, basin-level irrigation water management, animal production systems emphasizing disease prevention without antibiotics, and genetic improvement of crops to resist pests and disease and to use nutrients more efficiently (Pretty, 2018).

The central role of women in agriculture has been acknowledged, though truly inclusive policies have not yet been achieved

There is finally acknowledgment of the central role women play in agricultural development. This recognition has manifested itself through broad efforts to make mainstream agriculture programs more gender inclusive, including extension, technology development and strengthening of farmer organizations (World Bank, 2015).

However, while there is clearly more effort made toward greater equity, it is not yet clear whether there has been much impact in achieving true gender parity in agricultural development and improved quality of life.

With increasing globalization, agricultural value chains are becoming disintermediated

Countries in tropical regions grow more agricultural commodities than those in colder climates. Some of these commodities, such as cocoa and coffee, have become increasingly valuable exports to industrialized markets, with both consumption and prices steadily growing over the past several decades (International Coffee Organization, 2014). As a result, large food companies are beginning to pay more attention to the quality of raw produce and working much more closely with farmer groups on training and quality control.

Global climate change is projected to negatively impact agricultural yields

Rising temperatures and altered precipitation due to climate change are projected to significantly affect crop yields and food security. At lower latitudes including tropical regions, crop productivity is forecast to decrease with even a small rise in average temperature. Yields of important crops, such as wheat, rice, maize and soybean, are expected to decline due to rising temperatures.

Changes of average precipitation in a much warmer world will not be uniform, with some regions experiencing increases and others decreases or little change. Precipitation is expected to increase in many wet tropical areas and in high latitudes. Many mid-latitude and subtropical arid and semi-arid regions will likely experience less precipitation. The Asian monsoon is expected to increase in average total precipitation but with greater variation from year to year.

Currently, the primary focus of agricultural development is sub-Saharan Africa

The Green Revolution beginning in the 1950s led to tremendous improvements in agricultural productivity in Latin America and Asia. Combined with other forms of economic development, many of these countries have reached middle-income status and most are now self-sufficient with respect to food. While there is still a significant concentration of poverty and food insecurity in South Asia (especially in areas like India's lower Ganges plain, which were not integral to the Green Revolution), a number of influential funders of agricultural development programs are dedicating much more resources to sub-Saharan Africa than to South Asia.

This chapter focuses on the key factors that can improve food security and smallholder farmer incomes: increasing yield, preserving food, improving market access, reducing workload (especially for women) and making agriculture more sustainable. These issues are discussed in the following dedicated sections:

- **Irrigation**
- **Soil health and plant nutrients**
- **Biotic stresses**
- **Post-harvest handling and storage**
- **Extension services**
- **Livestock**
- **Fisheries and aquaculture**
- **Agricultural sustainability**

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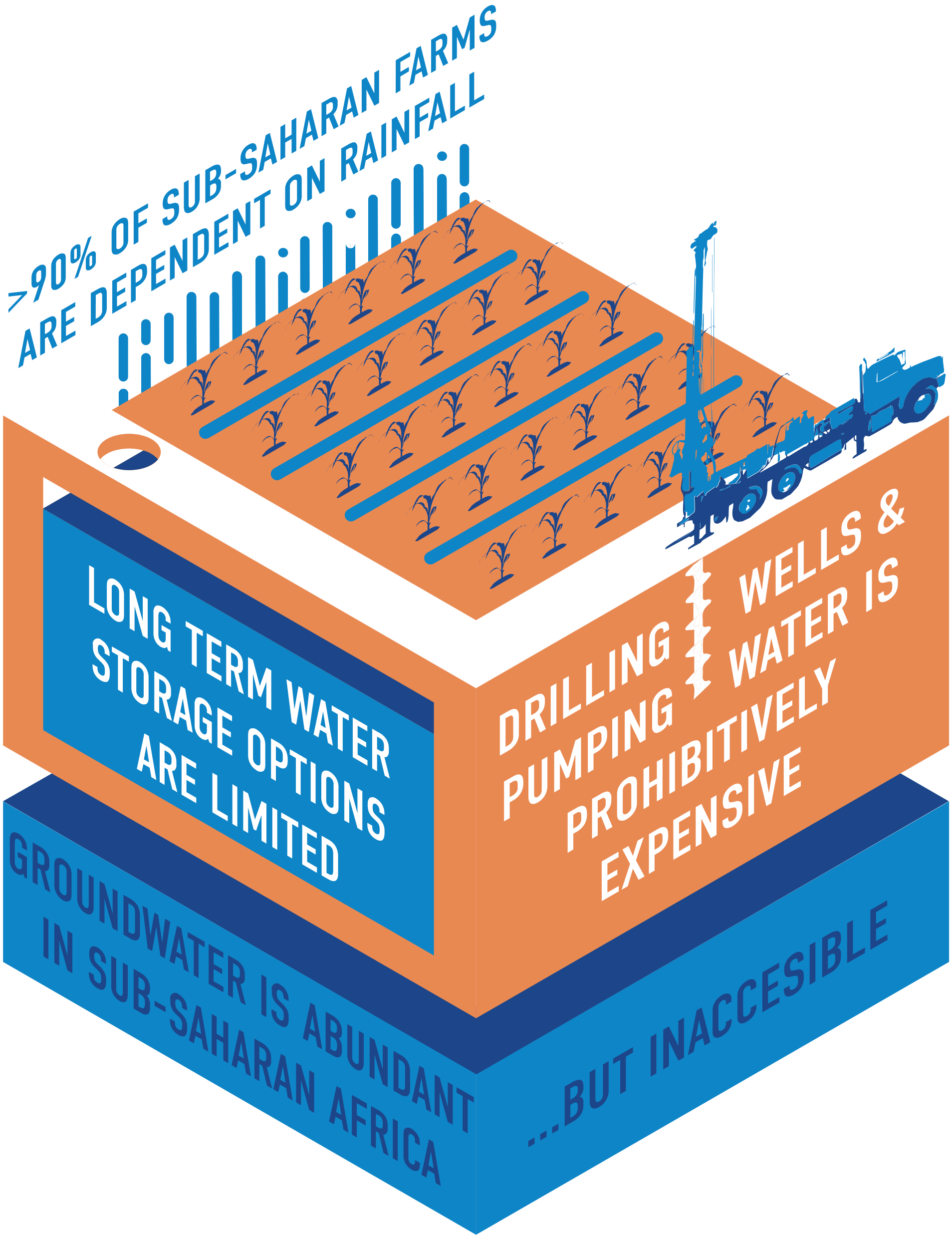

>90% OF SUB-SAHARAN FARMS ARE DEPENDENT ON RAINFALL
LONG TERM WATER STORAGE OPTIONS ARE LIMITED
DRILLING WELLS & PUMPING WATER IS PROHIBITIVELY EXPENSIVE
GROUNDWATER IS ABUNDANT IN SUB-SAHARAN AFRICA
...BUT INACCESIBLE

IRRIGATION

INTRODUCTION

The lack of proper irrigation is a critical constraint to increasing agricultural productivity for smallholder farmers in sub-Saharan Africa.

With proper irrigation, not only can farmers improve their crop yields, but also diversify their crop portfolio toward higher income crops and increase the total number of harvests in a given year. However, smallholder agriculture in sub-Saharan Africa is largely rain-fed, which results in a limited window for farmers to irrigate their fields.

There are a number of reasons why African farmers do not have access to irrigation systems: there is limited awareness of the value of irrigation; diesel pumps are currently too expensive and diesel supply is both sparse and expensive; even most manual pumps are too expensive, in addition to being very strenuous to use (especially for women); lastly, digging wells is also a prohibitively expensive proposition.

Current data suggests that there is an adequate supply of shallow groundwater (rechargeable by rain) across much of sub-Saharan Africa. However, the experience from intensified agriculture in South Asia demonstrates that groundwater can easily be depleted if not sustainably used. Our analysis concludes that four technological breakthroughs can lead to significant improvements in the overall agricultural productivity of smallholder farmers in sub-Saharan Africa.

- Breakthrough 1. A low-cost system for precision application of agricultural inputs, ideally combining water and fertilizer
- Breakthrough 2. A very low-cost scalable technique for desalinating brackish water
- Breakthrough 6. Low cost drilling technologies for shallow groundwater, which reduce the cost to less than $100 per farmer
- Breakthrough 7. Affordable (less than $50), lightweight, energy-efficient, solar-powered irrigation pumps

Soil moisture, usually enabled by irrigation, is one of the key drivers of agricultural productivity. Studies have found that irrigation can lead to substantial increases in productivity from 50 percent to more than 100 percent. Irrigation also reduces variability in yield from year to year, leading to more reliable harvests.

CORE FACTS AND ANALYSIS

1. Irrigation is expanding in all global regions except sub-Saharan Africa

Irrigation offers several critical benefits for smallholder farmers including increased crop yields, the possibility of cultivation during dry seasons and droughts and the opportunity to grow high value, high nutrition crops. Since the Green Revolution, intensified agricultural practices in many parts of the developing world have led to greater adoption of irrigation.

In South Asia, for example, the share of farmland that is irrigated increased from 24 percent in 1973 to 46 percent in 2013 (**Exhibit 1**). Sub-Saharan Africa has lagged far behind, however, where only 3.4 percent of farmland is irrigated (FAO, 2016).

Where irrigation is used, both groundwater and surface water are withdrawn for irrigation (**Exhibit 2**).

Groundwater is more commonly used in South Asia and North America, while surface water is used more in other regions. Most smallholder farmers in Africa have traditionally relied on rainfall as the sole source of farm water, and continue to do so. Irrigation technologies remain largely out of their economic means.

As a result, cereal production closely follows the amount of rainfall in any given year (**Exhibit 3**) (McIntyre, et al., 2009; Molden, 2007).

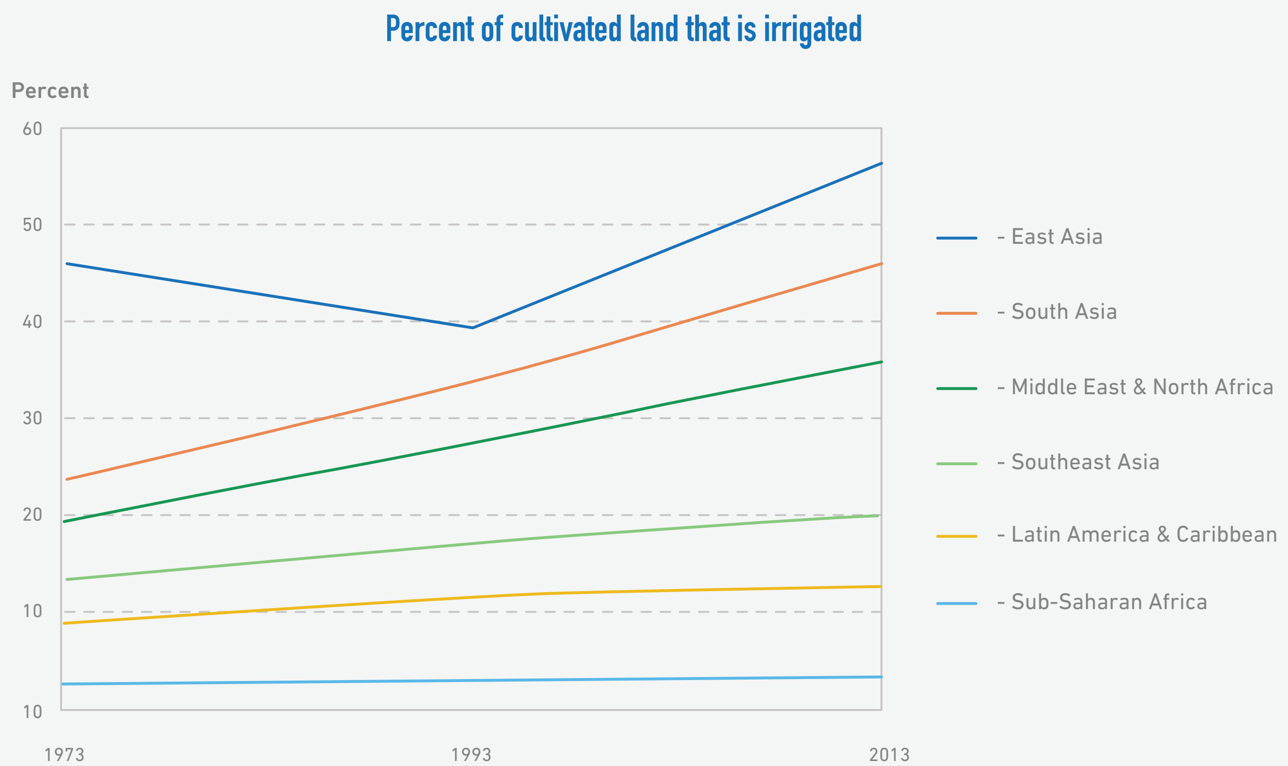


Exhibit 1: The percentage of irrigated cultivated land is increasing in all regions. About half of farmland in South Asia and East Asia is now irrigated.[1] Very little farmland in sub-Saharan Africa is irrigated. (Source: FAO, 2016)

[1]The decrease in East Asian irrigation percentage between 1973 and 1993 was due to a strong increase in non-irrigated cultivated land. The area of irrigated land in East Asia also increased during that period, but at a slower rate.

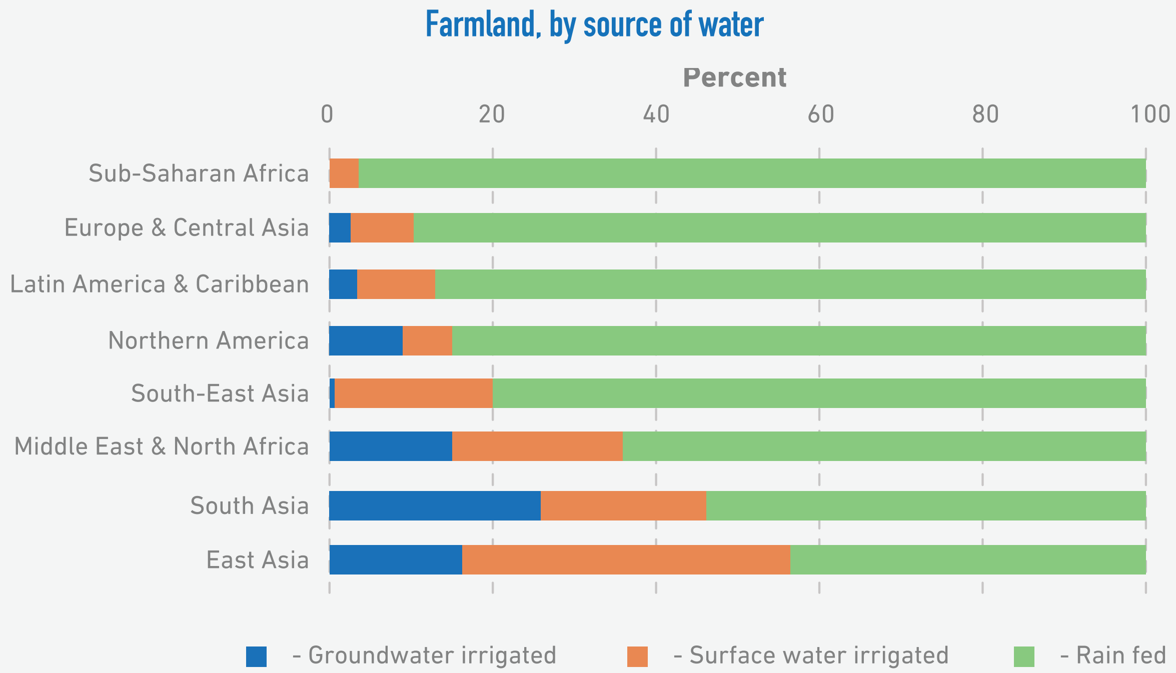


Exhibit 2: Most of the world's agricultural land is rain-fed and not irrigated. When irrigated, either groundwater or surface water is used; groundwater is more commonly used in South Asia and North America, while surface water is more common in other regions. (Source: FAO, 2016)

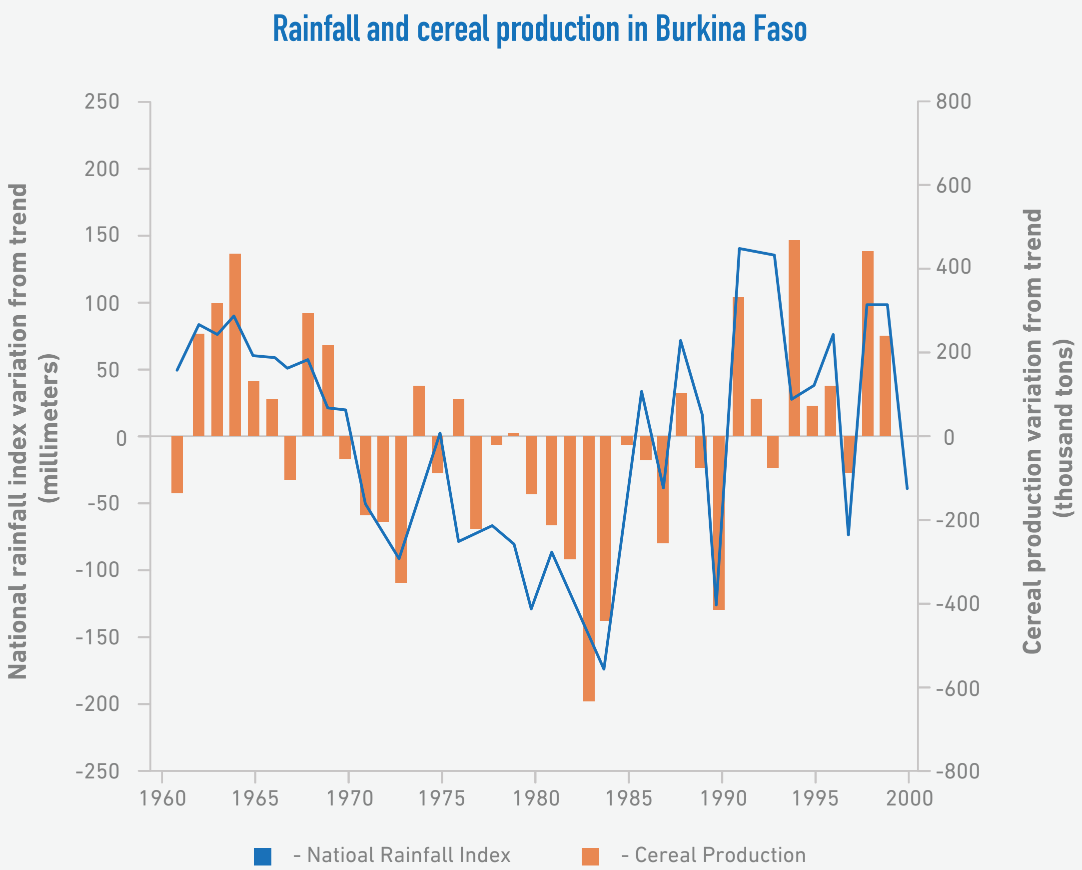


Exhibit 3: Cereal production in Africa is closely linked to rainfall, as shown in this study of Burkina Faso (Faurès, et al., 2007).

It is important to note that South Asia and sub-Saharan Africa face different challenges with regard to irrigation. Much of south and central Asia[2] is struggling with major long-term physical water scarcity, which is strongly exacerbated by water withdrawals for irrigation (illustrated in **Exhibit 4**, and described in detail above in the chapter on Water Security).

Farmers in Sub-Saharan Africa, on the other hand, face little physical water scarcity (see **Exhibit 4**), but instead suffer from inadequate access to available water.

Irrigation water stress

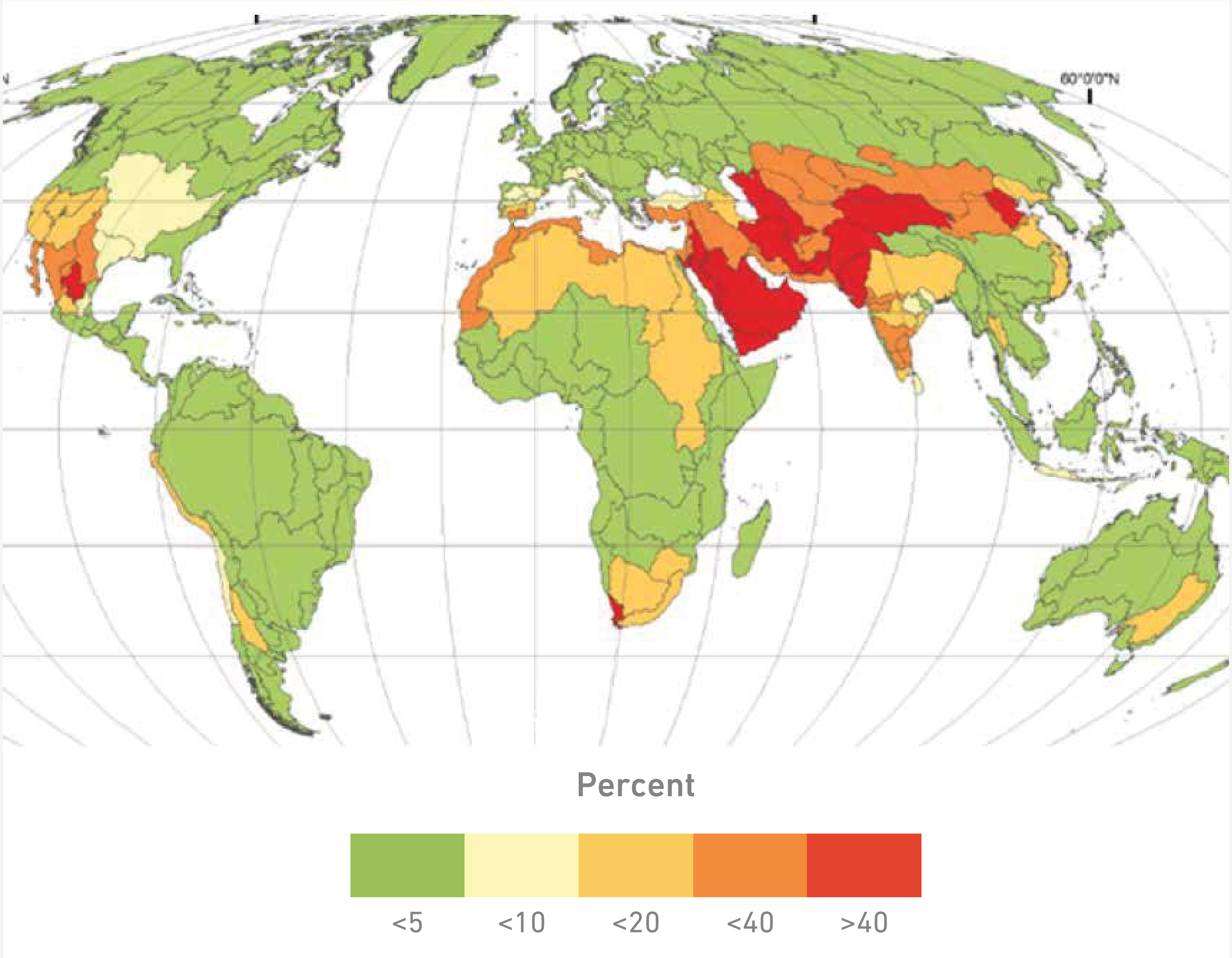


Exhibit 4: The Middle East and Central Asian regions face the highest water stress due to irrigation, while sub-Saharan Africa faces very little irrigation water stress. The map shows the irrigation water stress by major river basins, calculated as the incremental evaporation caused by irrigation as a percentage of total generated groundwater and surface water resources. (Source: Hoogeveen, et al., 2015)

[2]With the exception of Bangladesh and Indian states, such as Orissa and Bihar, which were not deeply involved in the Green Revolution.

2. There is abundant shallow groundwater in sub-Saharan Africa that could be used for irrigation

Exhibit 5 shows hydrological maps of Africa, according to which there is abundant shallow groundwater (at a depth of 7 meters or above) through much of sub-Saharan Africa (MacDonald, et al., 2012).

In Ethiopia, for example, it is estimated that roughly 1.9 million hectares of arable land can be irrigated using household-level irrigation systems, which is five times the total area currently irrigated (ATA, 2013). Despite the availability of groundwater, most African smallholder farmers do not have the economic wherewithal to access the water because pumps and other irrigation equipment are too expensive. As such, sub-Saharan Africa is considered to be a region of economic water scarcity (FAO, 2012).

Groundwater in Africa

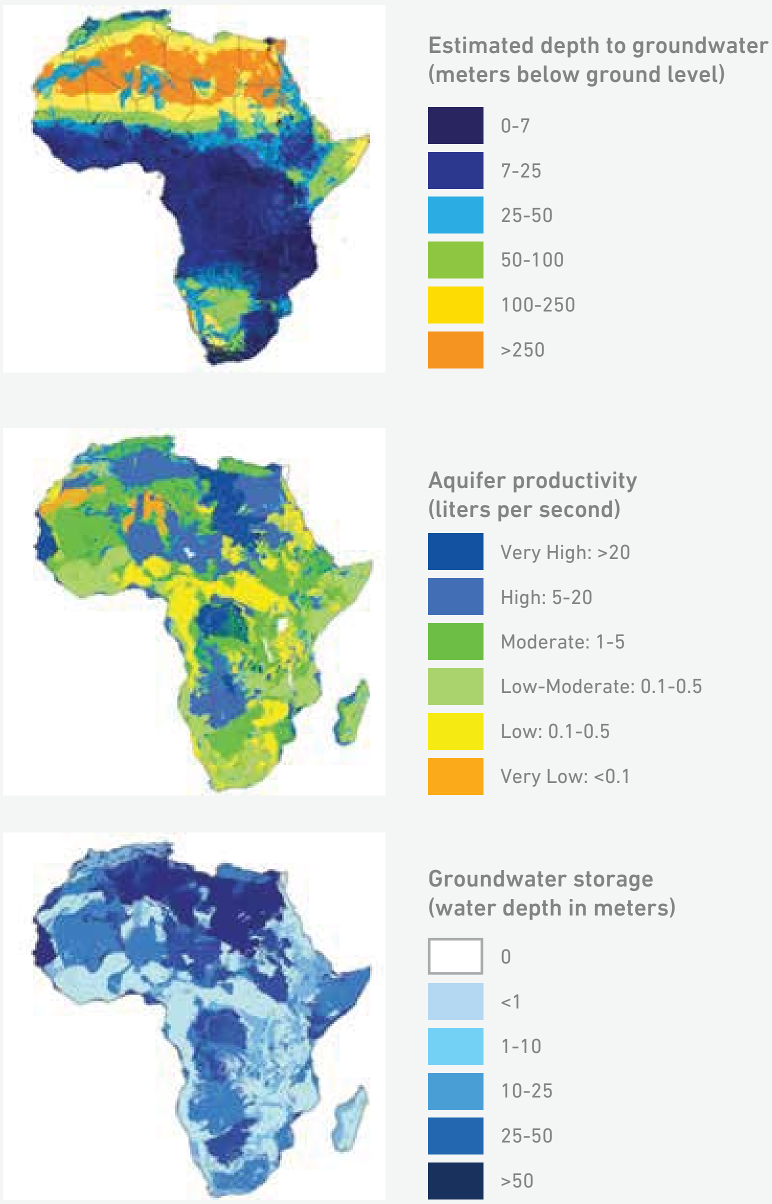


Exhibit 5: Groundwater is available at relatively shallow depths throughout much of sub-Saharan Africa (top). The aquifers vary widely in terms of productivity (middle) and storage volume (bottom). (Source: MacDonald, et al., 2012)

Economic water scarcity for agricultural irrigation is most common in Sub-Saharan Africa, among communities using low-yielding and highly-variable subsistence rain-fed farming methods, despite abundant shallow groundwater. The lack of irrigation is a critical constraint to increasing agricultural productivity for smallholder farmers in sub-Saharan Africa. With proper irrigation, farmers can increase their crop yields and make them more consistent. They can also diversify their crop portfolio toward higher income crops and increase the total number of harvests in a given year.

Generally, there is a lack of demand for irrigation among smallholder farmers in sub-Saharan Africa, where only 3.4 percent of farmland is irrigated. Irrigation is a relatively new practice in much of sub-Saharan Africa, and few farmers have witnessed the tangible economic benefits they can derive from irrigation.

Most farmers in the region are subsistence farmers, and are understandably wary of investing their scarce resources into expensive, and seemingly unproven, irrigation systems. As a result, they have been less willing to change traditional practices and still depend on rainfall as the primary source water for their crops.

Interventions in the water sector have varying opportunities to alleviate economic water scarcity among farmers, depending on climate, crops, geology and existing level of economic development. Within Africa, the greatest opportunities are in semi-arid regions where potential agricultural production is relatively high, and where water is sufficient in absolute physical terms but is a limiting factor because of seasonal and interannual variability and lack of water control (see **Exhibit 6**). These regions are priority areas for expanding food production through interventions in irrigation, rain-fed agriculture, rainfall harvesting and conservation of soil moisture.

Water access and poverty reduction

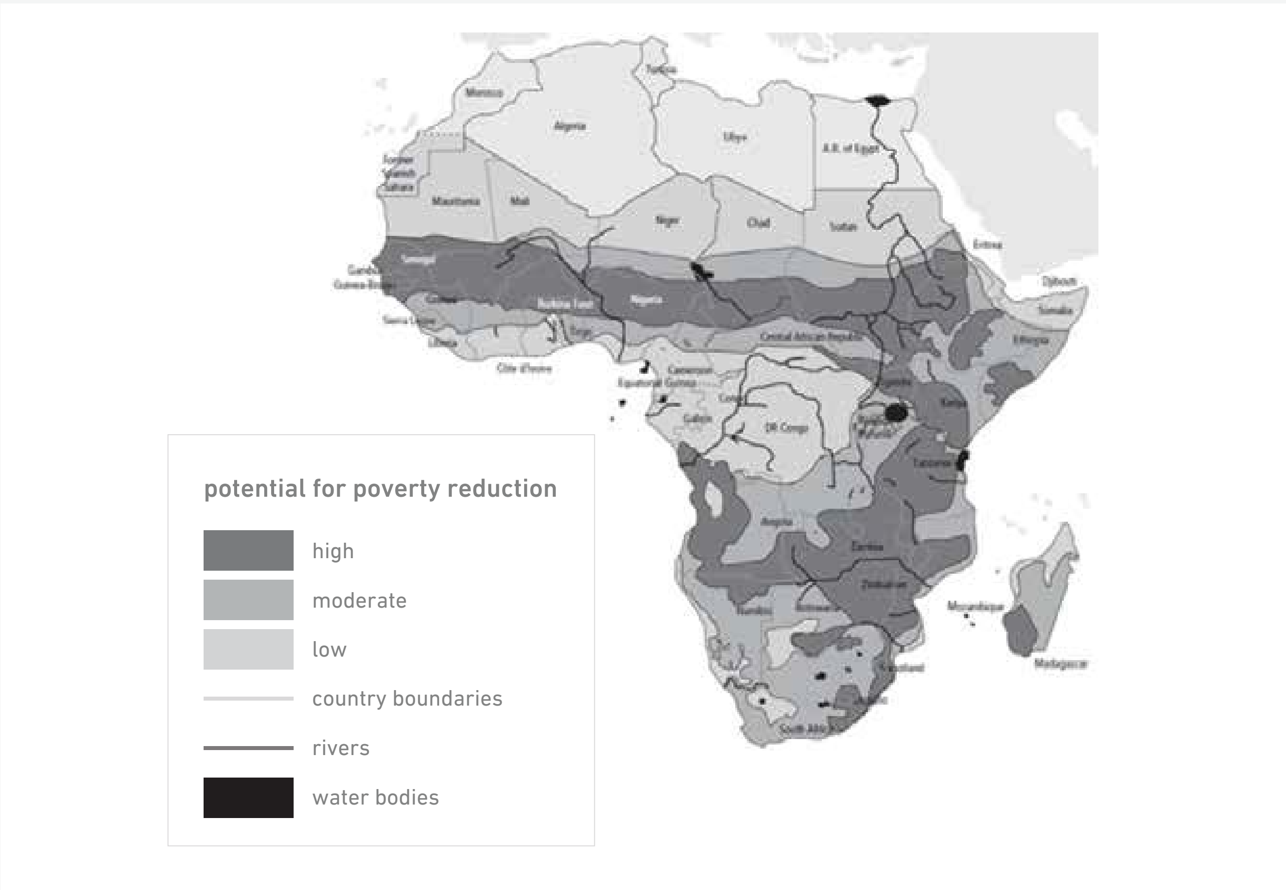


Exhibit 6: Water sector interventions have the greatest opportunity for poverty reduction in semi-arid regions of Africa that have high agricultural potential but production is limited due to significant seasonal and interannual variability in water supply. (Source: FAO, 2008)

3. There are many ways to drill a well—most, however, are too expensive for smallholder farmers

Groundwater well drilling played a major role in the Green Revolution and is an important part of water supply development in South Asia. Many millions of borewells have been drilled in South Asia since the 1960s, and strong local expertise has been developed in siting and drilling wells, as well as in producing and maintaining drilling equipment.

This expertise is currently lacking in most parts of sub-Saharan Africa, as well as some parts of South Asia not affected by the Green Revolution. A variety of drilling technologies are available, depending on soil characteristics and required depth (see **Table 1**).

Geological conditions		Percussion drilling	Hand-auger drilling	Jetting	Sludging	Rotary percussion drilling	Rotary drilling with flush	Air lift reverse circulation
Gravel	Unconsolidated formations	✓ ?	✗	✗		✓ ?	✗	✓
Sand		✓ ?	✓	✓	✓	✓ ?	✓	✓
Silt		✓ ?	✓	✓	✓	✓ ?	✓	✓
Clay		✓ slow	✓	?	✓	✓ slow	✓	✓
Sand with pebbles or boulders		✓ ?	✗	✗	✗	✓ ?	✗	?
Shale	Low to medium -strength formations	✓	✗	✗	✗	✓ slow	✓	✗
Sandstone		✓	✗	✗	✗	✓	✓	✗
Limestone	Medium to high-strength formations	✓ slow	✗	✗	✗	✓	✓ slow	✗
Igneous (granite, basalt)		✓ slow	✗	✗	✗	✓	✗	✗
Metamorphic (slate, gneiss)		✓ v slow	✗	✗	✗	✓	✗	✗
Rocks with fractures or voids		✓	✗	✗	✗	✓	?	✗
Above water table		✓	✓	?	✗	✓	✓	✓
Below water table		✓	✗	✓	✓	✓	✓	✓

✓ - Suitable drilling method ✓ ? - Danger of hole collapsing ? - Possible problems ✗ - Inappropriate method of drilling

Table 1: A range of well-drilling technologies has been developed to create borewells in different geological conditions. (Source: adapted from WEDC, 1994)

The difficulty and cost of digging wells is a direct function of the depth of the water table.

- When groundwater is available at depth less than 4 meters, manual digging or drilling is adequate. Shallow hand-dug wells are inexpensive, with the primary cost being a farmer's time.
- When water is between 4 and 7 meters deep, hand-dug wells can still be used but require a robust lining of brick, concrete or other material. Human-powered drills, especially in soft soils, could be utilized to make shallow borewells. In Kenya, drilling a 7-meter well in soft soils costs about $300 to $400 (Kickstart, 2013).
- For water tables of 7 to 20 meters, wells become more expensive and the risk of hitting rock increases as the well goes deeper. More sophisticated equipment like motorized percussion drills are often used. Borewells of this depth cost roughly $1,000 in Kenya.
- Deeper wells much greater than 20 meters are typically drilled using truck-mounted mechanized drilling machines. Such wells can, at times, cost more than $10,000. Innovative semi-mechanized techniques could reduce the cost of drilling deeper wells.

Numerous manual drilling techniques have also been developed, which can produce borewells with less cost, and in locations that would be inaccessible to mechanical drilling rigs (see **Exhibit 7**).

These manual techniques often involve community participation as drilling labor. Manual techniques are, however, typically slow and limited in the geological strata they can drill.

Manual well drilling techniques

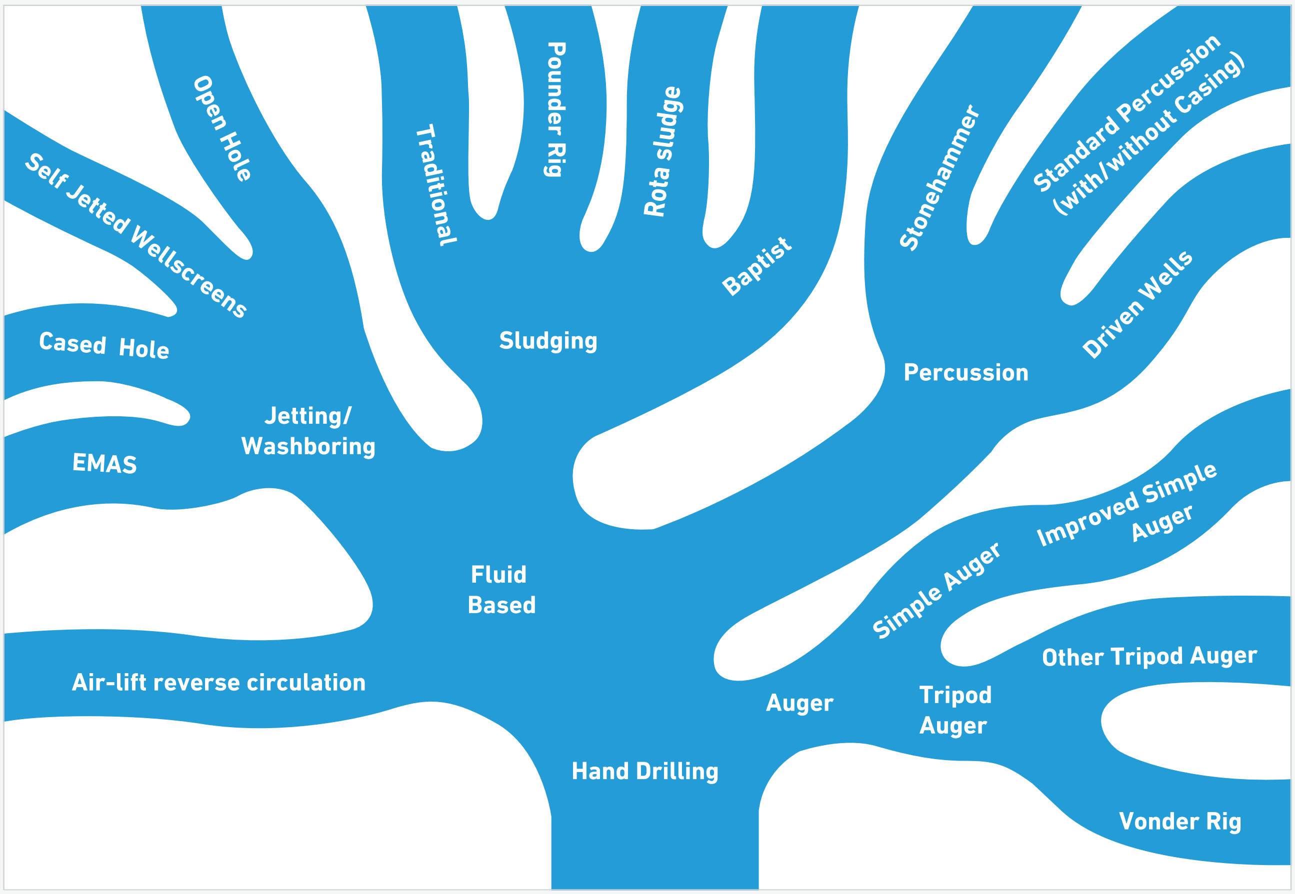


Exhibit 7: Numerous techniques have been developed for manual well drilling. (Source: adapted from RWSN, 2009)

Mechanized drilling of deeper wells is typically unaffordable for subsistence farmers. This kind of drilling is typically performed with portable diesel-powered rigs, such as percussion and rotary percussion methods.

Powered mechanical rigs are cost more than $100,000 and have limited mobility to reach remote areas. They can effectively and relatively quickly drill through most geological features. The cost of drilling is largely driven by capital equipment, fuel and labor.

A case study in Ethiopia analyzed a 150-meter deep borewell (Rural Water Supply Network, 2006) costing $18,000 (**Exhibit 8**), and found that the cost per meter is roughly $120, with about 75 percent of this cost being expense for capital equipment, fuel, and labor.

High competition in emerging economies like India has historically pushed down the overall costs of drilling a bore. Such competition does not yet exist in Africa, hence the cost of equipment is generally higher.

Cost per meter of a 150-meter borehole in Ethiopia

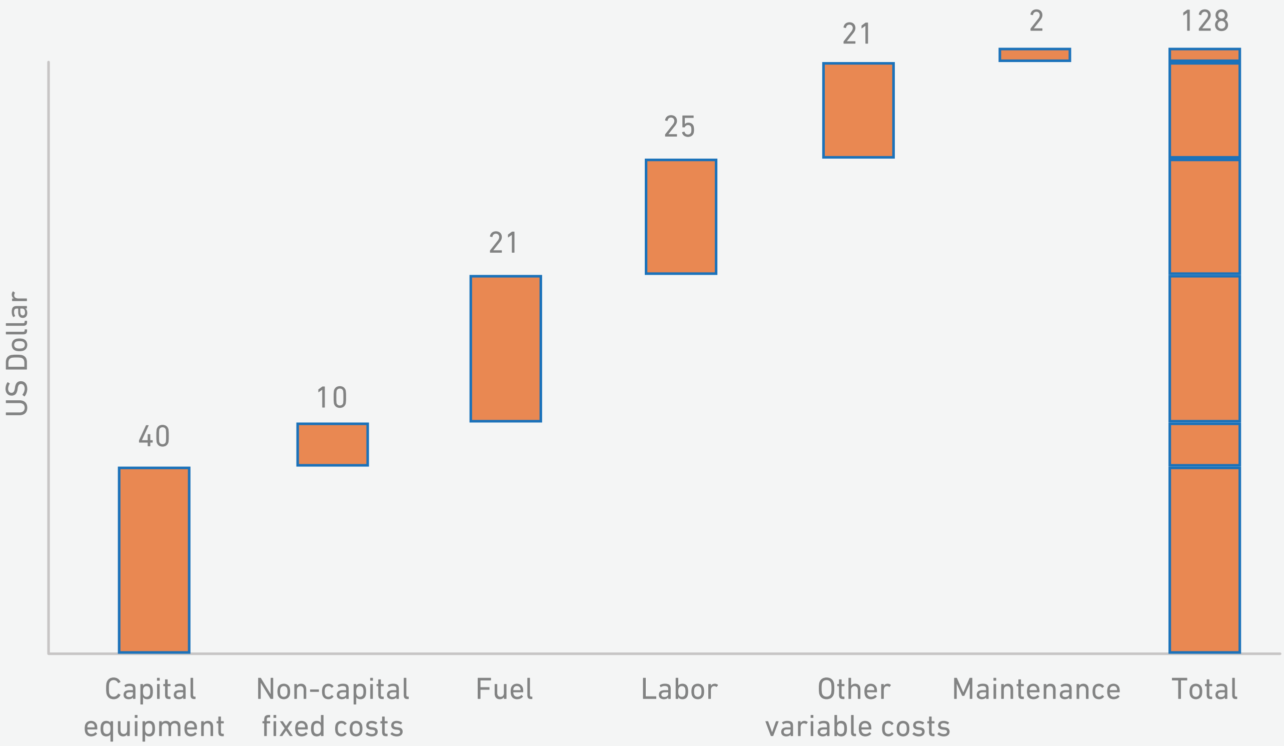


Exhibit 8: Mechanized drilling of a 150-meter borewell costs roughly $120 per meter. About 75 percent of this is expense for capital equipment, fuel and labor. (Source: RWSN, 2006)

Most current well drilling technologies suffer from high cost, limited portability, slow drilling rate, or limited geologic suitability. To expand groundwater opportunities to rural populations facing economic water scarcity, a drilling technology is needed that combines the speed and capability of powered equipment with the portability and low cost of manual techniques.

Such a technology like the innovative air-lift reverse circulation drill recently introduced in India by ITT, could enable more accessible borewells in regions suffering from economic water scarcity, such as sub-Saharan Africa and northeastern India (**Exhibit 9**).

Exhibit 9: The air-lift reverse circulation drill is an example of a drilling technology that combines hand-operated portability with mechanized productivity. (Photo source: Sai Madhavi Antharam)

4. Water pumps are expensive to buy and operate

There is a broad range of water pumping technology, which can be categorized in various ways. One important distinction is based on pumping depth: shallow or deep. The divide occurs at a depth of about 10 meters, which is the longest column of water that can be drawn up a pipe. Shallow pumps are located at the surface and pull water up from the well. Beyond 10 meters, deep well pumps must be used. These pumps are inserted into a well and push the water up to the surface.

Some form of power must be transferred from the surface down to operate the pump. This transfer takes the form of reciprocating metal rods in most handpumps, rotating shafts in line shaft pumps and electrical current in submersible electric pumps.

Another important pump distinction is based on the source of motive power, whether the pump is driven by human muscles or some external energy source like electricity or diesel. Manual-powered pumps are commonly used to lift water from boreholes and shallow wells for household use in rural areas. Technologies for shallow and deep handpumps were significantly advanced during the International Drinking Water Decade, from 1981 to 1990.

Robust community-scale pumps, such as the India Mark III and the Afridev were designed and widely deployed, with attention not only to technical efficiency but also to user ergonomics and practical maintenance. While marginal improvements may be made to handpump technology, no radical innovations are expected. Rather, water supply could be improved by increasing coverage and ensuring timely maintenance and repairs.

Another advancement in manual pumping is the treadle pump, developed in Bangladesh during the 1970s and 1980s. This low-cost, shallow pump is actuated by strong leg muscles and pumps sufficient water for irrigating smallholder farms. Treadle suction pumps that cost between $30 and $150 can draw water from up to a depth of 7 meters and irrigate 0.25 hectares per 4 hours of labor (Kickstart, 2013; ATA, 2013). These pumps are easy to service as the entire pumping mechanism is above the surface.

In recent years treadle pumps have achieved some adoption in a few regions: IDE has sold 1.4 million treadle pumps in South Asia since 1985 and Kickstart sells about 25,000 pumps each year in East Africa. A portion of the Kickstart pumps are bought by NGOs, who then handle distribution to farmers (Kickstart, 2013; ATA, 2013). Despite some success, treadle pumps are still relatively expensive for smallholder farmers and labor-intensive, especially for women.

Most irrigation pumps are powered by an external energy source, usually grid electricity or diesel fuel. Electrical pump sets are common in much of India, while diesel-powered pump sets are more common in Pakistan, Bangladesh and eastern India (see **Exhibit 10**).

A study of efficiency of electrical pump sets in Haryana found an average efficiency of 24 percent (World Bank, 2001), while other studies of South Asia suggest average pump efficiencies of about 30 percent (Singh, 2009; Kaur, et al., 2016). These efficiency levels are much lower than typical pump set efficiencies of at least 50 percent in industrialized countries, and well below the practical efficiency limit of about 85 percent.

One can increase efficiencies by matching the size of pumps and motors to their tasks, as most pump sets in South Asia are larger than they need to be. Renovation of existing pump sets could increase their efficiency by replacing foot valves and suction and delivery piping to reduce frictional losses.

Currently, however, generous subsidies on pumping electricity discourage the adoption of more efficient pumping techniques or more rational irrigation water use (Singh, 2012).

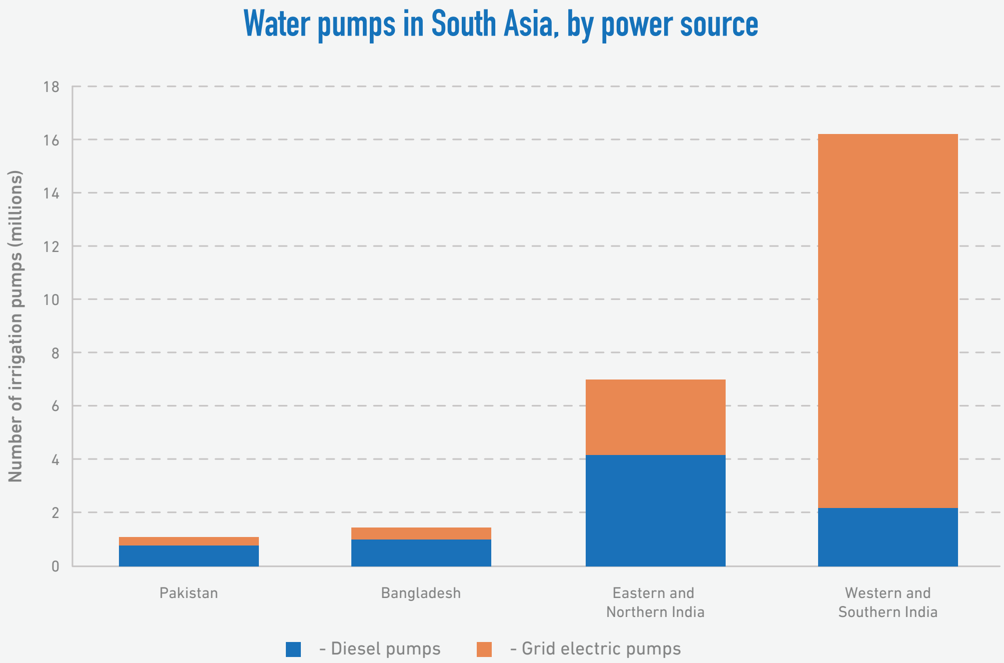


Exhibit 10: In South Asia, diesel powered irrigation pumps are most common in Pakistan, Bangladesh and eastern and northern India.[3] Grid electric powered irrigation pumps are most common in western and southern India.[4] (Source: ITT, 2018)

Diesel powered pumps are more often used where grid electricity is not available, such as parts of sub-Saharan Africa and South Asia. In markets like Kenya, motorized pumps that can irrigate 3 hectares are becoming available for $150 to $200 (Kickstart, 2013; ATA, 2013). However, the cost of diesel—roughly $120 per hectare per year in East Africa—necessary to run these pumps, increases the overall operating cost for farmers.

The pumps have also been prone to damage after a few years of use. The low demand for irrigation systems in sub-Saharan Africa has made it less attractive for the private sector to enter markets with suppliers and after-sale-service providers. There are few private sector suppliers and after-sale-service operators in sub-Saharan Africa. This further weakens the broader ecosystem for irrigation equipment. Without sufficient industry competition, equipment prices in sub-Saharan Africa are higher than in countries like India.

Solar powered electric pump sets, which use photovoltaic (PV) arrays to convert sunlight to electricity that then powers submersible or surface-mounted electric pumps, are under development (GIZ, 2013). The number of PV pumps and the land area they irrigate, is still small globally.

Roughly 15,000 solar irrigation pumps have been installed in India, mainly in the states of Punjab, Rajasthan and Haryana (KPMG, 2014). The technology nevertheless has the potential to significantly scale up in the future, as part of a long-term transition toward renewable energy sources.

[3]Eastern and northern India is here defined as Assam, West Bengal, Bihar, Odisha, Jharkhand, Uttar Pradesh and Uttarakhand states.
[4]Western and southern India is here defined as Andhra Pradesh, Gujarat, Haryana, Karnataka, Kerala, Madhya Pradesh, Maharashtra, Punjab, Rajasthan and Tamil Nadu states.

Direct solar pumping can be quite efficient, as all harvested power is used for pumping, and there is no need for batteries and associated losses. Modern positive displacement pumps have efficiencies of up to 70 percent (GIZ, 2013).

There is also potential for solar pumping to be integrated into village-level solar-powered mini-grid systems. Such integration may bring advantages to the farmer (for example. the high capital cost of PV system is spread across many users) as well as to the mini-grid utility (such as, having flexible and reliable pumping loads).

However, the economic value of pumped irrigation water, expressed as willingness to pay by mini-grid users, is likely to be much less than that of competing uses of limited electrical power by households and industry.

There are significant barriers to the scale-up of PV-powered irrigation pumps including the high upfront cost of PV systems, which are typically 10 times that of conventional pumps (KPMG, 2014). This cost difference is diminishing over time as PV system costs decline.

Other challenges include the present lack of maintenance skills and services, low awareness of PV pumps among farmers and the risk of theft (Bassi, 2018). Furthermore, since there is zero marginal cost for additional water pumping, there is a risk of unrestrained aquifer depletion if the technology is scaled up in the absence of rational water allocation systems.

Despite the very low operating costs of PV irrigation pumps, the high capital cost leads to long economic payback times, unless substantial subsidies (approximately 80 percent) are offered by government (KPMG, 2014).

Economic payback periods for solar pumping systems in South Asia range from zero to 14 years on subsidized prices, and from six to 25 years on non-subsidized prices (FAO, 2018).

Experience in the India states of Bihar (GIZ, 2013) and Rajasthan (Kishore, et al., 2014) shows that wealthier farmers are better positioned to take advantage of subsidies on PV pumps, suggesting that the existing technology is more suitable for economic development of commercial farmers, rather than alleviation of economic water scarcity among poor subsistence farmers.

KEY CHALLENGES

In developed agricultural ecosystems, water is captured either by a dam or deep boreholes. Lift is achieved with large electric or diesel pumps and water is then stored in large reservoirs, and/or distributed directly to the points of usage via extensive canal networks.

Finally, it is applied to the crops via large pivot sprinklers for broad application on large farms, or intricate drip systems for more targeted application. Such irrigation infrastructure and technologies are neither available nor affordable for smallholder African farmers. The following are some of the major hurdles.

1. There is a lack of demand for irrigation among African smallholder farmers

Irrigation is a relatively new practice in much of sub-Saharan Africa, and few farmers have witnessed the tangible economic benefits they can derive from irrigation. Most farmers in the region are subsistence farmers and are understandably wary of investing their already scarce resources into expensive, and seemingly unproven, irrigation systems.

As a result, they have been unwilling to change traditional practices and still depend on rainfall as the primary source water for their crops. While irrigation system costs could theoretically be shared among farmers within a community, such models have not yet shown the ability to scale.

2. Drilling wells is unaffordable for subsistence farmers in sub-Saharan Africa

The cost of drilling is driven by capital equipment, fuel and labor. High competition in emerging economies like India has historically pushed down the overall costs of well drilling. Such competition does not exist in Africa, and hence the cost of equipment is generally higher.

Meanwhile, extreme economic inequity means that the poorest of the poor have very little purchasing power. While the number of extreme poor (defined as living on less than $1.90 per day, based on 2011 purchasing power parity) is decreasing for the world as a whole, it continues to rise in sub-Saharan Africa (**Exhibit 11**). Most potential solutions involve costs (both capital and operational) that are unaffordable for these households not firmly engaged in the market economy.

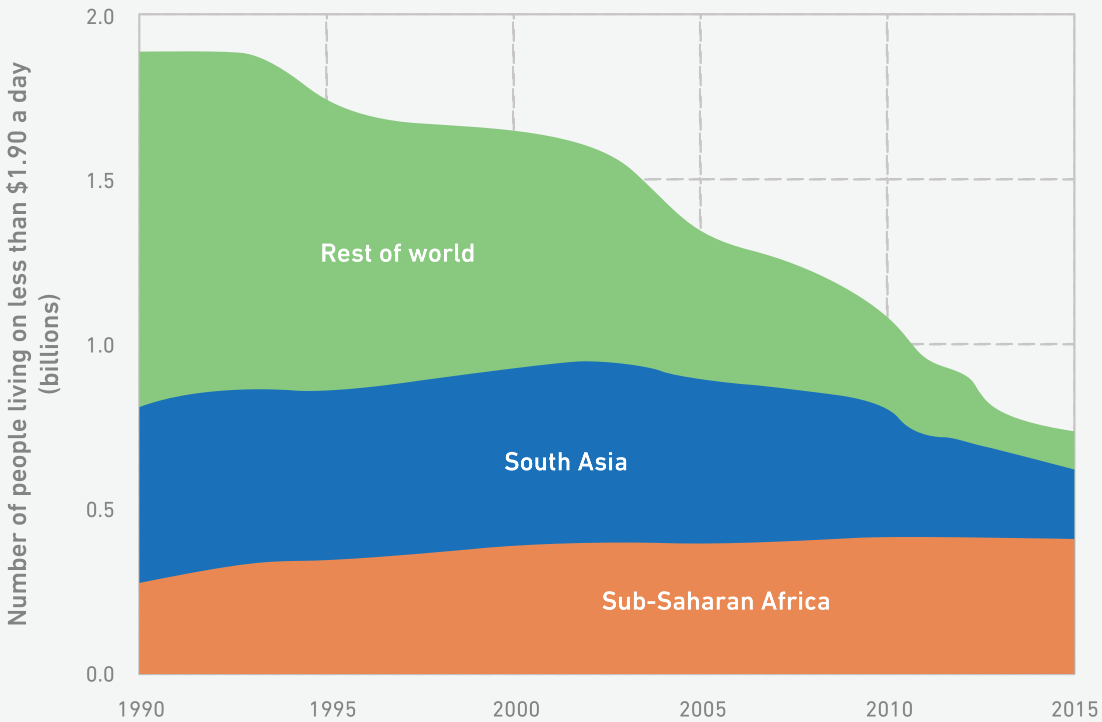


Exhibit 11: The number of extremely poor people who live on less than $1.90 per day (2011 PPP), is decreasing in most regions of the world. In sub-Saharan Africa, however, the absolute number of extremely poor people continues to rise. (Source: World Bank, 2018; data on South Asia for 2015 is provisional)

3. Pumps available on the market today are too expensive for smallholder farmers

Once a well is dug, the type of pump required to lift water varies in cost and functionality, depending on water depth. Treadle suction pumps that cost between $30 and $150 can draw water from up to a depth of 7 meters and can irrigate 0.25 hectares per 4 hours of labor (Kickstart, 2013) (ATA, 2013).

These pumps are easy to service as the entire pumping mechanism is above the surface. In recent years treadle pumps have achieved some adoption in a few regions, which indicates this core technology is feasible. IDE has sold 1.4 million treadle pumps in South Asia since 1985, and Kickstart sells about 25,000 pumps each year in East Africa.

A portion of the Kickstart pumps is bought by NGOs, who then handle distribution to farmers (Kickstart, 2013) (ATA, 2013). Despite some success, treadle pumps are still relatively expensive for smallholder farmers and labor-intensive, especially for women.

Manual rope pulleys that cost around $100 can draw water from up to 18 meters below surface and irrigate roughly 0.1 hectare per 4 hours of labor (ATA, 2013) (Kickstart, 2013). Hand pumps, on the other hand, cost upwards of $500 (McKenzie & Ray, 2009). Like treadle pumps, hand pumps are manual but are more laborious to operate since they use only the arm muscles, not use the stronger leg muscles used by treadle pumps.

The cost of motorized pumps ranges from $100 to $3,000 and depends on the mechanism they use: suction (drawing water up from 7 meters or shallower depths), displacement or pressure (pushing water up from 12 meter depth or more). Motorized pumps can irrigate 3 hectares per hour on average (Kickstart, 2013) (ATA, 2013).

While some types of motorized pumps are now becoming available in markets such as Kenya for as little as $150 to $200, they have been prone to damage after two to three years of use. Moreover, the cost of diesel—roughly $120 per hectare per year in East Africa—necessary to run these pumps, increases the overall operating cost for farmers.

4. There are few methods for storing rainwater for long periods

There are almost no highly efficient structures for holding large volumes of rainwater. Typical storage ponds used to capture and store rainwater tend to have high losses due to evaporation and seepage. These are also costly to construct. As a result, there is little storage of water for anything more than a few weeks or months. So far, structures that can store water efficiently and can be built at a low cost do not exist.

5. There are few private sector suppliers and after-sale-service operators in sub-Saharan Africa

A major challenge with any irrigation system is maintenance. Pumps, in particular, are prone to breakdown. The low demand for irrigation systems has made it unattractive for the private sector to enter markets with suppliers and after-sale-service providers. This further weakens the broader ecosystem for irrigation equipment. Without sufficient industry competition, equipment prices in sub-Saharan Africa are higher than in countries like India.

SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

Making irrigation affordable, desirable and sustainable will require a combination of technologies, along with innovative business models for sales, distribution and maintenance.

A core assumption about the irrigation context in sub-Saharan Africa is that there is an abundant supply of shallow groundwater that can be sustainably tapped without endangering long-term water security.

Under this assumption, there are four potential breakthrough technologies that can drive the adoption of irrigation across sub-Saharan Africa.

Breakthroughs:

1 2 3 4 5 6 7 8 9 10
11 12 13 14 15 16 17 18 19 20
21 22 23 24 25 26 27 28 29 30
31 32 33 34 35 36 37 38 39 40
41 42 43 44 45 46 47 48 49 50

1 A low-cost system for precision application of agricultural inputs, ideally combining water and fertilizer

In some regions like South Asia, the Green Revolution has brought unfortunate consequences including over-exploitation of groundwater resources and over-application of synthetic fertilizers. In other regions like sub-Saharan Africa, the Green Revolution has not arrived and there is under-utilization of groundwater resources and ongoing nutrient mining of soils. There is need for a low-cost, robust, scalable technology to precisely meter and distribute irrigation water and fertilizer to field crops. This would allow farmers to apply the right amounts of water and nutrients (not too much or too little) at the right time to maximize economic returns and reduce nutrient loss. If made affordable, precision application systems for irrigation and fertilizers, calibrated to local crop type and soil conditions, could be a very effective way to increase agricultural yields, while also reducing negative impacts on the environment.

Enabling better management of the timing and formulation of irrigation and fertilization in cropping systems would ensure that water and nutrients are available where and when needed by the plant roots. Crop yields respond very well with initial inputs of fertilizer, but as additional nutrients are supplied the marginal yield increase becomes smaller. Optimal results occur somewhere along that gradient, depending on the cost of fertilizer and seeds, land and selling price of harvested crops. For maximum returns, it is necessary to not just apply the right quantity of fertilizer, but to also apply it at the right time and place for optimal nutrient uptake by the plant. This would also protect watersheds and populations downstream from farm fields, by greatly reducing runoff.

The efficiency of using agricultural inputs, such as fertilizer is low in conventional farming. It is estimated that overall efficiency of applied fertilizers is about 50 percent for nitrogen, less than 10 percent for phosphorus and about 40 percent for potassium. The rest is wasted as runoff. The mismatched timing between availability of nitrogen and crop need for nitrogen is likely the single greatest contributor to excess nitrogen loss in annual cropping systems. Ideally, nutrients should be applied in multiple small doses and when plant demand for them is greatest.

Current State

Development Stage: Engineering

Time to market (years): <3 | 4-6 | 7-10 | 10+ (7-10)

Deployment: Challenging

Associated 50BT Chapters

Food Security | Global Change

SDG Alignment

Impact

Increased Access to Food (# of People): <1M | 10M+ | 100M+ | 1B+ (1B+)

New Income Generated (# of People): <1M | 10M+ | 100M+ | 1B+ (10M+)

Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

In principle, variations of existing programmable irrigation and fertigation systems used in industrialized countries can be adapted to the needs of smallholder farmers. Already, small-scale drip and sprinkler systems—along with other methods for increasing water usage efficiency—are beginning to emerge in markets like India.

Cultivated area under drip irrigation in India has grown from 71 km^2 in 1992, to 2,460 km^2 in 1998, to 18,970 km^2 in 2010, up to 33,700 km^2 in 2015. The cost of such systems will continue to drop as scale of production increases.

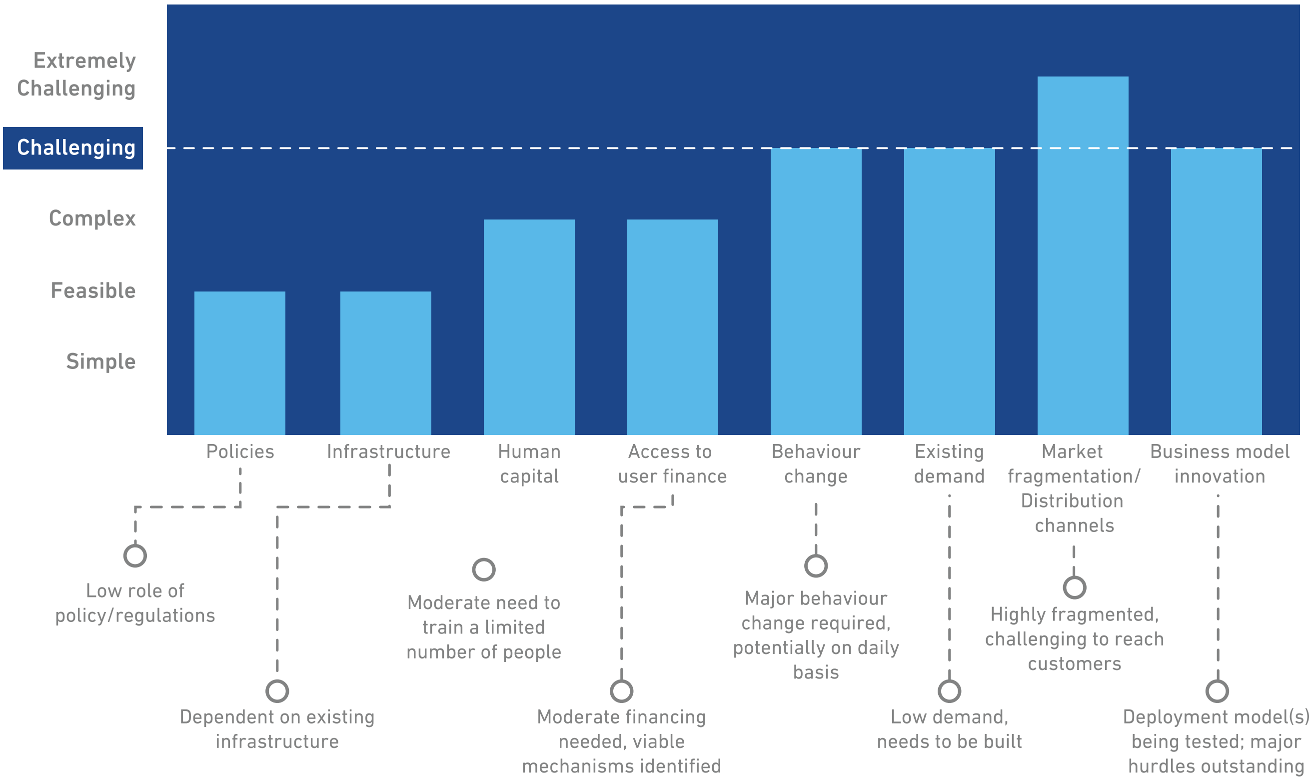
This breakthrough would be strongly leveraged by three other breakthroughs, 5 Low-cost shallow groundwater drilling technologies, 6 Affordable solar-powered irrigation pumps, and 9 Low-cost soil nutrient analysis device.

Overall, such devices would help farmers better predict crop nutrient requirements, better schedule irrigation and fertilizer applications, and avoid over-fertilization and nutrient runoff. If complemented with adjusted crop rotation patterns and additional biotic complexity, it could improve the plant community's ability to take up more of the available nutrients.

However, there is limited evidence to suggest that users—farmers or otherwise—will be interested in spending money on technologies to conserve water when the resource itself is available free of cost. The potential for saving fertilizer can prove to be a positive incentive, although the current demand for fertilizers is very low in sub-Saharan Africa.

It will face some deployment challenges that are common to the African smallholder farmer market, including structural barriers such as a fragmented market of farmers, limited access to finance for potential users, and lack of training to install, use and maintain the technology. The difficulty of deployment in this case would be CHALLENGING.

Breakthrough 1: Difficulty of deployment



2. A very low-cost scalable technique for desalinating brackish water

This breakthrough focuses on developing and enabling systems for very low-cost, high-efficiency desalination of brackish water resources. Households, industries and farms can utilize such systems to provide additional freshwater supplies for water-constrained regions. The introduction of very low-cost desalinated water could enable sustainable irrigation in vast regions of the world that contain brackish groundwater.

Desalination is increasingly used to provide household and industrial water in regions with scarce freshwater but abundant salt water. Most current desalination facilities are located in the Middle East, use seawater as feedwater and are powered by fossil fuels. The city of Chennai in southern Indian gets about a quarter of its municipal water from reverse osmosis seawater desalination plants.

Conventional desalination methods typically use seawater as feed. Seawater desalination technologies based on membranes, such as reverse osmosis, are approaching the thermodynamic limits of efficiency and have limited opportunity for further improvement. It is unlikely that major technology breakthroughs will fundamentally alter the seawater desalination landscape. Additionally, desalinated seawater is too expensive to use as irrigation water for crop production.

In contrast, there are large potential efficiency gains by using brackish water as feed. There are major opportunities for significant reductions in brackish water desalination cost and energy use through innovative electrochemical or other emerging techniques. The minimum theoretical energy requirement for desalination varies with the salinity of the feedwater—less energy is fundamentally needed to desalinate brackish water compared to seawater.

Electromagnetic desalination processes such as electrodialysis (ED) and capacitive deionization (CDI) are limited to low-salinity feedwater, but potentially have much lower cost and energy than pressure or thermal techniques. They offer many advantages when used with brackish feedwater, such as high water recovery and high brine concentrations. They also require little or no feedwater pre-treatment and membrane fouling can be prevented by reversing the electrode polarities.

However, electromagnetic processes only remove ions from the water, leaving organics and colloids in suspension—this is a concern for household water, but less so for irrigation water. Furthermore, the selection and configuration of membranes is currently highly dependent on feedwater characteristics, thus must be adapted to local conditions of feedwater composition and concentration.

Current State

Development Stage: Engineering

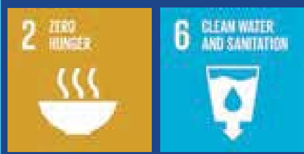
Time to market (years): <3 | 4-6 | 7-10 | 10+

Deployment: Complex

Associated 50BT Chapters

Water Security | Food Security

SDG Alignment



Impact

Increased Access to Food (# of People): <1M | 10M+ | 100M+ | 1B+

New Income Generated (# of People): <1M | 10M+ | 100M+ | 1B+

Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

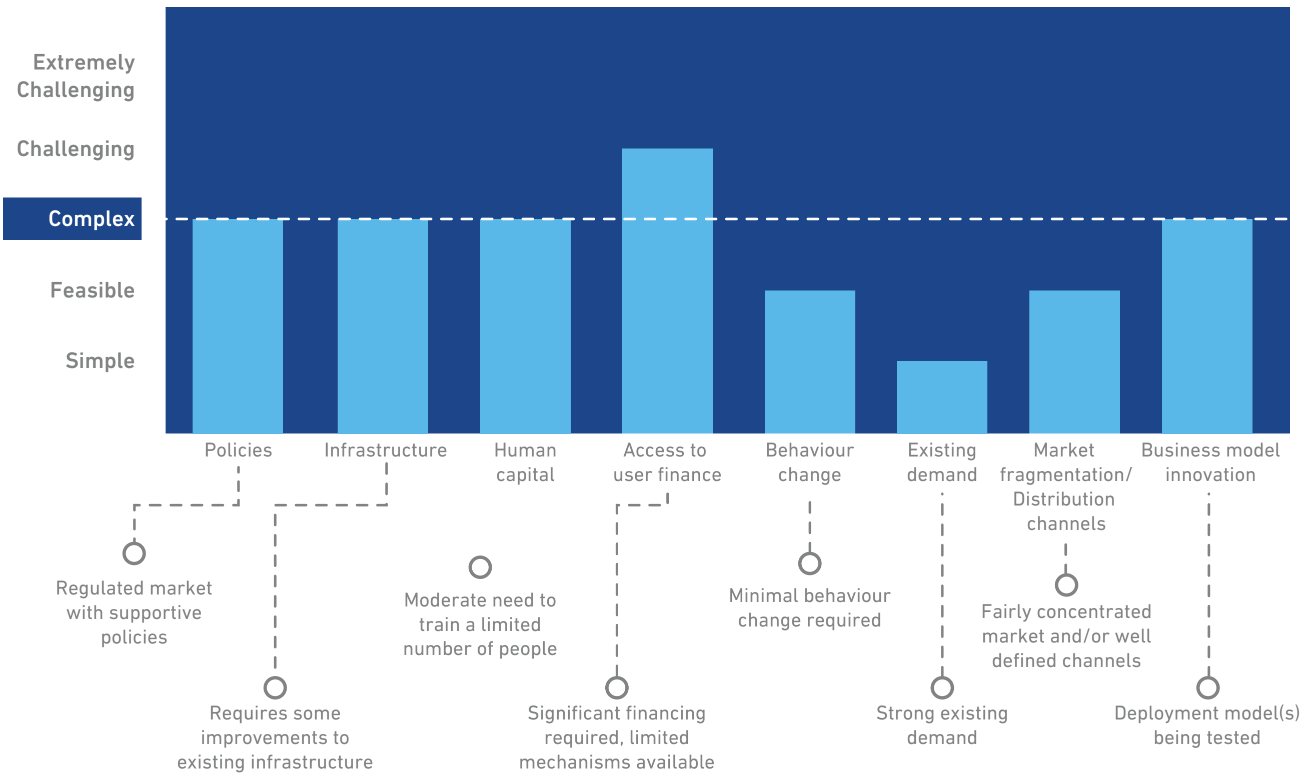
Concerted R&D efforts can overcome current obstacles to enable a major source of low-cost freshwater in regions with brackish resources. The appropriate unit scale of desalination facilities may vary depending on the application (such as household, irrigated farm, urban water utility). The salinity of the product water may also vary depending on the purity requirements of the end uses.

Costs can be further reduced by matching the salinity of the product water to the salinity thresholds for different uses; in other words, removing only enough salt to make the water viable for its intended use. Ideally, facilities will be powered by onsite renewable energy sources, such as photovoltaic solar arrays, to provide reliable and sustainable operation. Developing appropriate business models will be essential to ensure economic sustainability and continuing impact.

End-uses for the desalinated water will include drinking, cooking, washing and other domestic uses and industrial water uses. Efficient techniques for large-scale desalination of brackish water resources will also enable the use of desalinated water for production of agricultural crops using efficient irrigation techniques.

Substantial research and development work is required and we expect that it will take seven to ten years for this breakthrough to be ready. Deployment challenges include access to finance and policies regarding location and discharge streams. We rate the difficulty of deployment, COMPLEX.

Breakthrough 2: Difficulty of deployment



6 Low cost drilling technologies for shallow groundwater, which reduce the cost to less than $100 per farmer

Less than 5 percent of farmland in sub-Saharan Africa is irrigated, despite the presence of extensive, renewable, shallow (less than 10 meters) groundwater. An important reason for this lack of irrigation is the relatively high cost of well drilling in the region.

Mechanized drilling of wells is typically unaffordable for subsistence farmers. This type of drilling is typically conducted with portable diesel-powered rigs, such as percussion and rotary percussion methods. Powered mechanical rigs are expensive (more than $100,000) and have limited mobility to reach remote areas. High competition in emerging economies like India has historically pushed down the overall costs of drilling a well. Such competition does not yet exist in Africa, hence the cost of well drilling is generally higher.

Manual drilling techniques have been developed that can produce borewells more economically and in locations that don't have access to mechanical drilling rigs. These manual techniques often involve community participation as drilling labor. Manual techniques are, however, typically slow and limited in the geological strata they can drill.

Most current well drilling technologies suffer from high cost, limited portability, slow drilling rate or limited geologic suitability. To expand groundwater opportunities to rural populations facing economic water scarcity, a drilling technology is needed that combines the speed and capability of powered equipment with the portability and low cost of manual techniques. It should be comprised of lightweight, easily transportable components, yet powered by a portable mechanized source.

An affordable method to reach shallow groundwater will enable widespread irrigation in sub-Saharan Africa, providing smallholder farmers with increased crop yields, the possibility of cultivation during dry seasons and droughts and the opportunity to grow high value, high nutrition crops.

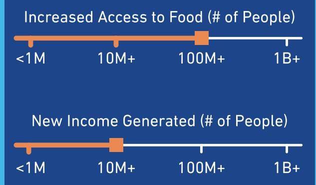
While shallow groundwater resources are rechargeable by rain and thus sustainable under moderate use, there is a risk of water over-extraction and aquifer depletion. This has occurred, for example, in parts of South Asia that practice intensive Green Revolution agriculture. Any low-cost drilling solution will have to be accompanied by some form of community-level metering and monitoring to ensure sustainability of available water.

Current State

Associated 50BT Chapters

SDG Alignment

Impact



Commercial Attractiveness

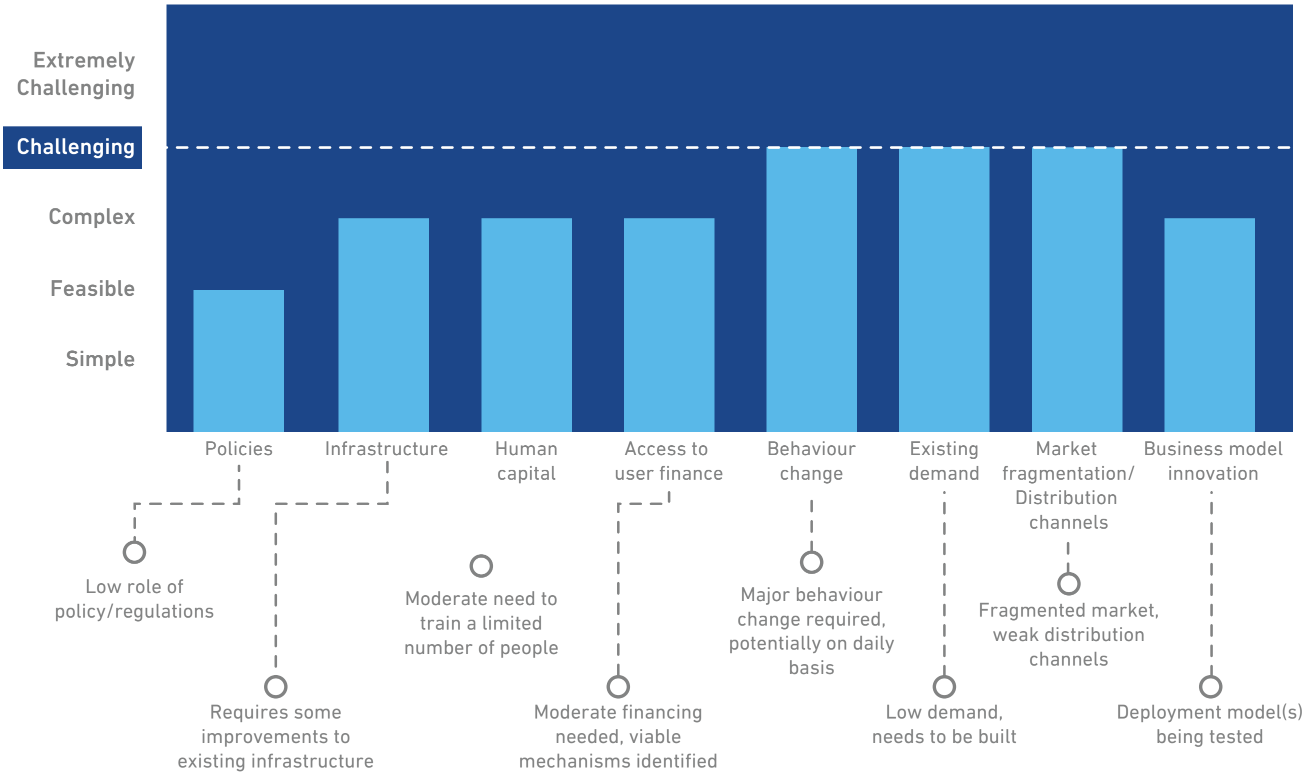
- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

Currently, there is extremely low demand among African smallholder farmers for irrigation. Depending on the cost of the technology that is developed, farmers may require financing to pay for construction and usage of wells (even for community-level wells).

Such a technology will also have to overcome many of the typical challenges faced by products and services in this market: fragmentation and the lack of an ecosystem of suppliers and after-sale-service providers.

However, based on the agricultural development experience in South Asia and what can be seen in areas of Africa that have access to irrigation services, there is reason to believe that appreciation of the benefits of irrigation can become apparent within a short period of time. Hence, we believe such a technology is four to six years from becoming market-ready. Overall, we believe deployment will be CHALLENGING.

Breakthrough 6: Difficulty of deployment



7 Affordable (less than $50), lightweight, energy-efficient, solar-powered irrigation pumps

Irrigation is one of the most significant levers for increasing on-farm yield. However, currently available manual irrigation pumps (for example, treadle pumps) are quite strenuous to use and often not suited to the needs of women farmers. Motorized pumps available on the market are even more expensive, and the cost hurdle is compounded by the recurring cost of diesel fuel. In remote areas, the paucity of distribution networks for diesel is an additional constraint.

A solar powered pump that costs under $50, and pumps enough water for a typical smallholder farm, could dramatically increase access to irrigation. Direct-drive photovoltaic solar pumping can be quite efficient, as all harvested power is used for pumping and there is no need for batteries and associated losses.

Modern positive displacement pumps have efficiencies of up to 70 percent. Nevertheless, a significant barrier to the scale-up of PV-powered irrigation pumps is the high upfront cost of PV systems, which are typically 10 times that of conventional pumps. Despite the very low operating costs of solar irrigation pumps, the high capital cost leads to untenably-long economic payback times. Strongly reducing cost, while ensuring reliable service, is thus essential.

Considering the effort being dedicated to this problem and the pace with which this market is developing, it is likely that low-cost market-ready pumps will become available within the next two to three years. A number of organizations are developing solar pumps, a small number of which are already being used in India and other developing regions.

The biggest hurdle appears to be throughput: the more the volume of water pumped, the larger and more expensive the solar panel needs to be.

Current State

Development Stage: Engineering

Time to market (years)

<5 5-7 7-10 10+

Deployment: Complex

Associated 50BT Chapters

Water Security

Food Security

SDG Alignment

2 ZERO HUNGER

6 CLEAN WATER AND SANITATION

Impact

Increased Access to Food (# of People)

<1M 10M+ 100M+ 1B+

New Income Generated (# of People)

<1M 10M+ 100M+ 1B+

Commercial Attractiveness

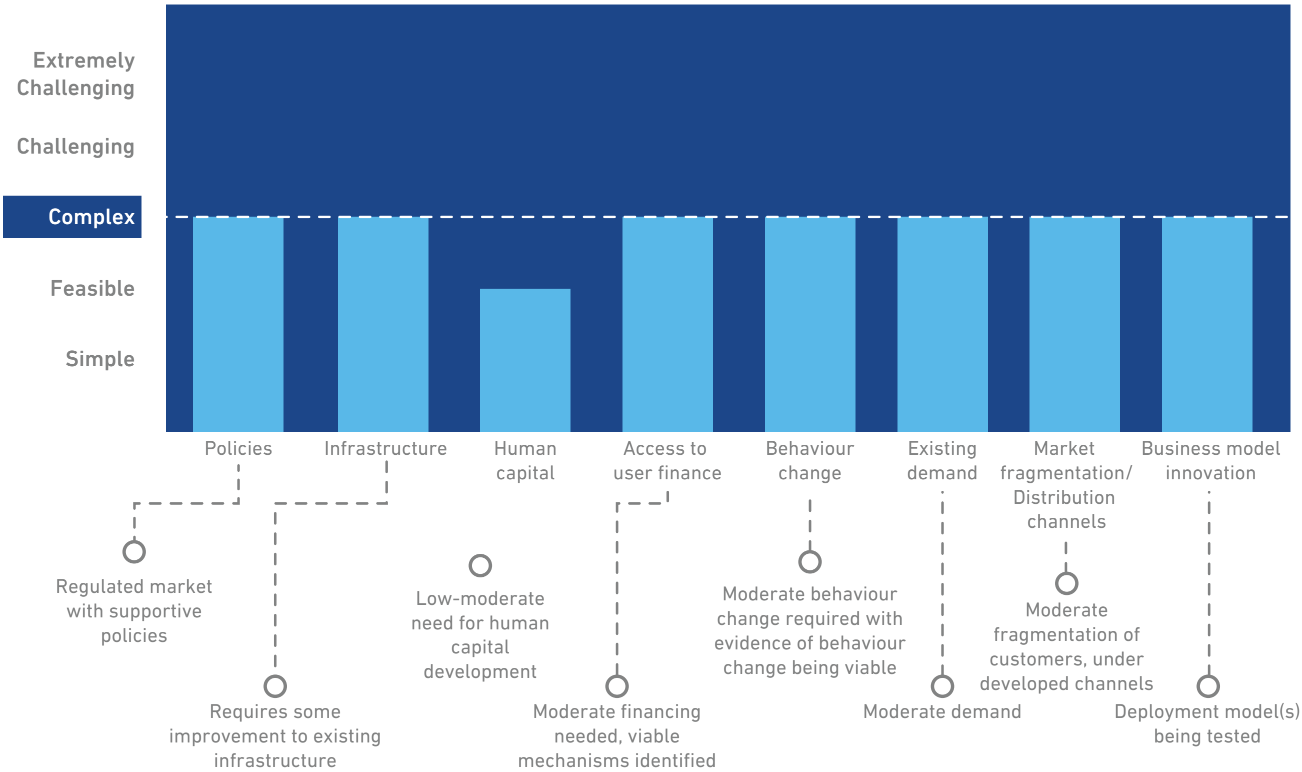
- Attractive for industrialized markets (high profits)
- **Attractive for emerging markets (lower profits)**
- Emerging markets potential; requires derisking (sustainable)
- Non-commercial (unprofitable)

However, even if solar pumps become available, there are a number of deployment hurdles: the majority of African farmers are still extremely poor, live in remote areas and are accustomed to rain-fed farming.

Considerable effort will be required for creating demand and providing financing and training. A critical lesson from the decades of agricultural development in South Asia is that water can easily be overused and groundwater easily depleted.

Since there is zero marginal cost for solar water pumping, there is a risk of unrestrained aquifer depletion if the technology is scaled up in the absence of rational water allocation systems. Enforcing any such system will be very challenging. Hence, we believe that deployment will be COMPLEX.

Breakthrough 7: Difficulty of deployment



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SOIL HEALTH AND PLANT NUTRIENTS

INTRODUCTION

Soil fertility management has been among the most significant drivers of increases in food production over the past few decades.

Whereas the pace of natural plant growth depends on whatever underlying nutrients the soil has to offer, the growth and harvest cycles in agriculture require that the soil be regularly enriched, to compensated for nutrients exported in the harvested biomass. A variety of nutrients are needed for crop growth, including nitrogen, phosphorus, potassium and a host of micronutrients needed in small quantities. Nutrients are applied to farmland by fertilization, either by biological pathways such as manure, or chemical pathways such as synthetic fertilizers.

Agricultural yields in Africa have historically been too low to ensure broad food security, and soil nutrients are being mined and not replenished in many areas. Beyond overall agricultural yield, another outcome of low rates of fertilization in some countries is deforestation. Soil loses nutrient content with every crop cycle and farmers in Africa have had to continuously extensify to more fertile land to maintain their total agricultural output.

Unlike South Asia, there is very low demand for fertilizers among African smallholder farmers. This is compounded by the fact that there are no fertilizer factories in sub-Saharan Africa (outside of South Africa). Fertilizer has to be imported from other countries and the cost of distribution can exceed the cost of production, driving up end user costs. Almost all of the fertilizer used today is produced with methods that are extremely capital-intensive, location-sensitive and environmentally damaging. While phosphorus and potassium are usually mined, nitrogen is extracted from the air using the Haber-Bosch process.

Factories that produce fertilizers using this process cost hundreds of millions of dollars and need to be located near sources of natural gas.

There is also a flip side to fertilizer use. Where fertilizer is easily available, overuse causes significant damage to the environment. Excess fertilizer finds its way into waterways through runoffs and leads to excessive growth of algae and cyanobacteria, in turn, creating marine dead zones where fish and other animals cannot survive.

There is a long tradition and continuing interest to convert biological residues from plants, animals and humans into fertilizer, but such approaches face a number of problems: nutrient content and release can be highly variable; human waste contains many harmful pathogens and improper handling can cause major health problems; and fertilizer made from human waste is unlikely to be easily accepted by the market.

We believe three technological breakthroughs can address these problems.

- Breakthrough 1. A low-cost system for precision application of agricultural inputs, ideally combining water and fertilizer
- Breakthrough 8. New processes of nitrogen fixation that are less capital intensive than current (Haber-Bosch) processes
- Breakthrough 9. A low-cost, point-of-use device to evaluate soil nutrient content and recommend tailored use of fertilizers for specific crops

Synthetic fertilizers—those made in factories using chemical processes—have been one of the most significant contributors to global food production over the last 50 years. By some measures, synthetic nitrogen fertilizer enables food production for 40 percent of the world's population (Smil, 2002). Since the widespread adoption of intensive agricultural processes in the 1960s, global production of cereals and the global consumption of nitrogen, potassium and phosphorus (the three major ingredients in fertilizer) have tripled. Conversely, where fertilizers have been available, they have often been overused, leading to runoff into waterways and significant environmental damage. Indeed, the process of producing fertilizer, itself, leaves a substantial environmental footprint.

CORE FACTS AND ANALYSIS

1. Soil health and plant nutrient availability are essential for sustainable agriculture

Soil is the foundation in which farming activities are conducted. Healthy soil is a mixture of organic and inorganic materials containing a variety of micro-organisms and macro-organisms (**Exhibit 1**).

Effective long-term agricultural production requires an understanding and appreciation of the many physical, chemical and biological processes continually occurring in farm soils (Amundson, et al., 2015).

The soil food web

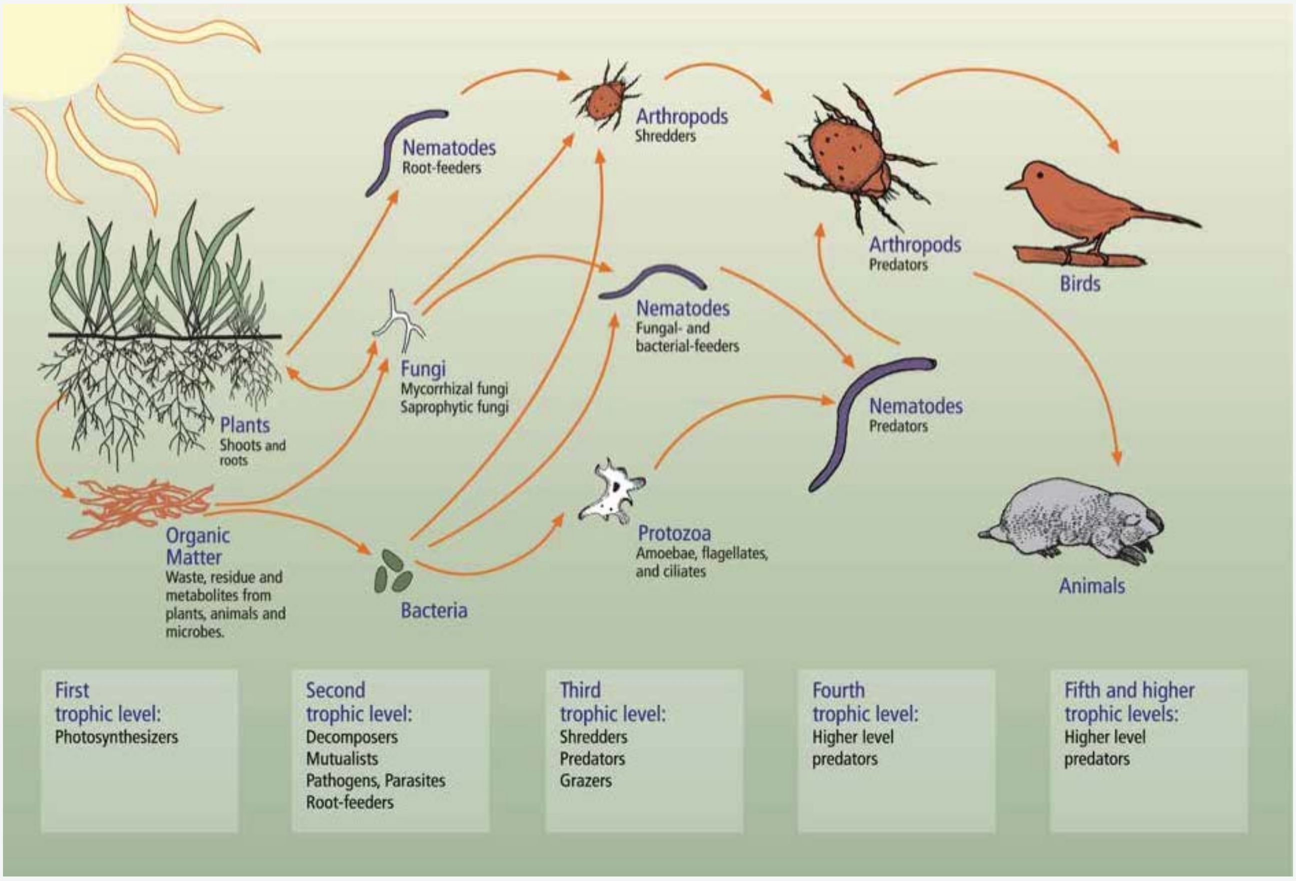


Exhibit 1: The soil is host to a diverse range of micro-organisms and macro-organisms that create conditions favorable to crop growth. (Source: USDA, 2018)

Growing plants require numerous essential elements from soil. Three elements, termed macronutrients, are typically needed in the largest amounts: nitrogen (N), phosphorus (P) and potassium (K) (Silva & Uchida, 2000). There are numerous soil micronutrients that also affect crop production, such as iron, copper, zinc, boron, chromium, chlorine, manganese, selenium and molybdenum. In natural systems, each of these nutrients enters the soil through different processes (**Exhibit 2**).

Nitrogen is abundant in the air, but is relatively inert in that form. To be absorbed by plants, it needs to be converted into more usable forms like ammonia (NH_3) or nitrate (NO_3). This conversion—nitrogen fixation—occurs naturally through bacteria (and to a much smaller extent, by lightning). Phosphorus is found in soil through the gradual breakdown of various inorganic (phosphate rocks) and organic compounds (plant residue and animal waste). Potassium is a core part of particular types of soil, especially those with high clay content.

Sources of 3 key soil nutrients, and how they are lost

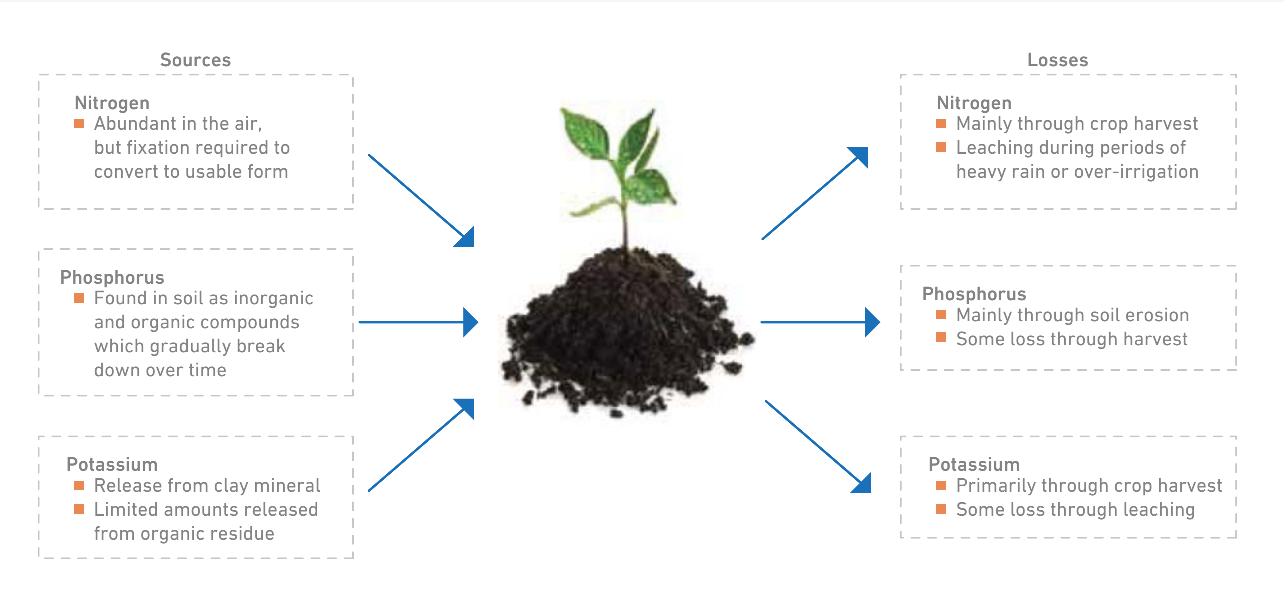


Exhibit 2: Three nutrients, all of which occur naturally, are essential for agriculture. However, intensive agricultural cycles cause rapid depletion of these nutrients from the soil (Source: Silva & Uchida, 2000).

In the natural cycle of plant growth, decay and rebirth, key nutrients are replenished slowly through biogeochemical processes. That replenishment rate determines, in large part, the pace of plant growth. Compared to natural ecosystems, agricultural systems typically have a more rapid flow of soil nutrients and nutrients are more likely to deplete faster than they can be naturally restored.

Nitrogen and potassium are primarily lost through harvesting of crops. Nitrogen can also be leached from the soil during periods of heavy rain or over irrigation.

Phosphorus is mainly lost due to soil erosion, and to a lesser extent through harvesting. The replenishment of depleted nutrients is now largely based on synthetically produced fertilizers, in much of the world outside of sub-Saharan Africa.

A small number of plants, such as legumes, are able to fix nitrogen naturally, because they contain symbiotic rhizobia bacteria in their root systems. Such plants have been used for crop rotation—in traditional agronomy, as well as in newer sustainable farming systems in many parts of the world—to organically enrich soil.

The essential idea in crop rotation is to alternate between the main food crops (like maize or wheat) and nitrogen-fixing crops, so that the need for synthetic fertilizers is diminished.

Unfortunately, crop rotation is not widely practiced in sub-Saharan Africa, because of pressures to maximize utilization of farmland to meet minimum food requirements. As a result, farmers have prioritized the immediate need to increase the total output of main food crops over the long-term health of the soil.

2. Loss of fertile agricultural soil due to erosion has significant impacts on farm yields and food security

Soil erosion is the removal of soil from the land surface, typically carried away by rain or wind. Some level of soil erosion is natural and over geologic time spans has shaped the river valleys and deltas of our landscape. Soil erosion under native vegetation occurs at roughly the same rate at which new soil is produced through natural geomorphological processes.

However, agricultural practices, such as tillage and heavy grazing, remove vegetative cover and expose the soil surface to rain and wind. Soil erosion in agricultural fields occurs at rates 10 to 100 times greater than erosion from natural land surfaces (Pimentel, 2006; Montgomery, 2007).

Such soil displacement and degradation is widespread: Moderate to severe erosion affects about 80 percent of global agricultural land (Pimentel & Burgess, 2013). Erosion is much greater on sloping land, where flowing water carries away soil particles downhill. Wind can also carry soil particles over long distances.

Soil erosion by water is the most serious cause of soil degradation globally and heavy rainfall and extreme weather events aggravated by climate change increase soil erosion (Panagos, et al., 2017). **Exhibit 3** shows a global map of estimated soil erosion (Borrelli, et al., 2017). A global total of 36 billion tons of soil is estimated to erode each year.

The continent of Africa has the highest average erosion rate, with 3.9 tons of soil eroded per hectare per year. South America has the next highest erosion rate at 3.8 tons per hectare per year, followed by Asia at 3.5 tons per hectare per year.

Global hot spots with soil erosion exceeding 20 tons per hectare per year include China (6.3 percent of the country), Brazil (4.6 percent of the country), equatorial region of Africa (3.2 percent of the region), India (7.5 percent of the country) and the United States (1.9 percent of the country).

Global soil erosion

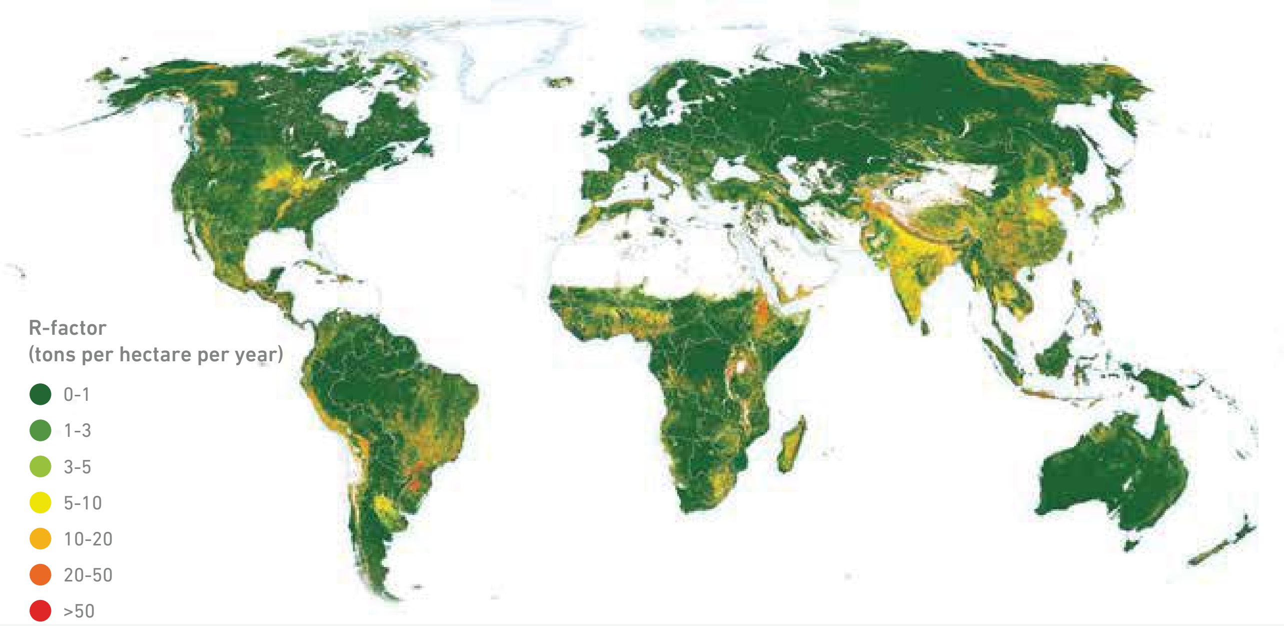


Exhibit 3: Soil erosion varies widely by region, depending on rainfall amount and timing, soil properties, land use, vegetation cover and other factors. Total global erosion is estimated at 36 billion tons of soil per year. (Source: Borrelli et al., 2017; JRC, 2017)

Soil erosion affects global development by reducing food security. Loss of fertile, nutrient-rich cropland soil reduces the productive capacity of the land and causes lower harvest yields.

This is a major problem for poor rural populations living on marginal land with low soil quality and steep topography. As the productivity of agricultural fields goes down, farmers are compelled to apply fertilizers to maintain yields (Lal, 2009).

Eventually, when enough productive soil is lost, the land is not worth using and is abandoned. According to FAO (2012), about 3 million hectares of cropland worldwide are abandoned annually because of productivity declines due to severe land degradation.

A related issue is desertification, or the gradual degradation of drylands to become infertile. While traditionally ascribed to overgrazing, it is now known that many factors—including soil erosion, climate change, soil nutrient management and water cycle changes—affect desertification (D'Odorico, et al., 2013).

Underlying driving forces consist of demographic, economic, technological, institutional, socio-cultural and meteorological factors.

Land degradation and desertification is caused by interactions between natural processes, such as weather variability including droughts and floods and human actions of unsustainable land use practices on fragile resources.

External forces are also key drivers, including inadequate governance mechanisms, ineffective land tenure and global economic forces. Locally, this leads to decreased land productivity, overexploitation and a worsening spiral of land degradation, poverty and food insecurity.

3. Nutrient mining has highly degraded agricultural soil in Africa

Decades of cultivation, combined with minimal application of soil nutrients, have degraded agricultural soil across sub-Saharan Africa (**Exhibit 4** and **Exhibit 5**). This process of depleting soil nutrients through crop harvesting, without ongoing replenishment, is known as nutrient mining.

Studies of nutrient mining among smallholder farmers in Africa found that 85 percent of African farmland has nutrient mining rates of more than 30 kg per hectare per year and 40 percent had rates greater than 60 kg per hectare per year (Henao & Baanante, 2006; Vitousek, et al., 2009).

This compares with a global average of 37 kg per hectare per year, meaning that arable land in Africa is losing nutrients and productivity faster than farms in other parts of the world.

Quantifying the impact of nutrient mining is difficult, but a 2005 synthesis of studies in Ethiopia found that land degradation was reducing agricultural productivity by 2 to 3 percent per year (Yesuf, et al., 2005).

Nitrogen balances in maize farming systems in different parts of the world

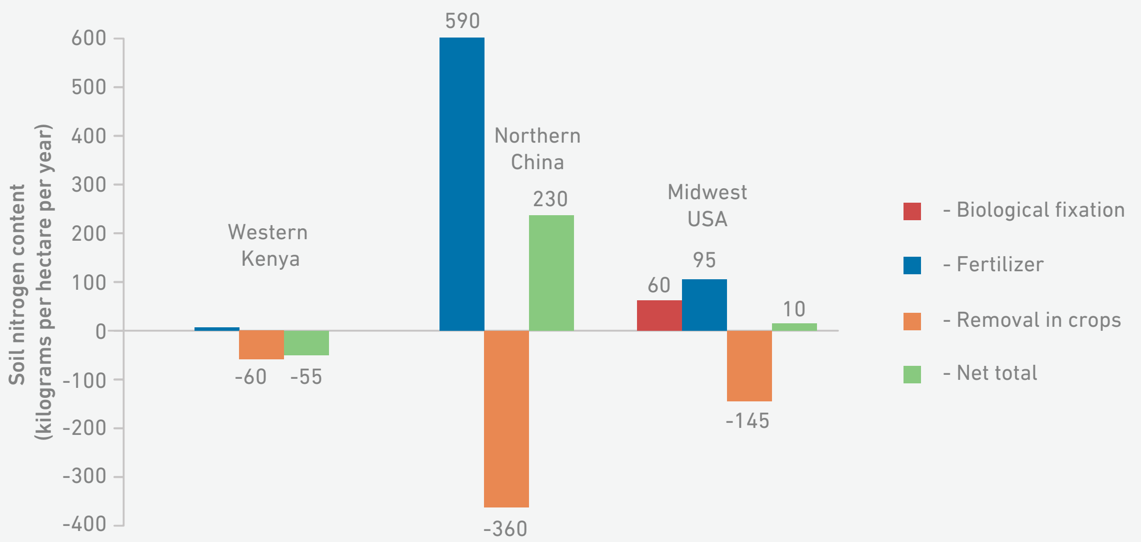


Exhibit 4: Soil nutrient losses in Africa are higher compared with most other parts of the world where much more fertilizer is used to replenish nutrient-depleted soil during crop growth and post-harvest. (Source: Vitousek, et al., 2009)

Soil nutrient losses in Africa

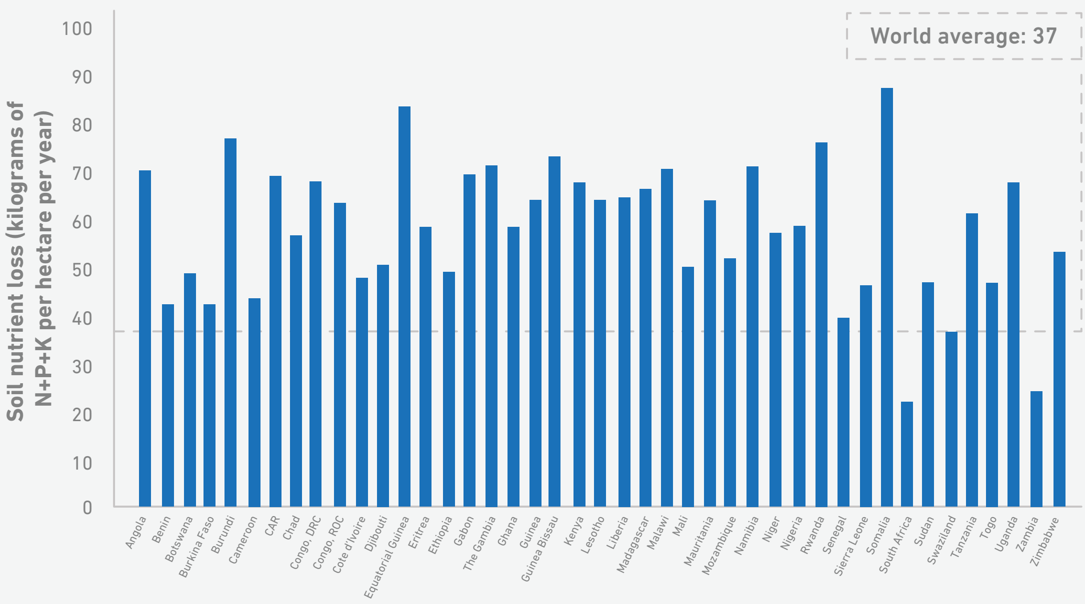


Exhibit 5: The problem of nutrient mining is common across sub-Saharan Africa; 85 percent of African farmland has nutrient mining rates of more than 30 kilograms per hectare per year and 40 percent has rates greater than 60 kilograms per hectare per year. (Source: Henao & Baanante, 2006)

4. Improving soil nutrient quality through fertilizers will significantly increase overall food production across sub-Saharan Africa

Agricultural yield increases with initial fertilizer application and gradually plateaus with additional application (**Exhibit 6**). Studies have shown that yield can increase by more than 50 percent with low levels of application and more than 80 percent with sufficient application (Pandey, et al., 2000). There are diminishing returns beyond a certain point (Roberts, 2007), but it is estimated that addressing soil nutrient deficiencies with fertilizers can close yield gaps in sub-Saharan Africa to almost 50 percent of maximum attainable yields (Mueller, et al., 2012).

Smallholder farmers in sub-Saharan Africa have historically never used much fertilizer and that trend continues to this day. For example, fertilizer use for maize, the most widely-grown staple crop on the continent, averages 40 kilogram per hectare in sub-Saharan Africa, compared with the world average of 153 kilogram per hectare, 70 kilogram per hectare in India, 210 kilogram per hectare in China, and 270 kilogram per hectare in the United States (**Exhibit 7**).

Fertilizer use in Africa is even lower for other staple crops like rice. As described later, there are a number of reasons behind this low usage: high cost, limited availability and a broad lack of awareness of the benefits of fertilizer.

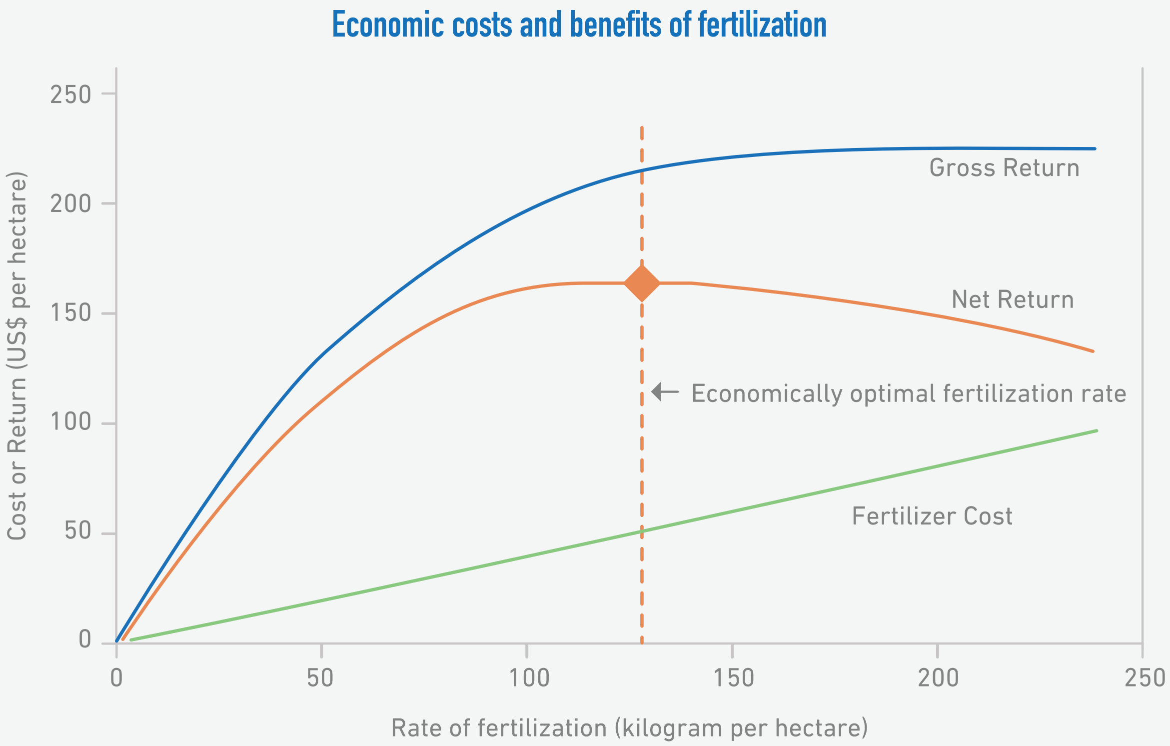


Exhibit 6: Fertilizer application leads to an initial strong yield increase, which tapers off as application continues. Fertilizer cost increases linearly, thus there is an optimal application rate and diminishing return after a certain point. The figure is illustrative, as the optimal rate will depend on local fertilizer cost, local crop prices and soil type, among others. (Source: adapted from Robertson & Vitousek, 2009)

Fertilizer use is low in sub-Saharan Africa

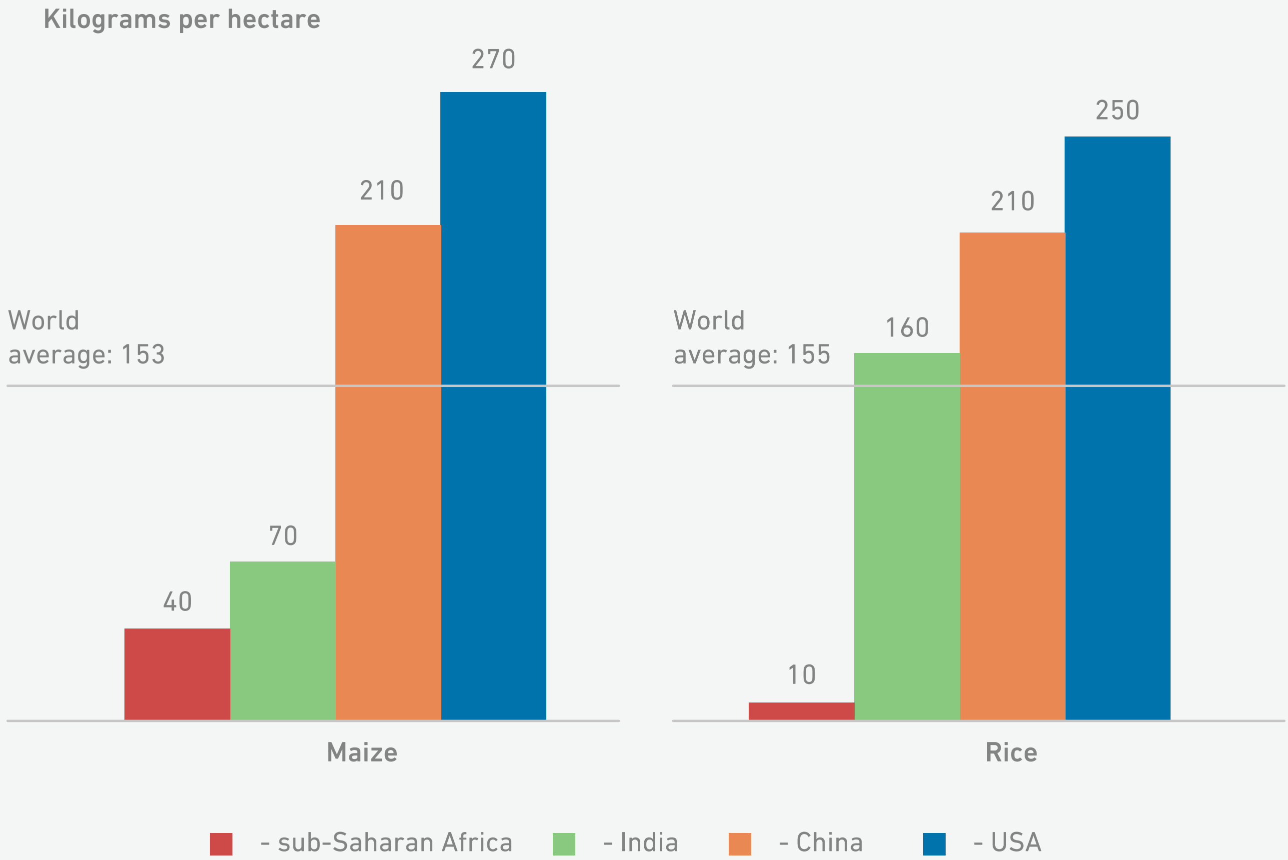


Exhibit 7: Fertilizer use in sub-Saharan Africa is a fraction of that in other parts of the world (Source: FAO, 2009).

The Green Revolution is considered by some to be among the most significant achievements in the history of global development (Spielman & Pandya-Lorch, 2009; Hazell, 2009). Building on the work of Nobel laureate Norman Borlaug, the Green Revolution led to the practice of intensified agriculture for smallholder farmers across much of Asia and Latin America.

One of the key elements of the Green Revolution is the use of synthetic fertilizer. A telling measure of the impact of intensified agriculture is a comparison of yields between South Asia and sub-Saharan Africa, from the 1960s (when the Green Revolution was launched) to now.

As **Exhibit 8** shows, between 1961 and 2009, yield of cereals in South Asia increased by 160 percent from the same amount of cultivated land. There was no similar intervention in sub-Saharan Africa, as a result of which farmers did not have access to synthetic fertilizers and soil fertility diminished. Between 1961 and 2009, there was only a 50 percent increase in per hectare cereal yield in sub-Saharan Africa and farmers have had to increase the amount of land for cultivation by 140 percent (VFRC, 2012).

Cereal production, yield and land usage in South Asia and sub-Saharan Africa, 1961 to 2009

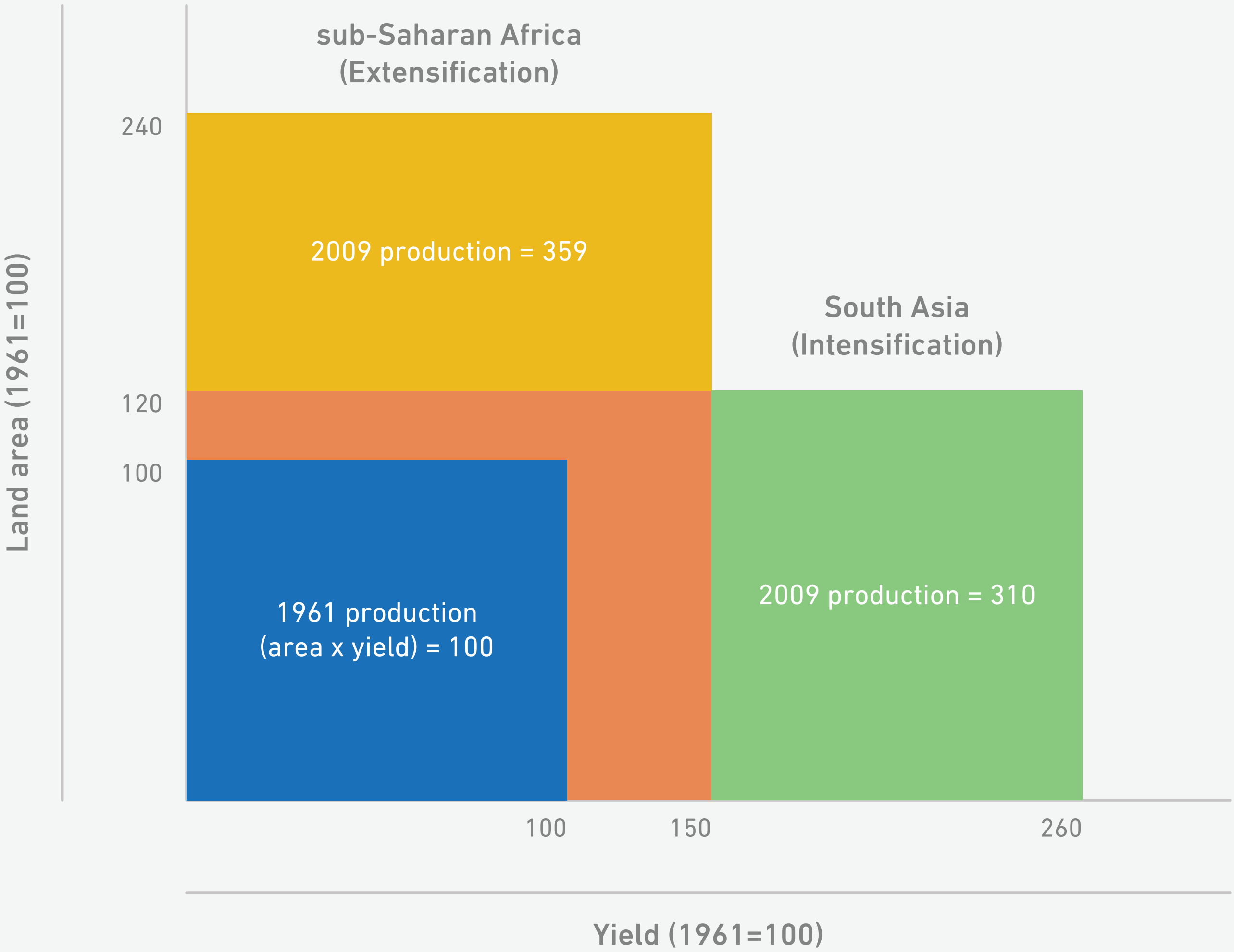


Exhibit 8: In South Asian countries agricultural yield increased dramatically over the past few decades due to intensified agricultural practices. Compared with 1961, per hectare cereal yield in South Asia has increased by 160 percent, leading to a total output increase of 210 percent, with only a 20 percent increase in cultivated land. During the same period in sub-Saharan Africa, there was a 140 percent increase in cultivated land and only a 50 percent increase in per hectare yield, for a total increase in output of 259 percent. (Source: VFRC, 2012)

5. Almost all the fertilizer in the world today is produced using capital-intensive methods with a heavy environmental footprint

The three main nutrients in fertilizers, nitrogen, phosphorus and potassium, depend on environmentally costly extraction processes. Nitrogen is extracted from the air and is converted to compounds that can be used by plants by chemical combination with hydrogen—mainly in the form of ammonia, urea or ammonium nitrate.

The only industrial scale nitrogen fixation process used today (the Haber-Bosch process[5]) requires fossil fuels both as a feedstock and an energy source. Approximately 2 percent of global energy use is dedicated to the manufacture of nitrogen fertilizer through the Haber-Bosch process (Sutton, et al., 2013). Currently, natural gas comprises 85 to 90 percent of operating costs for ammonia plants, making production feasible only at a large scale and near sources of natural gas (VFRC, 2012).

Furthermore, the chemical plants used to produce such compounds cost hundreds of millions of dollars due to the use of large-scale industrial chemical catalytic processes conducted at high pressures and temperatures. As a result, there is currently no synthetic ammonia production in sub-Saharan Africa.

Phosphorus on the other hand is typically extracted from mines as phosphate rock, which can take more than $1 billion in investment and several years to commission. Two-thirds of the world's phosphate rock is concentrated in China, the United States and Morocco, and none is extracted or exported from sub-Saharan Africa. Potassium, typically extracted in the form of potash salts, also comes from mines that can take several billion dollars and several years to commission.

There are no major potash mines anywhere in Africa, though in recent years there has been increased interest in potash mining in the Danakil Depression in Ethiopia and Eritrea and along the Atlantic coast of the Republic of Congo (Pedley, et al., 2016).

With the steady rise in global demand for fertilizer over the decades, the process has become commoditized and fertilizer is relatively affordable to farmers in countries where it is produced. However, with less than 0.1 percent of industry sales spent on R&D, there has been little effort to improve the production processes or make them less capital-intensive.

These factors, together with the extremely underdeveloped nature of the smallholder farmer market in Africa, have led to a state in which sub-Saharan Africa (excluding South Africa) accounts for less than 0.2 percent of global fertilizer production capacity (World Bank, 2006; FAO, 2017) (**Exhibit 9**).

As a consequence, whatever little fertilizer is used in sub-Saharan Africa is imported and the cost of distributing fertilizer exceeds the cost of producing it. By some estimates (World Bank, 2007), fertilizers cost the typical farmer in sub-Saharan Africa 50 percent more than a farmer in the United States (**Exhibit 10**).

[5]The Haber-Bosch process is named for the two German scientists who invented it, Fritz Haber and Carl Bosch, both of whom were awarded the Nobel Prize in Chemistry for this achievement.

Fertilizer production capacity: Global versus Africa

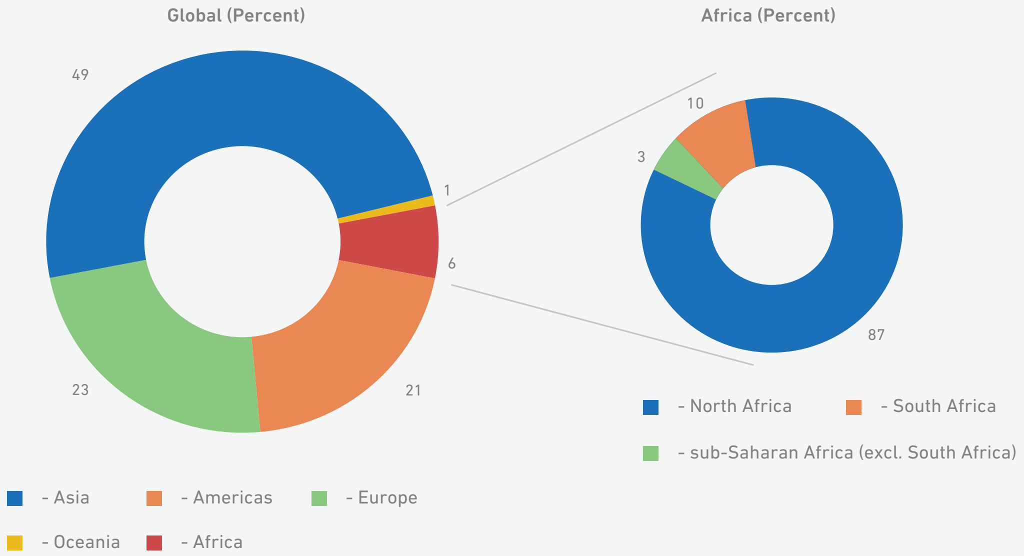


Exhibit 9: Less than 0.2 percent of the world's fertilizer production capacity is in sub-Saharan Africa (excluding South Africa). All of Africa accounts for 6 percent of global capacity, most of which is in North Africa, with South Africa accounting for most of the remaining. (Source: FAO, 2017; World Bank, 2007; production capacity includes sum of ammonia, phosphate and potash capacities measured in annual tons of N, P_2O_5 and K_2O)

End user cost of fertilizer in the USA versus in sub-Saharan Africa

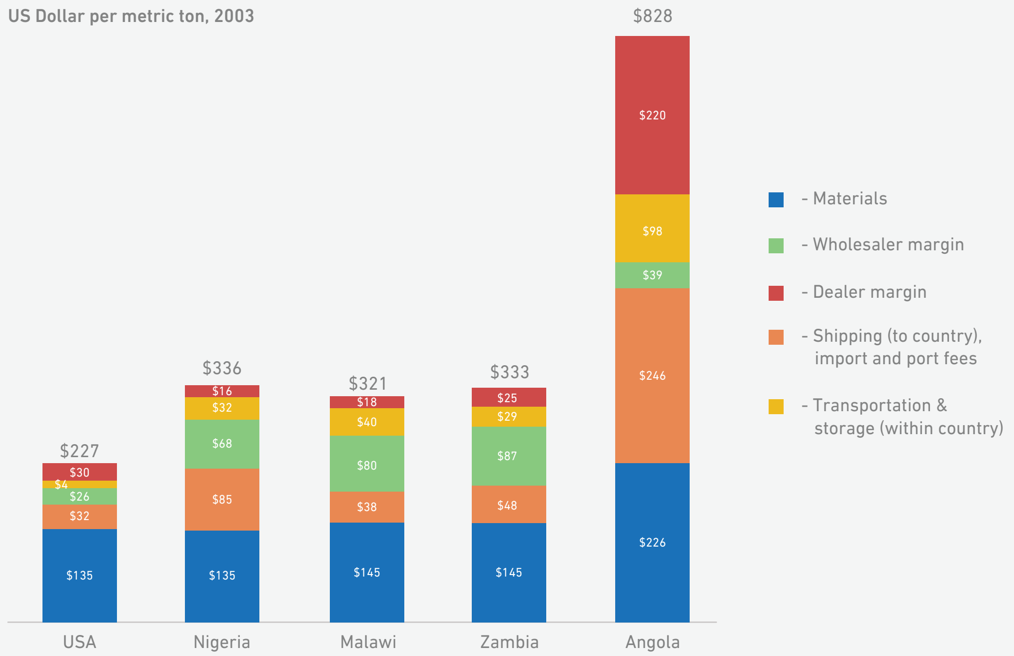


Exhibit 10: The high cost of shipping (to an African country) and transportation (within the country) has for the most part led to a significantly higher market price of fertilizer in Africa than markets like the United States. The market price also somewhat varies between different African countries. (Source: World Bank, 2007)

Fertilizer overuse is a source of significant environmental pollution

Most farmers who can comfortably afford fertilizer, tend to overuse it. While heavy overuse can cause major damage to the crops, the typical amount of overuse can harm the environment without necessarily hurting the crops. Runoff of nitrogen and phosphorus from farmland constitute a significant source of water contamination in many parts of the world (Conijn, et al., 2013).

Just as fertilizing agricultural fields can stimulate crop growth, increasing nutrient levels in water bodies can cause excessive growth of algae and other aquatic plants. This causes hypoxia (or depletion of oxygen in the water), which then causes the death of fish and other aquatic animals. In addition, the growth of cyanobacteria can also produce toxic compounds hazardous to humans and domesticated animals.

More than 400 marine dead zones resulting from nutrient runoff now exist worldwide, having approximately doubled in number each decade since the 1960s (Diaz & Rosenberg, 2008). **Exhibit 11** shows that many of the prolific food producing regions of the world face the problem of excess fertilizer runoff (MEA, 2005).

On global average, about 80 percent of nitrogen fertilizer and 25 to 75 percent of phosphorus fertilizer, where not temporarily stored in agricultural soils, is lost to the environment through leaching, erosion and other mechanisms (Sutton, et al., 2013). Areas with the greatest fertilizer overuse have the highest concentrations of marine dead zones.

Increase in reactive nitrogen flows in river systems since 1750

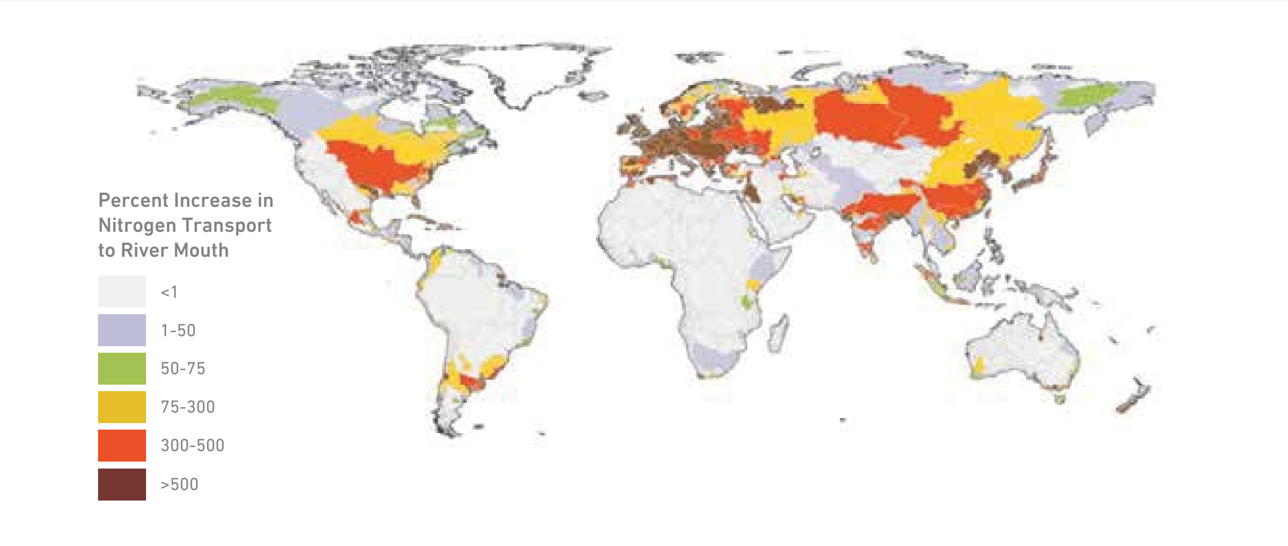


Exhibit 11: Reactive nitrogen flows in many river systems have increased dramatically in recent decades—primarily due to fertilizer runoff from agricultural lands—especially evident in Europe, Asia and North America. This has led to waterway dead zones. (Source: MEA, 2005)

7. Biological fertilizers are an alternative to synthetic fertilizer, but face a number of challenges

Biological fertilizers increase the total organic matter in soil and release nutrients gradually, sometimes over the course of several years, depending on the specific source. This can be beneficial for the soil in the long run, providing not only a rich source of nutrients but also reducing erosion. In addition, since biological fertilizers can be made from household and farm waste, the farmer does not need to purchase more expensive synthetic fertilizers (World Bank, 2007).

There have been promising cases of composting plant and animal waste into potent biological fertilizer. For example, farmers can convert coffee cherry pulp (usually discarded otherwise) into organic fertilizer using a variety of decomposition methods (such as vermicomposting, and use of sprays containing enzymes). It may also be possible to integrate nitrogen-fixing microbial associations, such as those found in legumes, into cereal crops (Deynze, et al., 2018). Several biotech firms, such as Pivot Bio and Azotic Technologies, are developing compounds to coat seeds prior to planting, which will fix atmospheric nitrogen for use by the growing crop.

Unlike in biological variants, nutrients in synthetic fertilizer are released quickly, enabling accelerated crop lifecycles. Because of this rapid release, nutrient flow can potentially be controlled and synchronized with the high nutrition need windows of a plant's life cycle, ensuring optimal growth.

These high-growth phases when a plant needs maximum nutrition for maximum yield vary from crop to crop. While these recent biological fertilizer trials mentioned above hold promise, large-scale production and distribution of biological fertilizers faces a number of challenges.

First, the nutrient content in biological sources of fertilizer is highly variable, depending on, for example, the nature of the food consumed by the animals whose manure is being used. Nutrient content also tends to be more diverse and present in smaller volumes.

Thus, while certain biological fertilizers have shown tremendous promise with cash crops and fruits and vegetables, their potential with cereals (which require high volumes of macronutrients) remains to be seen. More importantly, the timing of nutrient release in biological fertilizers is dependent on the rate of decomposition and is difficult to control. This means that, in the short run, the optimum amount of nutrients is usually not available to the plant when it needs them most.

Second, as opposed to being abundantly available like air is for nitrogen fixation through the Haber-Bosch process, the supply is less reliable and more susceptible to corruption during the conversion process. Biological fertilizers would likely be produced near the source of raw material, and most successful trials have been at the micro level, for example, a vermicomposting site near a coffee cherry pulping station.

Without the benefits that come with economies of scale, production of more complex forms of biological fertilizer is more labor intensive, a significant barrier to adoption. Currently, biological fertilizer is most prevalent in the form of waste produced by livestock and only available in small quantities.

Third, most biological waste in sub-Saharan Africa is already used for other purposes, such as building materials (for rudimentary construction in villages), food for animals and fuel for cooking and heating. Therefore, while there may not be a cash cost to biological fertilizer, there might be an opportunity cost to the farmer.

8. Human waste is unlikely to be a major source of fertilizer, but could provide some benefits

Recovering and reusing nutrients from human waste is one potential source for biological fertilizer, particularly for locations with high cropland density, nutrient-intensive crops and compact urban area (Trimmer & Guest, 2018). A number of organizations, such as SOIL in Haiti and Sanergy in Kenya, have launched sanitation programs to collect human waste and compost it into fertilizer. Converting human waste to fertilizer can have the added benefit of providing a financially sustainable model for sanitation.[6]

While some studies in Europe have demonstrated that the average adult human excretes enough waste (5.7 kilograms of nitrogen, 0.6 kilograms of phosphorus and 1.2 kilograms of potassium from 500 kilogram of urine and 50 kilogram of feces each year) to produce the fertilizer required to grow enough cereal for one adult human[7] (250 kg) (Heinonen-Tanski & van Wijk-Sjibesma, 2005), the nutritional content of human waste depends heavily on food intake. Therefore, it is likely to produce less rich fertilizer in Africa, where the quality and quantity of food intake tends to be lower (WHO, 2013).

Our analysis shows that the waste (feces and urine) from three Kenyan adults, if appropriately processed, can be used to provide a modest 14 percent boost for the typical Kenyan 1-hectare maize farm (from 1.6 tons to 1.9 tons)[8] (**Exhibit 12**). At a larger scale, if the waste from a much larger population in Kenya (including both farming and non-farming populations) were converted to fertilizer, food production could be increased by much more.

However, human waste is unlikely to be a major source of fertilizer in a developing country. As **Exhibit 13** shows, if 100 percent of the feces and urine from 100 percent of the adults in Kenya were converted to fertilizer, assuming some natural losses of nutrients during composting, it could lead to a 40 percent increase in the production of cereal in the country.

Collecting even 1 percent of the total waste, which in the case of Kenya would be the equivalent of collecting all the waste generated by more than 220,000 adults, is extremely difficult due to the lack of sanitation infrastructure. It is highly unlikely that enough human waste can be collected and processed to produce large quantities of fertilizer to boost cereal yields significantly. However, it is important to note that converting human waste into fertilizer can:

- help make sanitation solutions in developing countries financially sustainable (through the sale of the fertilizer),
- increase food production at a smaller scale, including for high nutrition crops (such as, vegetables),
- be a significant part of the solution to replace synthetic fertilizers in industrialized countries, where sanitation infrastructures are much more advanced and centralized.

[6]As described in the Global Health chapter, the lack of adequate sanitation is a significant driver of diarrheal disease, which is among the leading causes of childhood mortality in developing countries.
[7]Waste produced by children is not as useful for plants, since growing children absorb a much greater portion of the nutrients they ingest.
[8]Our analysis assumes that the waste in the typical adult in Kenya has two-thirds the nutrients cited in the European study (Heinonen-Tanski & van Wijk-Sjibesma, 2005), based on World Health Organization's estimates of the typical caloric intake in Sub-Saharan Africa vs. industrialized countries (WHO, 2013). We also assume that 50 percent of the nutrients are lost during the fertilizer conversion process and during nutrient uptake by the plants.

Potential yield increase on a 1 hectare maize farm in Kenya from using fertilizer made from human waste

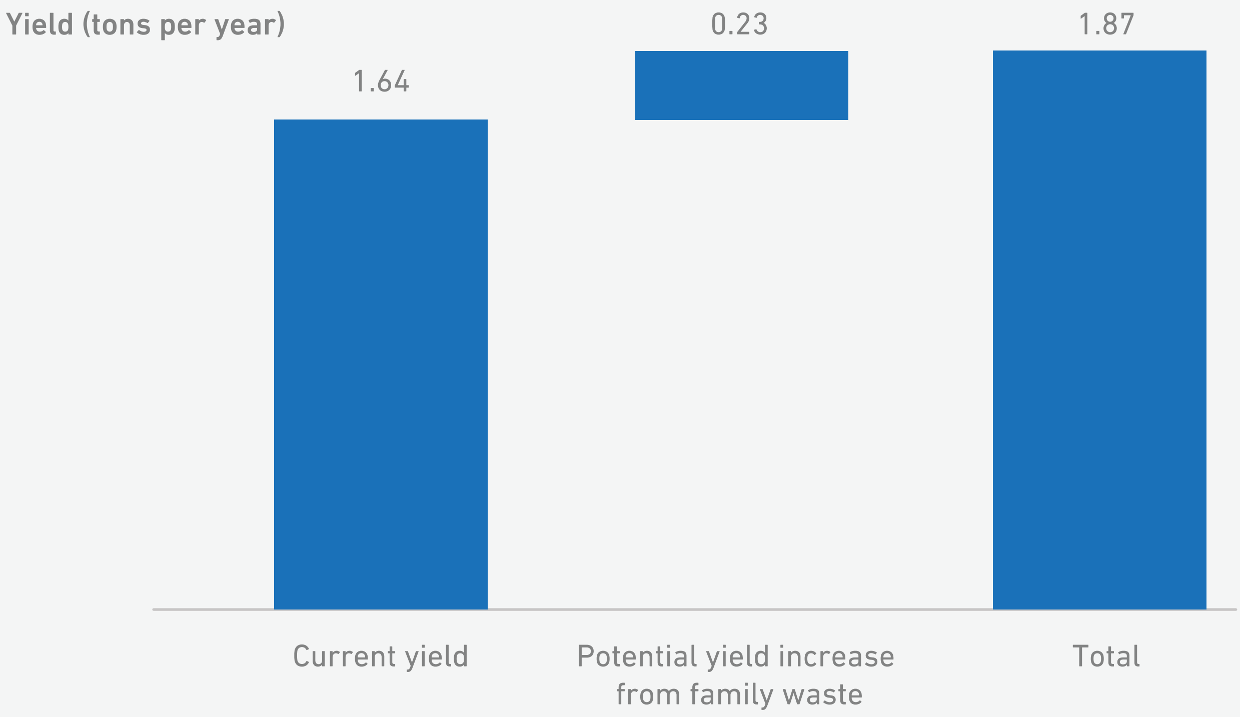


Exhibit 12: If appropriately processed, the fertilizer made from the waste (feces and urine) of three adults in a smallholder farming family can provide a modest boost to total crop yield; it can potentially increase yield on a 1-hectare maize farm in Kenya by 14 percent (from 1.6 tons to 1.9 tons). Higher and better-quality food intake by the adults producing the waste, reduction in nutrient loss during processing, and higher nutrient uptake efficiency of the fertilizer can increase this yield boost. (Source: ITT analysis)

Potential increase in cereal production versus percent of adult human waste utilized as fertilizer

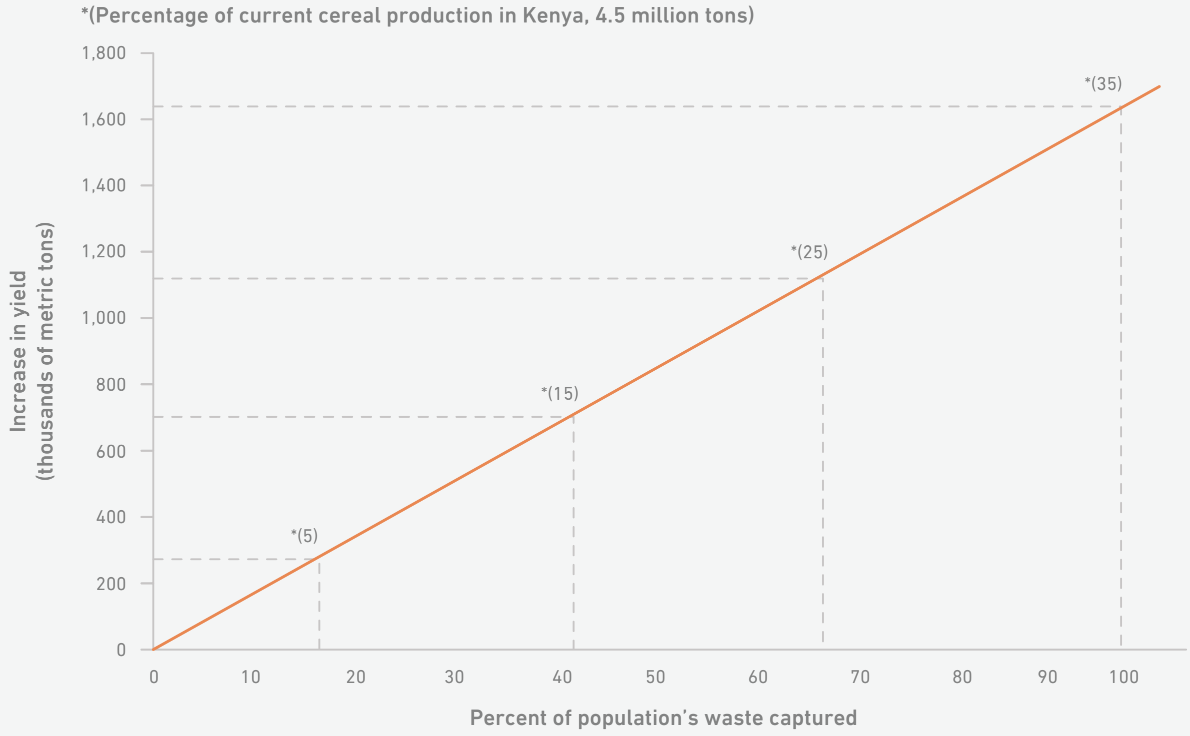


Exhibit 13: If 100 percent of the human waste in Kenya were composted and used as fertilizer, it could increase cereal production by about 35 percent. Given the poor sanitation infrastructure in a country like Kenya, it is unlikely to be a major source of fertilizer there. However, it can be a promising source of fertilizer in industrialized countries where sanitation infrastructure is well developed. (Source: ITT analysis)

Using human waste as feedstock for fertilizer faces a number of challenges.

- Human waste carries very harmful pathogens including bacteria, viruses and helminths. It must be carefully handled and processed for several weeks, depending on the environmental conditions, to fully eliminate health risks. Without appropriate mechanisms for safe collection and processing, human waste can increase the spread of disease.

- The process of converting human waste to fertilizer is relatively complicated. For example, it requires a carbon-to-nitrogen ratio (C:N) of 30:1, rather than 5:1 or 10:1, which is normal in human fecal matter. In addition, high-temperature treatment is required to kill the pathogens (SOIL, 2011). Both these steps require additional soil amendments. This means that specific training and, in most cases, a dedicated processing facility are required, for collection, storage, processing and quality control.

- Human waste is unpleasant. Unsurprisingly, there is taboo in many societies against handling human waste and even more so on applying it towards food production.

- Nutrient release from human waste is slow and unpredictable. As with other biological fertilizers, the challenge of slow nutrient release rates, as well as the variable amount of nutrients in the raw material, still remain.

KEY CHALLENGES

The crop nutrient challenge can be thought of as three separate issues, based on the state of economic and agricultural development in different parts of the world. Industrialized countries have stable fertilizer markets and there is limited economic incentive to migrate away from synthetic fertilizers, despite the environmental damage caused by overuse.

On the other hand, the robust sanitation infrastructures in these countries, combined with the amount of food waste and systems for collecting the waste, offer an opportunity to develop biological fertilizers at scale in a commercially sustainable manner. Green Revolution countries—like industrialized countries—have access to synthetic fertilizers and suffer from overuse.

However, they do not have robust infrastructures for sanitation or waste collection, nor do they have economic incentives for investing in alternatives to synthetic fertilizers.

Unlike either of the above-mentioned scenarios, sub-Saharan Africa has scant access to synthetic fertilizers and the current economics of the fertilizer industry suggest that local production in the foreseeable future is improbable.

The absence of fertilizers is continuing to deplete soil of nutrients, which, in turn, is leading to an increasing amount of land being used for agriculture. At the same time, the poor sanitation infrastructure, combined with the limited amount of food waste (and the lack of mechanisms to collect what food is wasted), make it difficult to develop biological fertilizers at any scale.

When it comes to using fertilizers for improving agricultural yields, smallholder farmers in sub-Saharan Africa face four specific challenges.

1. Synthetic fertilizer is very expensive for farmers in Africa

The core processes for manufacturing fertilizer, the Haber-Bosch process for nitrogen fixation and mining for phosphorus and potassium, are extremely capital-intensive. These production methods have not evolved or improved much in decades (VFRC, 2012). Poor transportation infrastructure in Africa increases the cost of distributing imported fertilizer to farmers. For most African countries, shipping (to the port), transport (within the country) and related costs add an extra 40 percent to the per-ton cost of fertilizer. Landlocked countries have to pay another 20 to 40 percent (World Bank, 2007).

2. There is limited demand for fertilizer among African smallholder farmers

There is a broad lack of fertilizer benefit awareness among smallholder farmers. Their limited economic means make them highly risk-averse too. Farm-gate prices for cereals in Africa are much more volatile than in other regions; maize prices have historically been twice as volatile in Africa than in Asia.

In addition, because most African farming is rain-fed, there can also be heavy weather-related fluctuation in yield. Even when fertilizer is used, the lack of knowledge about appropriate usage has resulted in very low nutrient uptake efficiency (NUE), which is 25 to 30 percent among smallholder farmers in Africa compared with 50 to 60 percent in developed agricultural systems.

Finally, the majority of sub-Saharan African countries utilize less than 25,000 tons of fertilizer each year; the volume at which fertilizer can be imported cost effectively (World Bank, 2006; 2007). All this has discouraged investment in fertilizers or other yield-enhancing inputs. Consequently, Africa accounts for less than 1 percent of the global fertilizer market.

3. The private sector supply chain for fertilizer in Africa is very weak

In addition to the low demand, there are other hurdles to private sector investment in the African fertilizer market. The lack of access to financing discourages local dealers, who typically need to build up large inventories since demand tends to be seasonal and agriculture largely rain-fed. Unfavorable business environments and uncertain political environments have made international firms reluctant to enter African markets. The little private sector activity that exists is limited to small dealer networks concentrated near urban centers, serving peri-urban or larger farmers rather than rural smallholder farmers (World Bank, 2007).

4. Biological fertilizers are not yet a feasible large-scale alternative to synthetic fertilizers

As discussed earlier, animal and plant waste are traditionally used for other purposes (energy and animal food, respectively) and several hurdles currently prevent large-scale conversion of biological waste into fertilizer.

SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

Those working on new breakthroughs in plant nutrients will have to explore multiple avenues, including production systems that are significantly less capital intensive than current methods, manufacturing processes that are more environmentally sustainable, greater efficiencies in application to prevent losses and runoffs, and significantly higher uptake efficiencies so that crops can maximize growth. These approaches are at the intersection of multiple scientific disciplines: the Haber-Bosch process and the production of the other reactive compounds is in the realm of chemistry and chemical engineering; how plants utilize nutrients falls in the field of crops sciences; and the broader question of soil health is in soil science. Developing breakthrough solutions to concurrently address food security and environmental protection will require cross-disciplinary research. Unfortunately, there appears to be very little cross-disciplinary work underway today. There are three technology breakthroughs to address the challenge of affordable, sustainable plant nutrients.

Breakthroughs:

1	2	3	4	5	6	7	8	9	10
11	12	13	14	15	16	17	18	19	20
21	22	23	24	25	26	27	28	29	30
31	32	33	34	35	36	37	38	39	40
41	42	43	44	45	46	47	48	49	50

1 A low-cost system for precision application of agricultural inputs, ideally combining water and fertilizer

In some regions like South Asia, the Green Revolution has brought unfortunate consequences including over-exploitation of groundwater resources and over-application of synthetic fertilizers. In other regions like sub-Saharan Africa, the Green Revolution has not arrived and there is under-utilization of groundwater resources and ongoing nutrient mining of soils. There is need for a low-cost, robust, scalable technology to precisely meter and distribute irrigation water and fertilizer to field crops.

This would allow farmers to apply the right amounts of water and nutrients (not too much or too little) at the right time to maximize economic returns and reduce nutrient loss. If made affordable, precision application systems for irrigation and fertilizers, calibrated to local crop type and soil conditions, could be a very effective way to increase agricultural yields, while also reducing negative impacts on the environment.

Enabling better management of the timing and formulation of irrigation and fertilization in cropping systems would ensure that water and nutrients are available where and when needed by the plant roots. Crop yields respond very well with initial inputs of fertilizer, but as additional nutrients are supplied the marginal yield increase becomes smaller.

Optimal results occur somewhere along that gradient, depending on the cost of fertilizer and seeds, land and selling price of harvested crops. For maximum returns, it is necessary to not just apply the right quantity of fertilizer, but to also apply it at the right time and place for optimal nutrient uptake by the plant. This would also protect watersheds and populations downstream from farm fields, by greatly reducing runoff.

The efficiency of using agricultural inputs, such as fertilizer is low in conventional farming. It is estimated that overall efficiency of applied fertilizers is about 50 percent for nitrogen, less than 10 percent for phosphorus and about 40 percent for potassium. The rest is wasted as runoff. The mismatched timing between availability of nitrogen and crop need for nitrogen is likely the single greatest contributor to excess nitrogen loss in annual cropping systems. Ideally, nutrients should be applied in multiple small doses and when plant demand for them is greatest.

Current State

Development Stage: Engineering

Time to market (years)

<3 4-6 7-10 10+

Deployment: Challenging

Associated 50BT Chapters

Food Security

Global Change

SDG Alignment

2 ZERO HUNGER

8 DECENT WORK AND ECONOMIC GROWTH

Impact

Increased Access to Food (# of People)

<1M 10M+ 100M+ 1B+

New Income Generated (# of People)

<1M 10M+ 100M+ 1B+

Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

In principle, variations of existing programmable irrigation and fertigation systems used in industrialized countries can be adapted to the needs of smallholder farmers.

Already, small-scale drip and sprinkler systems—along with other methods for increasing water usage efficiency—are beginning to emerge in markets like India. Cultivated area under drip irrigation in India has grown from 71 km^2 in 1992, to 2,460 km^2 in 1998, to 18,970 km^2 in 2010, up to 33,700 km^2 in 2015. The cost of such systems will continue to drop as scale of production increases.

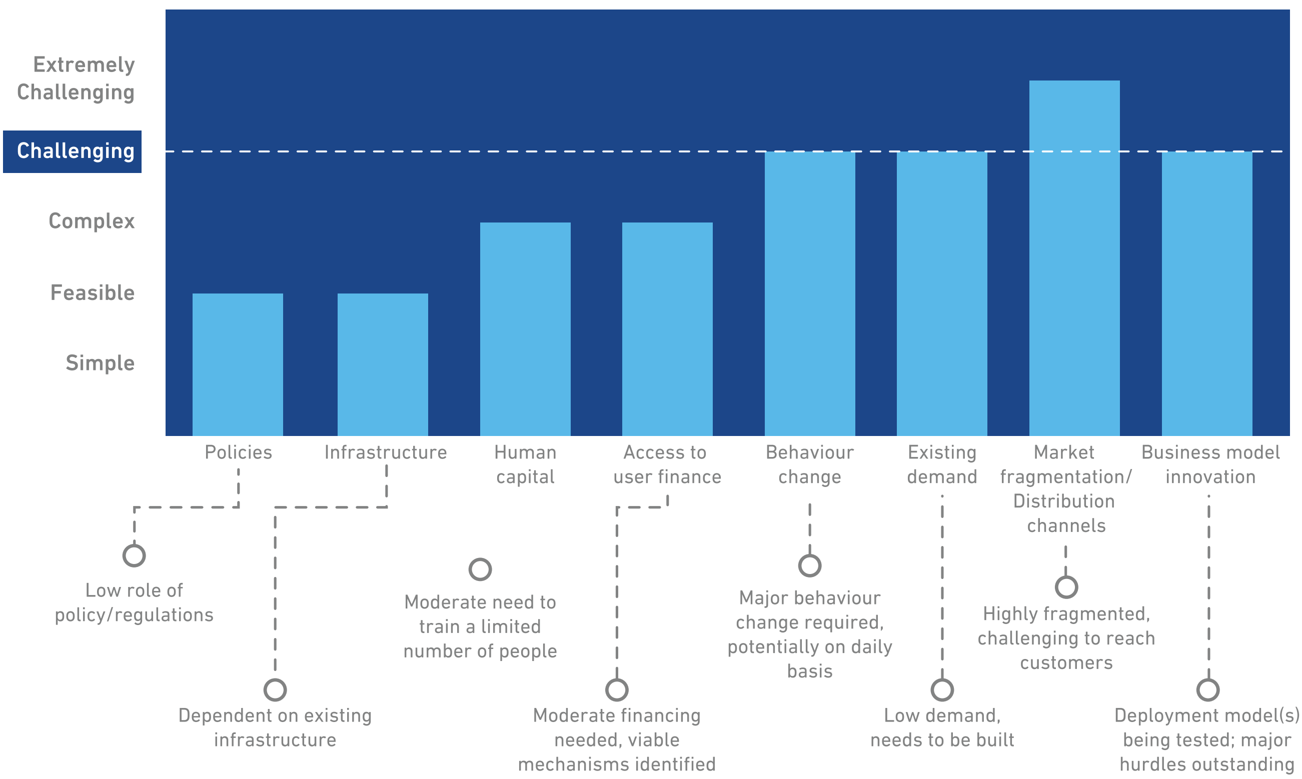
This breakthrough would be strongly leveraged by three other breakthroughs, 5 Low-cost shallow groundwater drilling technologies, 6 Affordable solar-powered irrigation pumps, and 9 Low-cost soil nutrient analysis device.

Overall, such devices would help farmers better predict crop nutrient requirements, better schedule irrigation and fertilizer applications, and avoid over-fertilization and nutrient runoff. If complemented with adjusted crop rotation patterns and additional biotic complexity, it could improve the plant community's ability to take up more of the available nutrients.

However, there is limited evidence to suggest that users—farmers or otherwise—will be interested in spending money on technologies to conserve water when the resource itself is available free of cost. The potential for saving fertilizer can prove to be a positive incentive, although the current demand for fertilizers is very low in sub-Saharan Africa.

It will face some deployment challenges that are common to the African smallholder farmer market, including structural barriers such as a fragmented market of farmers, limited access to finance for potential users, and lack of training to install, use and maintain the technology. The difficulty of deployment in this case would be CHALLENGING.

Breakthrough 1: Difficulty of deployment



8 New processes of nitrogen fixation that are less capital intensive than current (Haber-Bosch) processes

Perhaps the single most significant hurdle to the availability of affordable nitrogen fertilizer for smallholder farmers in sub-Saharan Africa is that the known processes for producing usable forms of nitrogen are extremely capital intensive, and must be located near the sources of particular natural resources.

For example, a facility for the Haber-Bosch process, the only known scalable process for synthetic nitrogen fixation, costs hundreds of millions of dollars to build, and needs to be located near a source of natural gas. As a result, there is virtually no fertilizer produced in sub-Saharan Africa (outside of South Africa), and what little is used has to be shipped in.

This means that the same fertilizer costs the African smallholder farmer considerably more than it costs a farmer in countries where the fertilizer is produced.

An ideal alternative will be significantly less capital-intensive, less energy-intensive, and will not require close proximity to sources of natural gas or other extractive resources. This will enable nitrogen fixation closer to farms, or even on farms, thus reducing or eliminating transport costs.

However, there are significant technical challenges involved, especially in splitting nitrogen bonds. The fact that the only scientists to solve this problem in the past (Fritz Haber and Carl Bosch) won the Nobel Prize, underscores the magnitude of the challenge. The solution can be biological or electrochemical or some yet-undiscovered method.

While some emerging technologies offer promise (such as intra-cellular transplantation of nitrogen-fixing bacteria from natural host crops to other crops), a scaled solution still appears to be far away. There is limited incentive for private sector investment to address this problem, given that synthetic fertilizer is very well accepted in most of the world, and natural gas supplies are currently abundant.

Therefore, we believe it will take more than 10 years for such a technology to come to market.

Current State

Development Stage: R&D

Time to market (years): <3 | 4-6 | 7-10 | **10+**

Deployment: Extremely Challenging

Associated 50BT Chapters

Food Security

SDG Alignment

2 Zero Hunger

12 Responsible Consumption and Production

Impact

Increased Access to Food (# of People): <1M | 10M+ | 100M+ | **1B+**

New Income Generated (# of People): <1M | 10M+ | **100M+** | 1B+

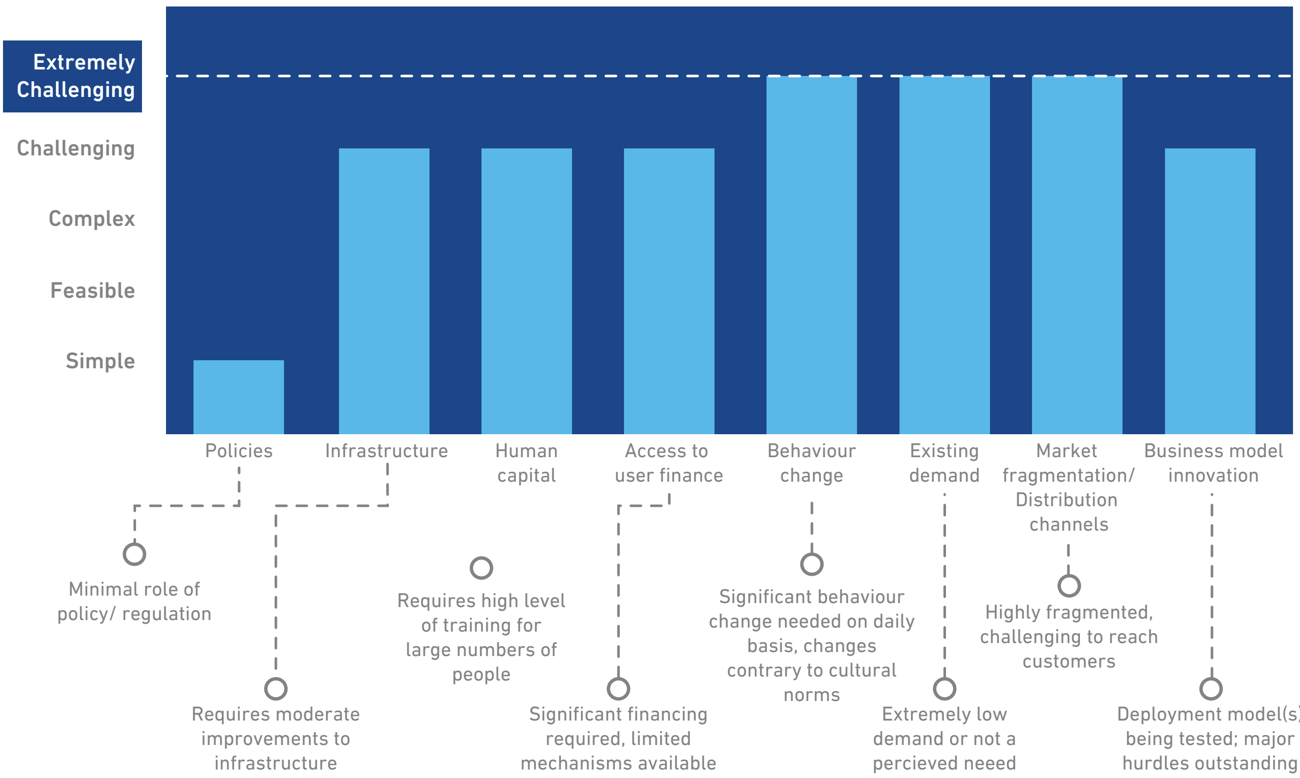
Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

Even when developed, such a technology will still face some deployment challenges, the most important being low demand from African smallholder farmers. Even if demand is created, low income farmers will need some form of financial support, possibly through micro-credit programs, so that they have the working capital to invest in fertilizer.

Extension services will likely be necessary for training farmers on how to use fertilizer appropriately. Overall, deployment will be EXTREMELY CHALLENGING.

Breakthrough 8: Difficulty of deployment



9 A low-cost, point-of-use device to evaluate soil nutrient content and recommend tailored use of fertilizers for specific crops

Understanding exactly which type of fertilizer is needed, how much should be applied and at what stage of the plant's lifecycle, is very critical for optimizing crop yields and maximizing returns on the farmers' investment. Smallholder farmers in Africa rely on advice from knowledgeable peers (like farmer cooperative leaders) or from extension workers.

A low-cost device, with a simple user interface, for rapid chemical analysis of the soil—tailored to the crop, underlying soil type, season and plant lifecycle—can prove extremely helpful in improving nutrient uptake, yield, and eventually demand for fertilizer. For greatest utility, the device would measure macronutrients like nitrogen, phosphorus and potassium, as well as essential micronutrients (like boron and manganese) that can limit crop growth. Using mobile technology for underlying computation, access to additional information and easy communication with appropriate extension workers can make such a tool more attractive for smallholder farmers.

Importantly, more precise knowledge of soil nutrient status would help avoid the problem of over-application of fertilizers. This would improve the economics of farming, and would also greatly reduce nutrient runoff which would protect watersheds and populations downstream from farm fields. In conventional farming practice, the efficiency of using fertilizer is very low. It is estimated that overall efficiency of applied fertilizers is about 50 percent for nitrogen, less than 10 percent for phosphorus and about 40 percent for potassium, while the rest is wasted as runoff.

Basic versions of such devices are in use in more developed markets. A recent wave of technological innovation has made them even more precise, and enhanced the benefits for farmers using such kits. However, these devices are still cost prohibitive for smallholder farmers in Africa and South Asia, and not necessarily intuitive to use by a person with limited formal education. While considerable reengineering is required to make such devices useful for smallholder farmers in low-income countries, there are no major scientific challenges involved.

Current State

Development Stage: Engineering

Time to market (years): <3 | 4-6 | 7-10 | 10+ (marked: 4-6)

Deployment: Challenging

Associated 50BT Chapters

Food Security

SDG Alignment

Impact

Increased Access to Food (# of People): <1M | 10M+ | 100M+ | 1B+ (marked: 1B+)

New Income Generated (# of People): <1M | 10M+ | 100M+ | 1B+ (marked: 10M+)

Commercial Attractiveness

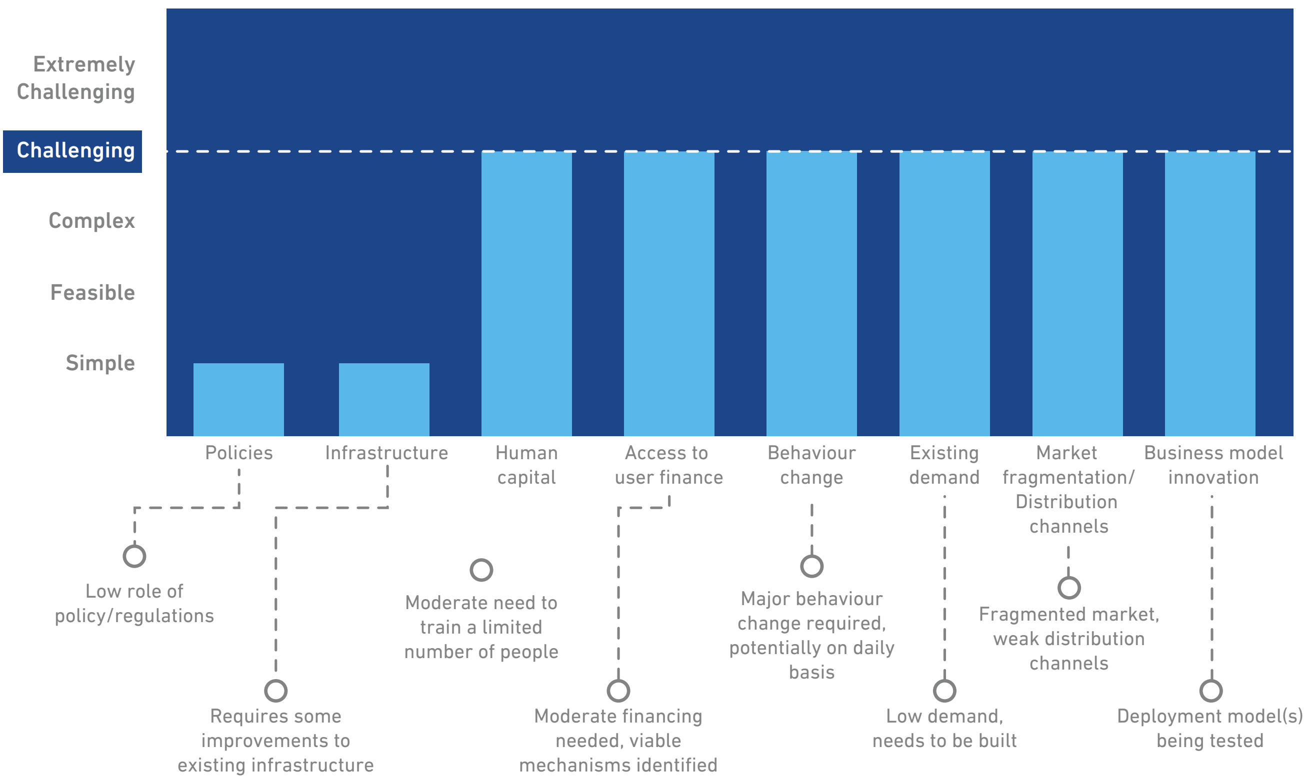
- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

However, demand for such a product is currently limited, and few resources are committed to making a low-cost device for analyzing soil nutrients. Based on the above assessment, the projected time to market readiness is about four to six years.

We anticipate that when such a technology is developed, there will be limited initial demand and it will have to overcome marketing and distribution challenges. Presumably, need for such a tool will depend on the demand for fertilizer and the value proposition of reducing the amount of money that farmers spend on fertilizer.

The rapid proliferation of smartphones and ICT tools for smallholder farmers is a positive trend that may help in the acceptance of such a technology. Still, until fertilizer demand and use increases, such a technology will not be widely used. Considering the above, deployment will be CHALLENGING.

Breakthrough 9: Difficulty of deployment



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BIOTIC STRESSES

INTRODUCTION

Biotic stresses—weeds, pests and pathogens—can collectively cause the loss of more than half the potential yield of smallholder farmers in sub-Saharan Africa and South Asia.

Mechanized tilling—one of the most common methods of dealing with weeds in industrialized countries—is too expensive for most smallholders in Africa and so are the chemical herbicides and pesticides commonly used in commercial agriculture.

In addition, weeds and pests can develop resistance to herbicides and pesticides, rendering them ineffective in the long run. They can also cause considerable damage to the farmers' health and environment if used inappropriately.

While many industrialized countries also rely on GMOs for combating biotic stresses, these enhanced seed varieties pose a number of unique challenges in developing countries. In order to overcome these biotic stresses, smallholder farmers need two technological breakthroughs.

- Breakthrough 10. New generation of affordable herbicides that are specific to most destructive weeds and are safe for humans
- Breakthrough 11. Novel, low-cost, environmentally friendly pest control mechanisms (chemical or spatial), specifically targeting the most destructive insects

A significant portion of agricultural produce is lost even before the crops are harvested, due to weeds, pests and pathogens. Addressing these stresses can lead to tremendous increase in food production among smallholder farmers.

CORE FACTS AND ANALYSIS

1. Weeds represent the most significant biotic stress on crops

Biotic stressors are living organisms, primarily weeds, pests and pathogens such as fungi, bacteria and viruses, that damage cultivated crops. These stressors can collectively reduce yield by more than 50 percent for smallholder farmers, who typically do not have the tools to combat them.

Exhibit 1 shows estimated losses (compared with potential yield) due to weeds, animal pests and pathogens (disease), from an aggregation of studies of cereal crops in sub-Saharan Africa (Shetto & Kwiligwa, 1990; Oerke, 2006). Losses in South Asia can also be significant.

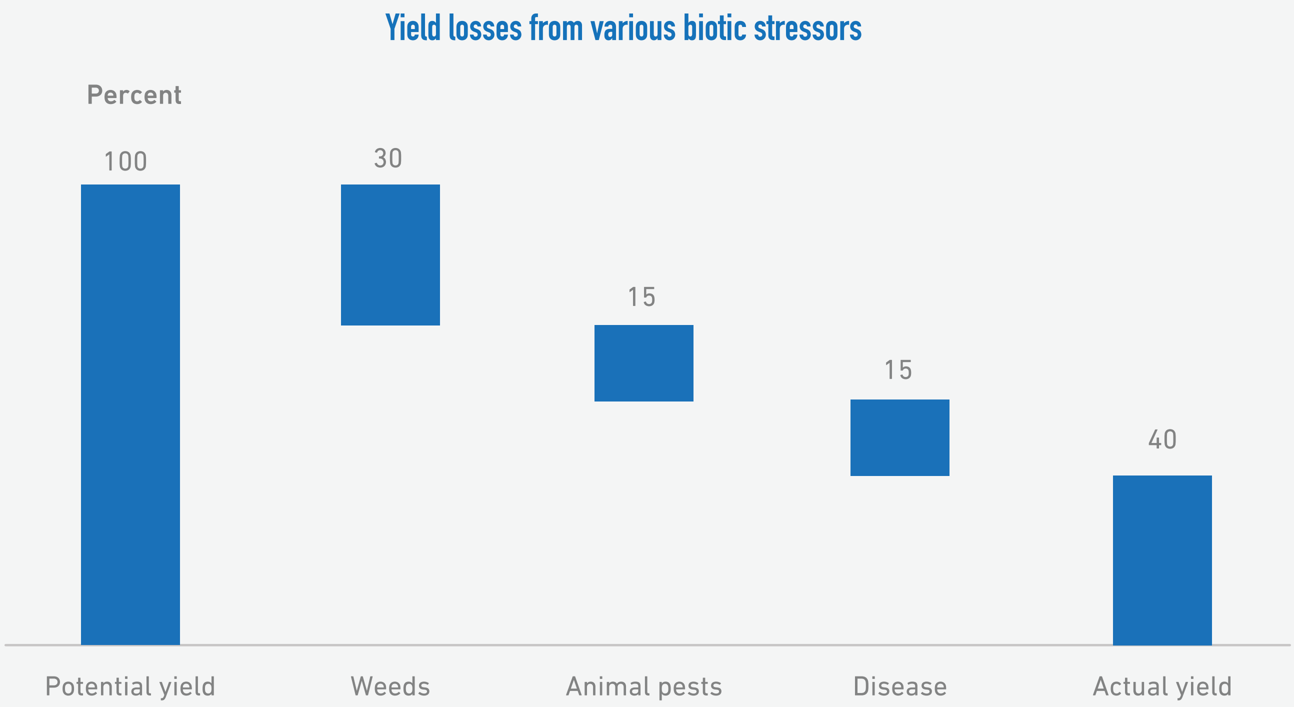


Exhibit 1: Based on a representative study of biotic stressors on cereal crops in sub-Saharan Africa, weeds are the largest driver of losses, followed by pests and diseases caused by a range of pathogens. Collectively, these stressors can reduce potential yield by as much as 60 percent. (Source: Shetto & Kwiligwa, 1990; Oerke, 2006)

Weeds are a major cause of crop loss in both sub-Saharan Africa and South Asia. By aggressively competing with crops for soil nutrients and water, weeds can cause losses of up to 30 percent for maize and between 10 and 20 percent for other crops across Africa (Shetto & Kwiligwa, 1990; Oerke, 2006). Losses in South Asia can also be significant, although farmers tend to have greater access to tools that can deal with the problem.

The specific variety and strain of weeds varies by geography but the example of Striga is illustrative of some of the challenges they pose. Also known as witchweed, Striga is among the most destructive weeds, causing losses of up to $1 billion each year across Africa (Berner, et al., 1995; AATF, 2014). Two species, Striga hermonthica and Striga asiatica, cause the most damage.

The weed is difficult to control because each plant can produce thousands of small and light seeds, which can be easily and widely dispersed by wind, water, animals and agricultural implements. The weed can also remain dormant for many years before proliferating (IITA, 2014).

Three weed-control mechanisms are commonly used in industrialized countries but the majority of smallholder farmers don't use any of them.

Mechanized rotary tillers or cultivators

These implements dig into the soil in order to aerate it and pull out weeds at their roots. Larger tillers are tractor-mounted and smaller ones are usually diesel-powered. The smallest and least expensive of these costs more than $200 to $300. Larger ones can easily cost several thousand dollars. All of them are currently far too expensive for low-income smallholder farmers.

While animal-drawn cultivators can help reduce a farmer's workload, their effectiveness and acceptance by farmers is limited (Shetto & Kwiligwa, 1990; Starkey, 1986). Despite its value in aerating soil and weed control, tilling can have negative consequences like soil erosion. The topsoil, loosened by tilling, can get washed away during heavy rain. Tilling and subsequent water-induced erosion also leads to carbon dioxide emissions (Chaplota, et al., 2012).

Herbicides

Over the past few decades, chemical herbicides have been a relatively low cost, easy-to-use method for killing weeds on farms in industrialized markets. However, these are too expensive for the typical smallholder farmer in developing countries and usually make economic sense only for high-value cash crops or in very heavily infested sites (Shetto & Kwiligwa, 1990).

A downside of using herbicides is that by the time the weeds are visible, they are already firmly rooted and the crop is already damaged. Hence, spraying herbicide above the ground may not be the most effective means of weed control (IITA, 2014). Herbicides can also damage the crops themselves (Kanampiu, et al., 2002) and traditional seed varieties in some contexts have been replaced by transgenically modified (GMO[9]) varieties so that the crop can resist the effects of the herbicide. The best-known example is the non-specific herbicide glyphosate (commercially known as Roundup®) and the subsequent Roundup Ready seeds, produced by Monsanto (which was acquired in 2018 by Bayer).

An important problem with using chemicals to tackle weeds is that the weeds themselves have shown the ability to adapt to the herbicide and resist its effects. This means that new varieties of herbicide, and consequently newer varieties of genetically modified seeds resistant to the modified herbicides, are required to maintain yields. Weeds are increasingly gaining resistance to glyphosate, with at least 43 weed species now showing resistance to the popular herbicide (Weed Science, 2018). Furthermore, using GMOs remains highly controversial in Africa and South Asia, and many countries have placed policy restrictions on their usage.

Regardless, the combination of effective non-specific herbicides and modified seeds resistant to that herbicide (through transgenic modification or conventional breeding) is in its infancy in developing countries. In Africa, efforts are underway to test the effectiveness of conventionally bred seeds to the herbicide Imazapyr (African Agricultural Technology Foundation, 2014). Another promising approach is the development of hormones that provoke germination of Striga seeds in the absence of a host plant, which is lethal to the Striga (Uraguchi, et al., 2018).

[9]Genetic modification is discussed in greater detail in the Emerging Technologies chapter.

Improved agronomic practices

Practices, such as crop rotation, intercropping and biomass density management can reduce weed prevalence. However, most smallholder farmers in South Asia and sub-Saharan Africa alike practice monocropping, thereby increasing vulnerability of their crop to weeds and other biotic stresses. As discussed in the Extension Services section, farmers in these regions receive very little training on improved agronomic practices.

In the absence of appropriate tools and agronomic training, the most common method employed by smallholder farmers to deal with weeds is to pull them out by hand. This is a very time-consuming process. The typical farmer spends 40 to 55 percent of the total time spent farming on manual weeding.

A single hectare takes up to 400 person-hours of manual weeding time (Shetto & Kwiligwa, 1990). Importantly, by the time the weeds become visible above ground, their roots have already damaged the crops by competing for scarce soil nutrients and moisture. Missing the optimal weeding time by even a single week can reduce yield by up to 33 percent. In effect, there is no affordable, reliable mechanism available for smallholder farmers (especially in Africa) to avoid losses due to weeds.

2. A range of animal pests are the second leading cause of crop losses

The large range of animal pests makes it difficult to develop specific solutions that do not have long-term negative consequences. Animal pests cause up to 15 percent of the yield losses for many crops across sub-Saharan Africa and South Asia in ways that are more visible than the damage caused by weeds. The major on-farm pests include insects (such as, borers, mealybugs and mites), nematodes and to some extent slugs and snails. Rodents, birds and mammals also cause damage, but these pests contribute to a larger portion of post-harvest damage rather than on the farm. Some of these pests are endemic to their geographies.

In other parts, alien species have encroached local ecosystems. In some cases, populations of endemic pests appear to have increased due to reductions in ecosystem biodiversity from monocropping, deforestation and heavy pesticide use.

Climate change is projected to increase insect losses of rice, maize and wheat by 10 to 25 percent per degree of global mean surface warming, particularly in temperate regions (Deutsch, et al., 2018). There are a number of possible mechanisms for dealing with animal pests, each with different degrees of effectiveness and its own set of negative consequences (Oerke, 2006; Williamson & Pretty, 2008; Khan, et al., 2000).

Pesticides

Chemical pesticides can be effective against a broad range of pests. Currently they are too expensive for most smallholder farmers in Africa, although usage is increasing. However, pesticides can also have considerable negative health and environmental impact, especially if they are used inappropriately. The United Nations Environment Programme (UNEP, 2012) estimates that from 2005 to 2020, the accumulated cost of illness and injury linked to pesticides in small scale farming in sub-Saharan Africa could be as much as $90 billion.

Pesticides may have unintended effects on non-target species such as honey bees, which provide an invaluable service by pollinating many crop plants. For over a decade, bee populations have suffered from the symptomatic disease of colony collapse disorder (CCD), apparently due to exposure to neonicotinoids (Lu, et al., 2014).

Neonicotinoids are a class of neuro-active, nicotine-based systemic insecticide that was brought into commercial use in the mid-1990s. Neonicotinoids have a high persistence in soil and water, resulting in sustained and chronic exposure of non-target organisms, such as honeybees and other invertebrates. Because they are relatively water-soluble, they run off into aquatic habitats easily and are still toxic even at very low doses.

Continued use of neonicotinoids is expected to result in substantial impacts on biodiversity and ecosystem functioning, including the distribution, abundance, and effectiveness of pollinators (van der Sluijs, et al., 2014). This could significantly impact food security due to reduced crop production.

Due to concerns about their adverse environmental impacts, three neonicotinoid insecticides (imidacloprid, clothianidin and thiamethoxam) were banned in 2018 from outdoor use in the European Union (EC, 2018). Problems of environmental toxicity are discussed further in the Resilience to Global Change chapter.

Genetically modified seeds

The most commonly cited example of transgenic modification, as a mechanism to deal with pests, is the insertion of a portion of the Bacillus thuringiensis (Bt) bacterium, naturally abundant in many insects and ecosystems, into seeds. Bt-enhancements to cotton have been deployed in India and China but results have been mixed compared with results from similar products in industrialized markets.

In China, for example, cultivation on Bt-enhanced cotton appears to have led to a resurgence of secondary pests (Wang, et al., 2008), leading to an erosion of the initial benefits from the enhanced seeds.

In Kenya, trials of Bt-enhanced maize have shown mixed results on economic returns for the farmers (Gouse, et al., 2006). In general, such genetic enhancements can get technically challenging as seeds need to be adapted to local conditions, and current evidence suggests that low-income farmers cannot afford the costs that stem from repeated seed enhancements.

As a result, GMOs are facing considerable policy hurdles, with the majority of African countries placing significant controls or outright bans.

Improved agronomic practices

Practices like crop rotation and intercropping increase biodiversity and can reduce pest density (Neuenschwander, et al., 2003). In particular, push-pull mechanisms, which push pests away from crops through intercropping with plants that repel the insects and pull them into less sensitive areas, have shown some promise (Adhiambo, 2011). Examples of successful push-pull systems include demonstrations in Ethiopia of using cover crops (desmodium, in combination with vetiver and Napier grass) to control borers and weeds attacking maize (ATA, 2014). However, in the absence of strong extension systems it has proven very difficult to get smallholder farmers to change agronomic practices.

Biological control measures

These measures include the introduction of predators or pathogens targeting the pests. Such methods, however, require significant and dedicated R&D. Needless to mention, they also carry a very high risk of major unintended, and sometimes unpredictable, consequences.

3. Crop yield losses caused by diseases are similar to those caused by pests, but few interventions have shown results

Like pests, a broad range of pathogens—fungi, bacteria, viruses and protists—are responsible for about 15 percent of on-farm losses. Fungal infections, which contribute to the bulk of disease in major staple crops like maize, are transmitted when fungal spores spread via the air, water or soil. Viruses and bacteria are generally spread through vectors, such as weeds and insects. Monocropping, which is practiced by the majority of smallholder farmers in Africa, increases susceptibility to these pathogens.

Due to the number and variety of potentially destructive pathogens in Africa, the absence of an R&D ecosystem to develop pathogen-specific solutions and the sparse nature of the African smallholder farmer market there have been few proven interventions (Oerke, 2006). Fungicides are expensive for smallholder farmers and require usage training. Hence they are used—if at all—only for high value cash crops.

Seeds can be bred (conventionally and through transgenic modification) to be tolerant to specific diseases. However, the sheer diversity of diseases across sub-Saharan Africa makes this approach unfeasible for more than a handful of highly prevalent diseases. Even then, the pathogens can evolve and become resistant, thereby requiring subsequent seed enhancements. Cassava is among the few staple crops that has demonstrated sustainable resistance to disease through (conventionally bred) improved seed varieties (Nweke, 2000).

KEY CHALLENGES

There are five main reasons why biotic stresses—which are dealt with easily in more industrialized economies—lead to such heavy losses for African smallholder farmers.

1. Integrated pest and weed control requires knowledge of sophisticated agronomic practices, which is beyond reach for most African smallholder farmers

Crop rotation, intercropping, push-pull mechanisms and management of soil and biomass, all require a robust understanding of agronomy. Most African farmers practice monocropping, and have limited understanding of the nuances of modern agronomy. Low rates of literacy, limited education and an inadequate system for agricultural extension services, all contribute to the continued lack of awareness of better agronomic practices. This greatly increases farmers' vulnerability to large-scale loss from infestation of weeds and pests.

2. Mechanized farming tools are not widely affordable

There are a large number of mechanized tillers available in industrialized countries at prices (for example, $200 to $500) that are quite affordable to middle class farmers. In a single use, such machines allow farmers to till the soil and effectively pull out and destroy weeds for the duration of the crop cycle.

However, such mechanized tools, and their fuel and maintenance supply chains, are too expensive for the typical African smallholder farmer. The lack of a larger distribution and repair services landscape across the region makes it less attractive for international companies to invest in developing lower cost mechanized tools specifically for African markets. Animal-drawn tillers can effectively reduce weeds and reduce farmers' workload compared to manual tilling, but their acceptance by farmers has been limited (Starkey, 1986).

3. General herbicides have not been available to smallholder farmers. Even if easily available, herbicides present secondary complications

Weeds are typically treated with general herbicides. While many of them have proven effective, general herbicides can also damage the crops they are intended to protect. In industrialized countries, farmers typically use enhanced (often transgenically modified) seed varieties. The lack of affordable herbicides, limited awareness of the value of herbicides and the absence of a distribution infrastructure for appropriate herbicides have all contributed to their limited use in sub-Saharan Africa.

There are also very few national-level R&D ecosystems, public or private, for developing improved seed varieties that are resistant to general herbicides and appropriate for local soils and other contextual factors. The absence of reliable local R&D ecosystems is particularly important, because seed varieties may need to be continuously improved in order to keep up with the evolving herbicide-resistance of the weeds. Where transgenic modification is the only option for continuous seed enhancement, the potential negative externalities associated with GMOs—and the policy restrictions—add further barriers.

4. Appropriate pesticides are either unavailable or unaffordable. Even where available, their risk of harm to health and the environment due to improper use is high

Pesticides tend to be available to farmers who live closer to urban areas. However, they have proven to be hazardous for both health and the environment, especially when used inappropriately. In sub-Saharan Africa, virtually all available pesticides are imported and smallholder farmers living in remote areas generally can't afford them. There has also been very limited R&D into pesticides using locally or regionally available raw materials and smaller scale production processes.

3. The private sector supply chain for fertilizer in Africa is very weak

In addition to the low demand, there are other hurdles to private sector investment in the African fertilizer market. The lack of access to financing discourages local dealers, who typically need to build up large inventories since demand tends to be seasonal and agriculture largely rain-fed. Unfavorable business environments and uncertain political environments have made international firms reluctant to enter African markets. The little private sector activity that exists is limited to small dealer networks concentrated near urban centers, serving peri-urban or larger farmers rather than rural smallholder farmers (World Bank, 2007).

4. Biological fertilizers are not yet a feasible large-scale alternative to synthetic fertilizers

As discussed earlier, animal and plant waste are traditionally used for other purposes (energy and animal food, respectively) and several hurdles currently prevent large-scale conversion of biological waste into fertilizer.

5. Dealing with native species of pathogens that adapt very well to local conditions often requires a range of localized products and interventions

Many pathogens tend to have two confounding characteristics: they come in a large number of locally-adapted strains and they can develop resistance to chemical/biochemical interventions. That, combined with many of the factors mentioned above (the unattractiveness of the African smallholder market, limited local/national R&D capabilities, the capital-intensive nature of factories to manufacture chemical/ biochemical products and the difficulty of distributing the products to remote areas) has meant that African farmers do not have access to the necessary products—biological or synthetic—to deal with pathogens.

SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

A small number of important systemic interventions are required to make fundamental improvements in the ability of African smallholder farmers to combat biotic stresses. These include improving agricultural extension systems and building an extensive, regularly updated registry of weeds, pathogens and animal pests in order to continuously collect local-level data on the evolving response of these biotic elements to changes in the ecosystem.

Beyond these interventions, two technology breakthroughs are required.

Breakthroughs:

1 2 3 4 5 6 7 8 9 10
11 12 13 14 15 16 17 18 19 20
21 22 23 24 25 26 27 28 29 30
31 32 33 34 35 36 37 38 39 40
41 42 43 44 45 46 47 48 49 50

10 New generation of affordable herbicides that are specific to most destructive weeds and are safe for humans

Herbicides are the most widely used method of dealing with weeds in industrialized markets. However, these are too expensive for the typical smallholder farmer in developing countries, and usually make economic sense only for high-value cash crops or in very heavily infested sites. Furthermore, most herbicides are non-specific, in that they can damage the crops in addition to the weeds.

As such, for optimum results they need to be accompanied by enhanced seeds. In addition, the ability of the weeds to develop resistance to herbicides means that the enhanced seeds will need to be periodically modified to keep up with adjustments in the herbicide to maintain crop yield. Given the limited R&D capacity in Africa and South Asia to continuously generate improved seeds, and the capital-intensive nature of herbicide production, it is not surprising that few customized solutions have been developed or scaled-up.

Novel herbicides are needed that specifically attack the most destructive weeds, but are harmless to the crops. Such herbicides must be more environmentally friendly than herbicides currently available in most markets, and be safe for human health.

To facilitate adoption and support local economies, an ideal herbicide would be based on agro-industrial raw materials and produced in smaller regional factories, thereby easing a major barrier to supply and distribution. Synthesizing such an herbicide will require significant R&D and will likely take 10 years (or more) to be market ready.

Current State

Development Stage: R&D

Time to market (years): <3 | 4-6 | 7-10 | 10+

Deployment: Extremely Challenging

Associated 50BT Chapters

Food Security

SDG Alignment

Impact

Increased Access to Food (# of People): <1M | 10M+ | 100M+ | 1B+

New Income Generated (# of People): <1M | 10M+ | 100M+ | 1B+

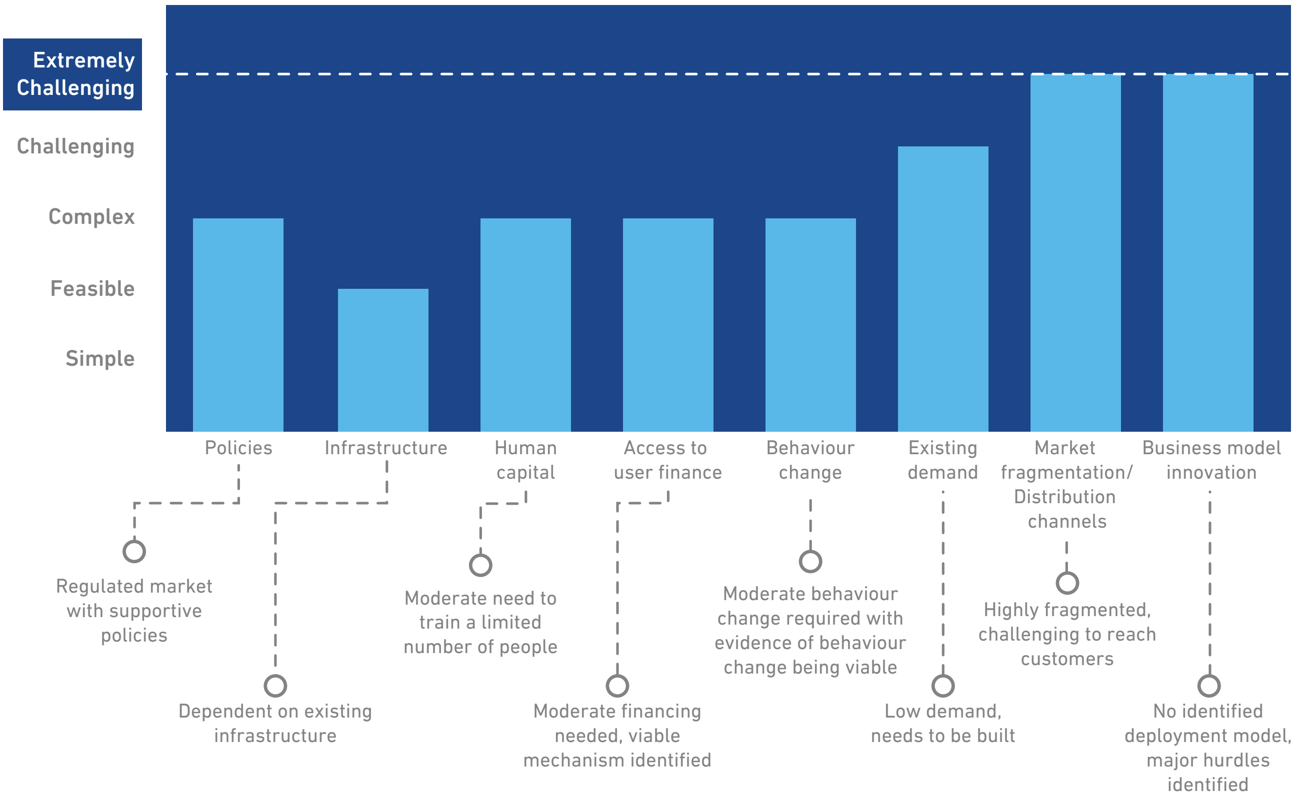
Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

Once such an herbicide becomes available, it will have to overcome limited demand, need for farmer financing, a highly fragmented market and a very sparse distribution network.

The difficulty of deployment will be EXTREMELY CHALLENGING.

Breakthrough 10: Difficulty of deployment



11 Novel, low-cost, environmentally friendly pest control mechanisms (chemical or spatial), specifically targeting the most destructive insects

Insects and other pests reduce potential yield by up to 15 percent for smallholder farmers in Africa. While crop damage is caused by numerous pests, a small number—borers, mealybugs, mites—cause a disproportionate share of these losses. Due to weak agricultural extension services, especially across Africa, it has proven extremely difficult to train smallholder farmers in optimal agronomic practices for integrated pest control.

A few farmers have access to general pesticides, but these tend to be harmful to the health of the farmers, as well as for the environment. Transgenic modifications to make crops repel pests (such as through the Bt bacterium) have many complicated externalities. Introducing them into any environment without the necessary infrastructure to study and manage these externalities can be a very risky proposition.

Spatial repellents emit particular sound frequencies and patterns, and may also be important for repelling on-farm as well as household pests. An important challenge is the limited scientific understanding of the sensory sensitivities of the many species of pests.

Considerable research is required to understand these sensitivities over the lifecycle of the pests, including variations between different sub-species.

Current State

Development Stage: R&D

Time to market (years)

<3 4-6 7-10 10+

Deployment: Extremely Challenging

Associated 50BT Chapters

Food Security

SDG Alignment

Impact

Increased Access to Food (# of People)

<1M 10M+ 100M+ 1B+

New Income Generated (# of People)

<1M 10M+ 100M+ 1B+

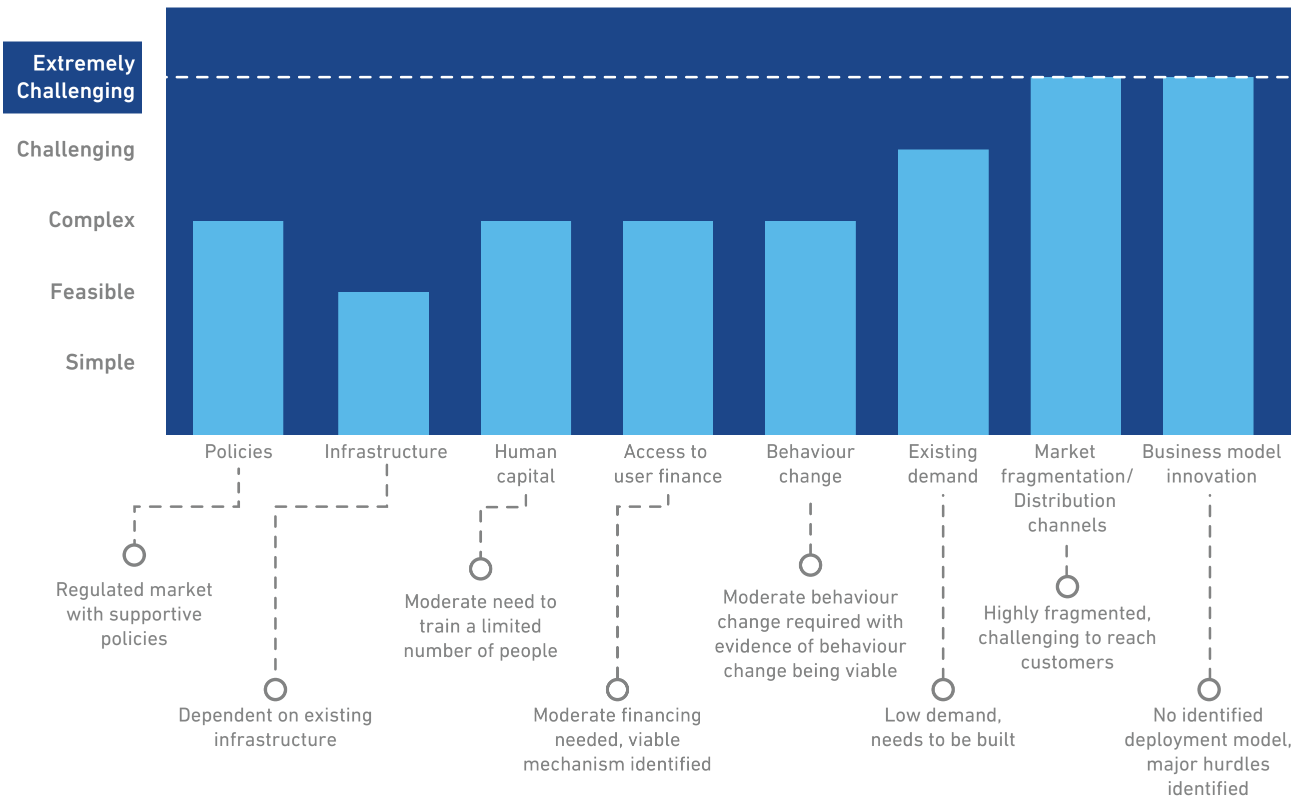
Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

A new type of pest control method is needed, specific to the most destructive pests and without negative effects on humans and the broader environment. If chemical-based, ideally it would be made from locally (or regionally) available agro-ingredients, to help catalyze the development of a large number of less capital-intensive production facilities closer to the market. Such a pesticide will require significant R&D; a major undertaking that may take more than 10 years before it becomes a reality.

It will also face many of the same challenges as a novel herbicide: low demand, need for financing, market fragmentation and the absence of reliable distribution networks. We expect that the difficulty of deployment will similarly be EXTREMELY CHALLENGING.

Breakthrough 11: Difficulty of deployment



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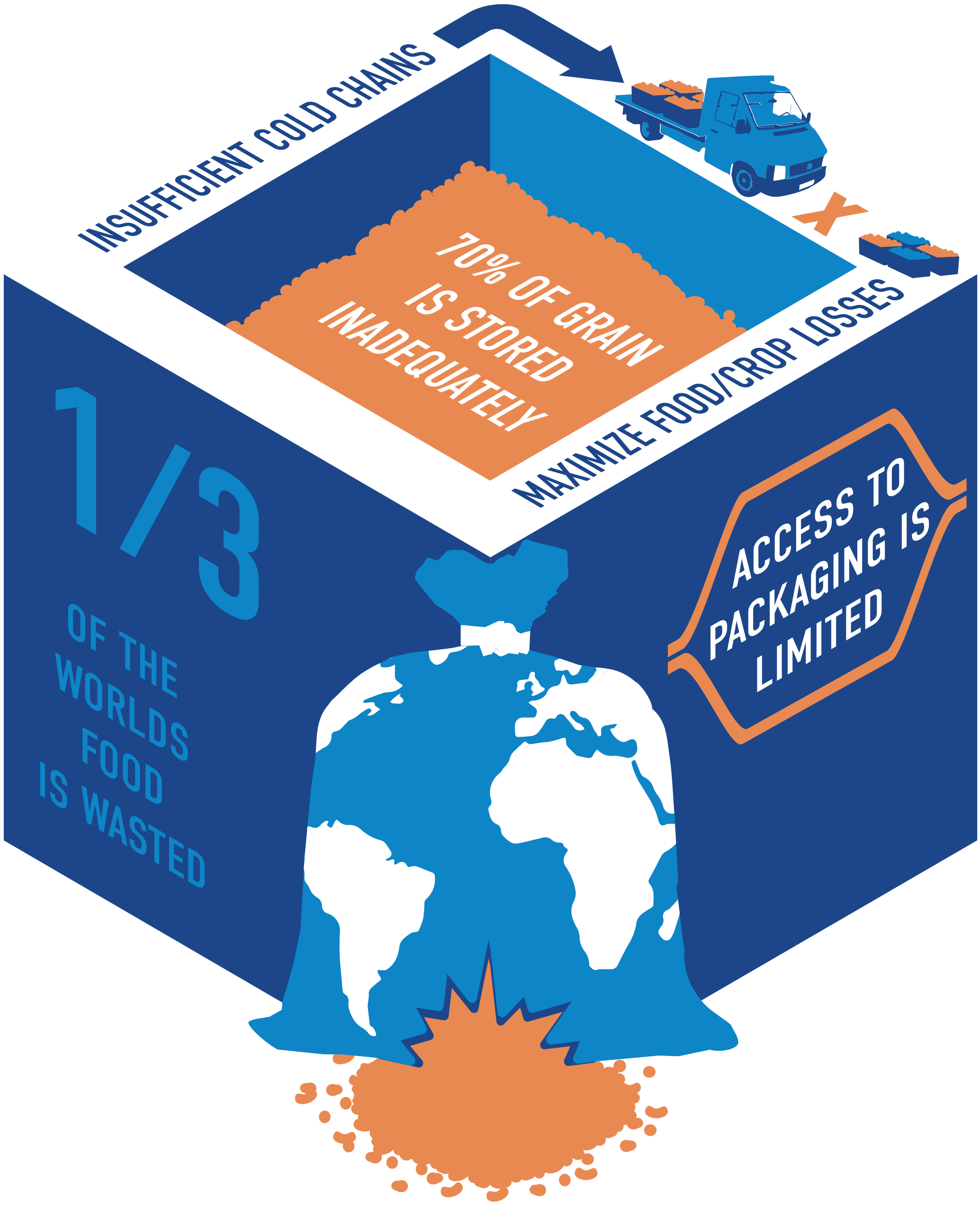


POST-HARVEST HANDLING AND STORAGE

INTRODUCTION

A substantial portion of the produce harvested in sub-Saharan Africa and South Asia is wasted before it can be consumed.

Considering the already low levels of productivity among smallholder farmers due to the factors discussed in other chapters (like lack of irrigation, fertilizers and nutritious fodder for livestock), this waste poses a significant additional economic burden on farmers, exacerbating the food insecurity they face. It is also a major contributor to the dearth of year-round, nutrient-rich food for farmers and their families.

There are a number of reasons behind post-harvest losses. To begin with, the lack of access to markets forces farmers to store their cereal in structures that offer inadequate protection from moisture and pests for many months. This problem is compounded by lack of access to adequate transport and limited local capacity to process the food. The absence of materials to appropriately package fruits and vegetables significantly reduces their shelf life. Finally, the lack of refrigeration makes it very difficult to preserve perishables like meat, dairy, fruits and vegetables.

Two technology breakthroughs can address these problems.

- Breakthrough 12. Affordable (less than $50) off-grid refrigeration for smallholder farmers and small agribusinesses
- Breakthrough 13. Commercial scale, affordable and energy efficient refrigeration/cold-chain systems for agribusinesses and transport of food

Four other innovations can also be important.

- Innovation: Easy-to-install, low cost structures for long-term grain storage
- Innovation: Improved processing and storage technologies to preserve food life and reduce degradation of nutritional content
- Innovation: Improved storage technologies for grains and pulses to reduce development of mycotoxins
- Innovation: Diagnostics to determine nutritional content and bioavailability of nutrients in foods

One-third of the food produced around the world for human consumption—totaling 1.3 billion tons—is lost or wasted. In industrialized countries most of the food wastage occurs after it reaches the consumer and is therefore not a burden on the farmer. In sub-Saharan Africa and South Asia, on the other hand, the bulk of the losses occur on the farm and during storage. This deprives smallholder farmers and small agribusiness of much needed income and exacerbates food insecurity.

CORE FACTS AND ANALYSIS

1. Large amounts of crops and food are wasted

Although the types of losses vary substantially between different parts of the world, food losses and waste occur everywhere. As **Exhibit 1** shows, North America, Oceania and Europe have the most per capita food losses, while South Asia[10] and sub-Saharan Africa suffer the least.

However, a larger share of losses in sub-Saharan Africa and South Asia occur before the food reaches the consumer and are therefore borne by the farmers. Combined with the comparatively lower production yields in both regions, these losses place a significant economic burden on smallholder farmers.

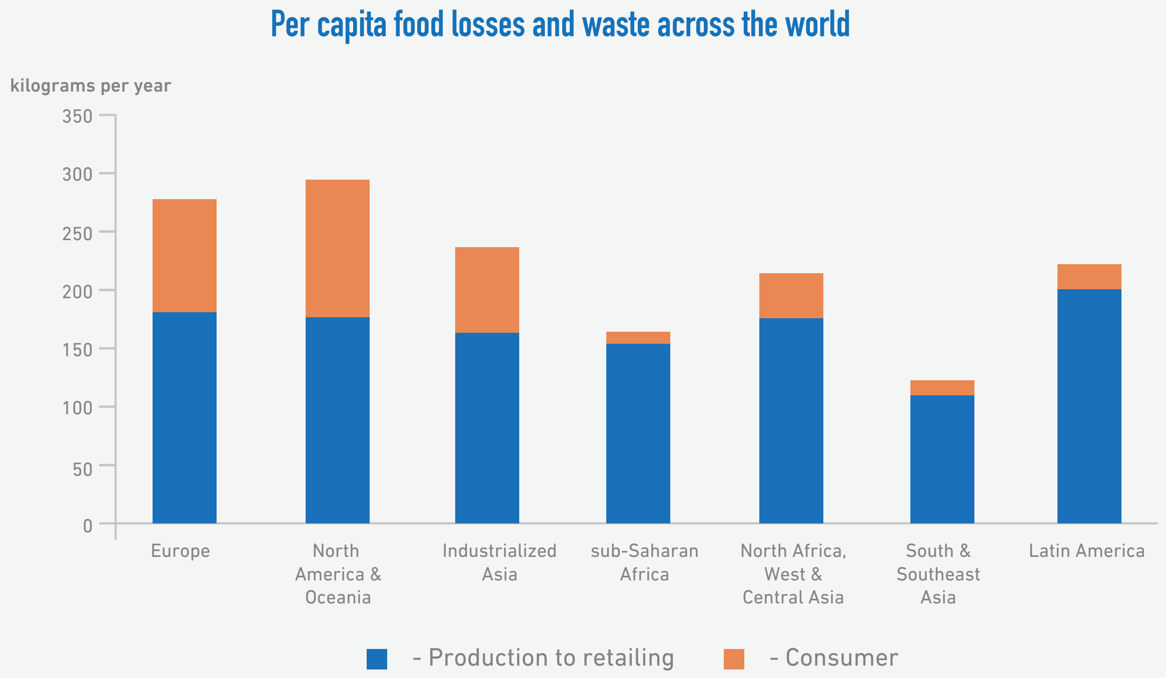


Exhibit 1: While food is wasted or lost in every part of the world, most of the losses in sub-Saharan Africa and South Asia occur before it reaches the consumer. (Source: FAO, 2011a)

2. While there are substantial losses of all types of food in sub-Saharan Africa and South Asia, perishable foods suffer much greater losses

Exhibit 2 shows the losses across regions and stages of the farm-to-consumer chain, for cereals, fruits and vegetables and meat. For all food types, a substantial portion of food loss in sub-Saharan Africa and South or Southeast Asia occurs well before it reaches the consumer. This is true of cereals, fruits and vegetables and meat.

The exhibit also shows that compared with cereals, there are higher losses of perishables between being harvested and distribution, because storing and preserving fruits, vegetables and meat requires more effort and resources.

Cereal losses occur due to moisture, temperature, pests, improper storage and incorrect handling, while the perishables are lost due to inadequate packaging and lack of access to refrigeration (FAO, 2011a; Gockel, et al., 2009). In addition to the economic loss, the wastage of such large quantities of fruits, vegetables and meat also deprives households and communities of much-needed nutrients.

[10]This exhibit from FAO combines data from South Asia and Southeast Asia.

Food losses and waste: cereals, fruits and vegetables, and meat

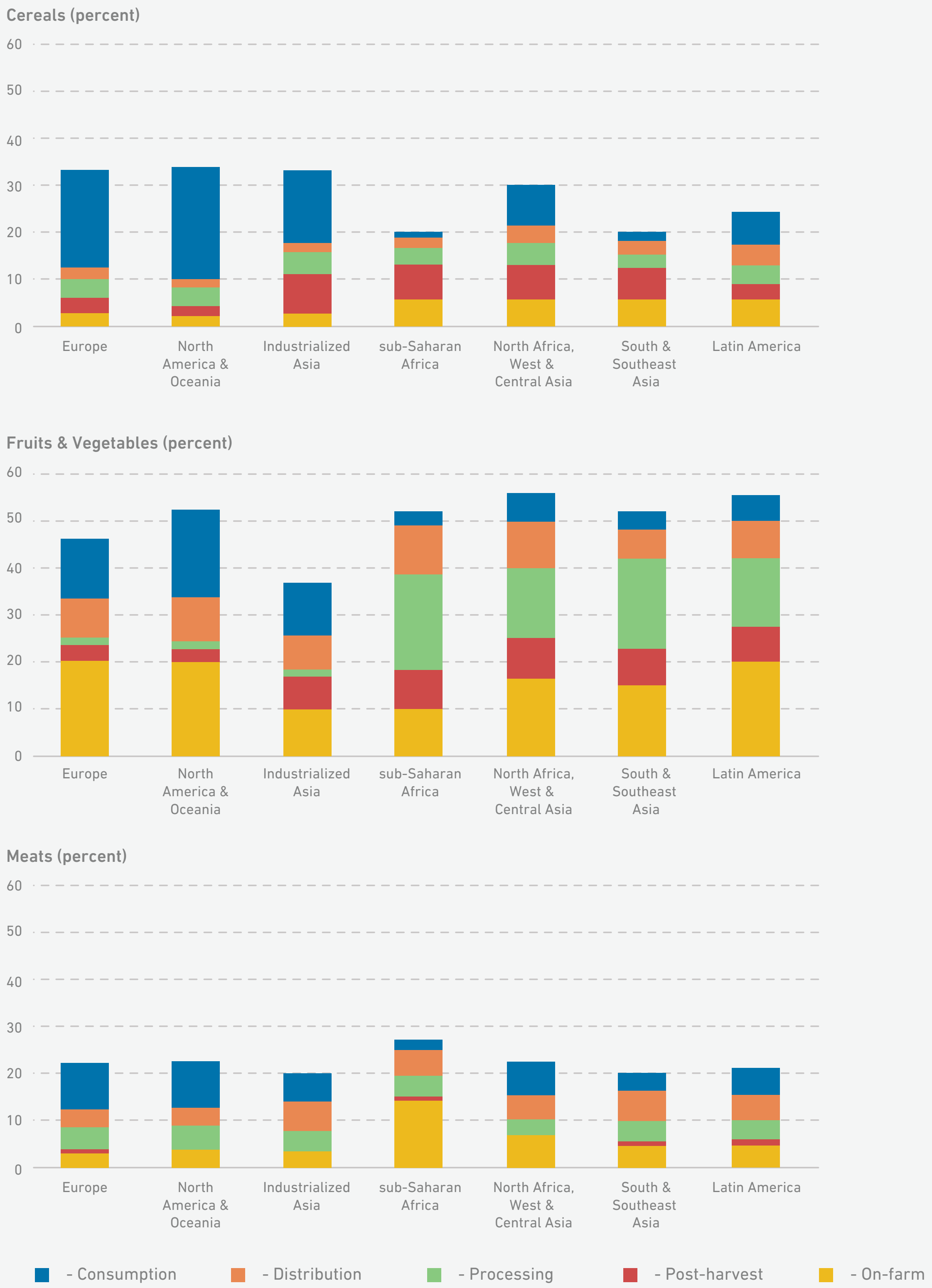


Exhibit 2: Across all types of commodities, smallholder farmers in sub-Saharan Africa and South Asia lose a substantial portion of their produce before it reaches the consumer or can be consumed by the farmers' families. Perishables (fruits, vegetables and meat) are lost more than cereals. (Source: FAO, 2011a)

In India, for example, a non-trivial portion of the total food production is wasted on the farm, during transport and storage or in the household. Jha et al. (2015) estimated that about 5 to 15 percent of most crops in India are lost during harvest or post-harvest (see **Exhibit 3**).

In general, dry crops, such as cereals and pulses, suffer less loss, while fresh crops such as fruits and vegetables show greater levels of loss. Crop losses occur during harvest due to farm-level technical and managerial issues. Spoilage during processing and distribution is largely a function of the available infrastructure (Lundquist, et al., 2008).

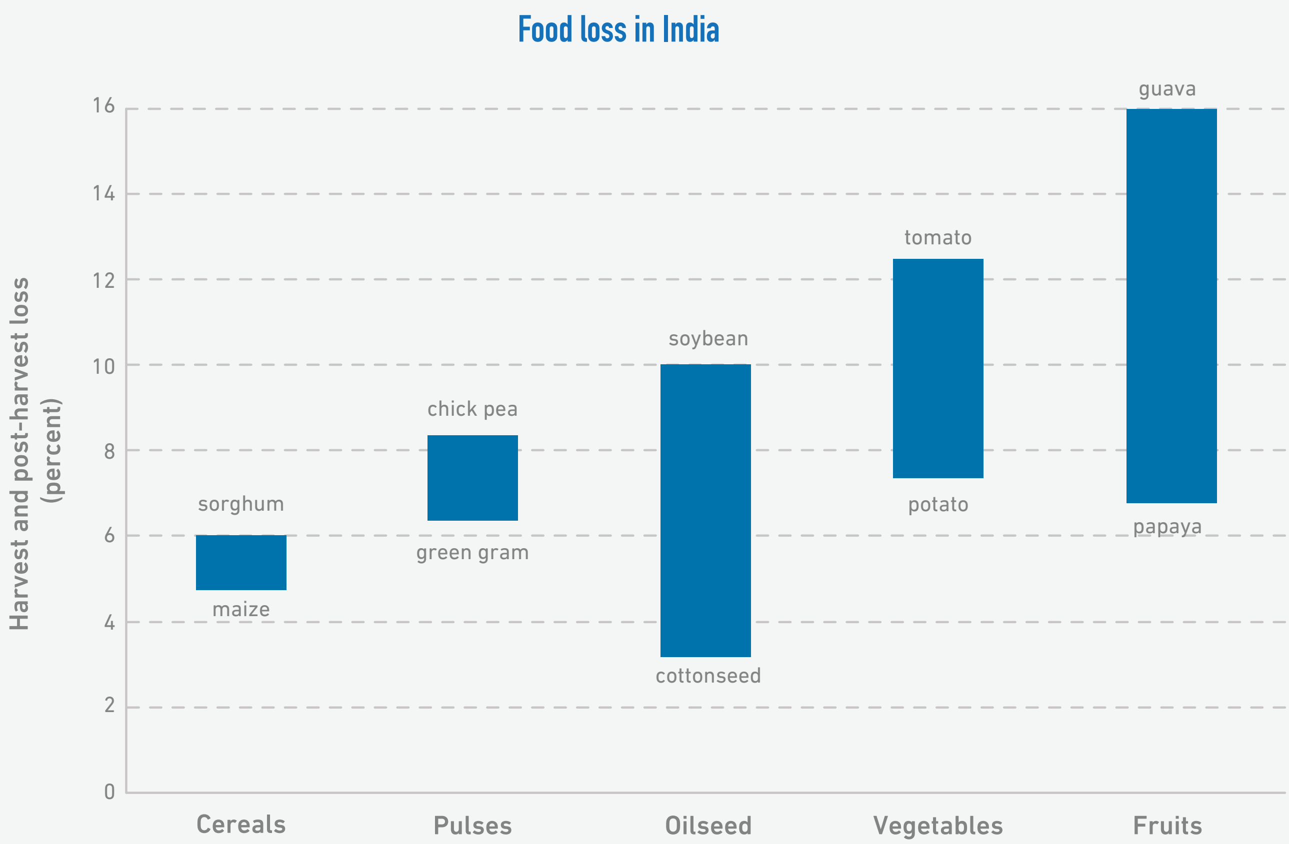


Exhibit 3: Roughly 5 to 15 percent of most Indian crops are lost during harvest or post-harvest. (Source: Jha, et al., 2015)

3. The specific causes of losses vary by type of commodity

Losses occur at various stages of the value chain and vary by type of commodity. Most of the losses for staple crops occur on the farm and post-harvest; cash crop losses occur on-farm, post-harvest and during processing, while the majority of horticulture losses occur during processing (FAO, 2011a).

Although the underlying drivers of these losses vary somewhat by type of crop, the absence of appropriate and affordable means for handling, storage and transport are the predominant factors.

Staple crops

Smallholder farmers who grow staple crops typically do not have access to farm machinery like threshing machines during or after harvest. As a result, 5 to10 percent of the output is lost during harvest and preparation. Another 10 to 15 percent of their produce is lost during on-farm storage (Gockel, et al., 2009). Farmers typically store the produce at (or near) their farms in structures that are highly vulnerable to pests such as rodents, weevils, large grain borers, moisture and excessive heat. Further losses occur when farmers try to access markets or processing facilities that are often far away and require transport.

The specific problems affecting staple crops are outlined below.

Drying
Inadequately dried produce results in diseases, such as aflatoxicosis, mold and rot. Many climates like that in much of West and Central Africa are not appropriate for effectively sun-drying crops. Most smallholder farmers do not have drying facilities and end up moving their produce to storage (which, as described below, is virtually always sub-standard) before it has dried adequately. Low-cost solar dryers are beginning to be used in some countries but have not yet achieved broad market penetration.

Packing and bagging
Grains must either be sealed (vacuum or hermetic) or packed with adequate ventilation. However, this is not common in Africa.

- 40 to 60 percent of smallholder farmers store grains for many months at home in bags made of plastic, jute or other fiber. Over-packing in such non-sealed bags can trap moisture and cause mold. Inadequate sealing allows additional moisture and pests into the bags. As a result, 30 to 45 percent of grain stored in such bags can be lost.

- 20 to 30 percent of smallholder farmers use metallic drums or clay pots to store grain at home. If stored in such containers without proper drying, the grain can rot due to moisture. Exposure of such containers to direct sunlight can accelerate grain deterioration. Between 20 percent and 30 percent of grain stored in such containers can be lost (FAO, 2011b; Gockel, et al., 2009).

- 5 to 15 percent of farmers use mud or brick silos, which offer adequate storage, but are too expensive for most smallholder farmers. Inadequate training in construction and maintenance can lead to losses of 5 to10 percent (FAO, 2011b; FAO, 1986; Natural Resources Institute, 2004).

- Fewer than 5 percent of smallholder farmers have access to reliable metal silos for storage. Even those who do, face the risk of theft (FAO, 2008).

Cash crops

Smallholder farmers tend to grow cash crops (like coffee and cocoa) only when they have reasonable access to markets, typically through a dealer or processor, as part of a value chain. There is a major dearth of local processing facilities for most cash crops produced in sub-Saharan Africa, which means that dealers and other intermediaries representing foreign buyers usually wield significant bargaining power in timing and price of purchase. Given the high premium placed on the quality of cash crops, sub-par produce can be devastating for farmers. Not only will such produce fetch lower prices but also a farmer's household cannot consume crops like coffee as a source of calories, resulting in not just economic loss but also food insecurity.

Most post-harvest losses of cash crops occur on the farm because farmers do not have an adequate understanding of, or tools to employ, optimal—often crop-specific—practices for harvesting and handling the produce. This risk of loss, combined with the absence of appropriate storage facilities and the urgent need for income, often forces farmers to sell their produce early, at below-market prices (as low as 30 to 50 percent of peak prices) (World Bank, 2011; Gockel, et al., 2009). The problems specific to cash crops are detailed below.

Crop-specific agronomy
Cash crops have very specific requirements in the harvest and preparation stages that are necessary for preservation and ensuring market-level quality of the output. Rough handling (for example, cotton stripping) during harvest can cause damage. Picking or harvesting when the produce is too immature, over-ripe or not uniformly ripe, leads to quality that is too low for buyers. (For example, coffee becomes too bitter if too many green cherries get mixed in). Post-harvest, when the produce takes too long to prepare (such as because the farmer does have the right tools like coffee pulpers) it deteriorates in quality and causes additional wastage.

When specific moisture-control conditions are not maintained during a crop's drying period, the produce can be susceptible to mold. Failure to adhere to crop-specific agronomic best practices results in up to 20 percent losses for many cash crops (FAO, 2001; International Cocoa Organization, 2012).

Transport
Cash crop farmers generally have target markets they need to access for their produce. However, limited availability of transport can lead to extended holding times, which leads to deterioration of quality. Across the various types of cash crops, up to 10 percent of market-ready produce is lost due to transportation delays (Hopper, 2013).

Processing
Most cash crops grown in Africa are processed elsewhere, because there is very little food processing capacity across the continent. Food processing equipment is capital-intensive and unaffordable for most African agribusinesses, and financing is not easily available. Consequently, African farmers capture a small fraction of the potential economic value of their produce.

Fruits and vegetables

Horticulture products (like fruits, vegetables and flowers) require very careful handling, packaging and often refrigeration in order to extend their life and maximize market value. Due to the lack of strong value chains and access to markets, few smallholder farmers who grow horticulture commodities sell their products—usually damaged to some extent during and after harvest—in local markets, often very low prices. Otherwise they consume the commodities at home. The specific problems affecting horticulture crops are outlined below.

Handling, sorting and disinfecting
Rough handling causes bruising and disease. Produce is often harvested too early (when it is not ripe) or too late (when it is overripe). Not eliminating decaying produce before storing it along with the rest of the produce causes fungi and bacteria to spread. Inadequate washing (such as, without soap or warm water) and poor short-term storage lead to infestation by insects and pathogens. Up to 30 percent of produce is lost due to such reasons (Kitinoja & Kader, 2003).

Refrigeration
Most fruits and vegetables are temperature-sensitive. Without reliable and affordable refrigeration for storage and transport,10 to 30 percent of produce is lost (Kitinoja & Kader, 2003).

Transport and processing
There is very limited food processing in Africa due to weak market linkages, high capital requirements and seasonal supply, which peaks immediately after harvest. As a result, farmers do not have the option of selling their produce in a functioning value chain.

Meat and dairy
Livestock food products are highly temperature sensitive and need to be consumed, processed, or refrigerated very soon after production. With milk, for instance, most of the losses occur during the processing and distribution stages (**Exhibit 4**), because rural smallholder farmers have little to no access to refrigeration and find it difficult to reach markets within the short shelf life of the product.

The lack of access to affordable, off-grid refrigeration is especially challenging for livestock farmers, since products deteriorate rapidly in warm temperatures (**Exhibit 5**). Fresh milk can last up to a day in 15 degrees Celsius but needs to be kept at 10 degrees Celsius to last two days and at 5 degrees Celsius to last three days. Fish needs to be at 10 degrees Celsius to last three days, while meat and butter can last longer in sub 20 degrees Celsius temperatures (Practical Action, 2012).

However, daily temperatures routinely get over 20 degrees Celsius in many tropical countries. In Kenya for example, the average daily temperature over the course of the year, across a nationwide cross-section of locations, is nearly 25 degrees Celsius. In many other countries, the average temperature is higher.

Waste in various stages of the livestock product value

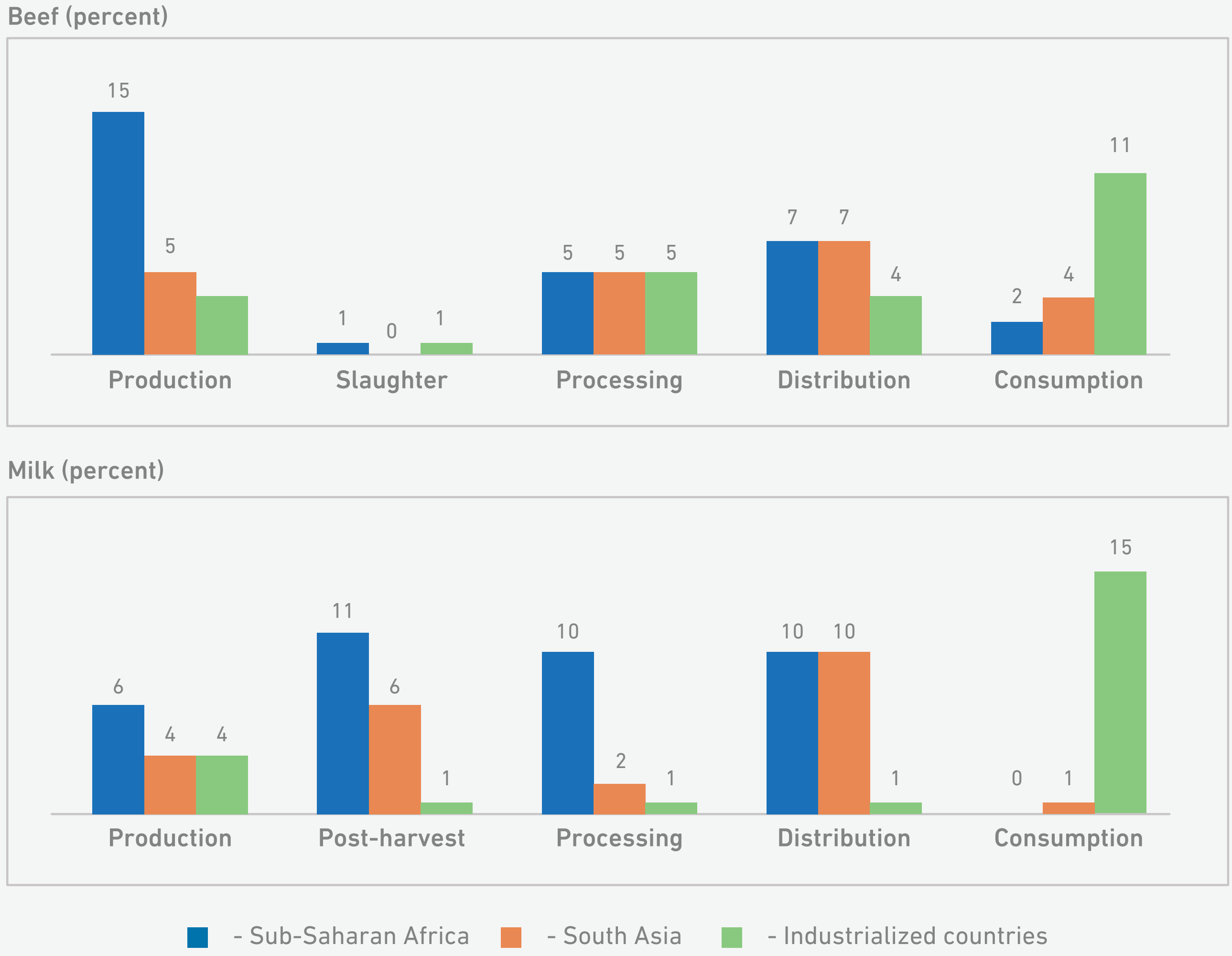


Exhibit 4: Across all types of commodities, smallholder farmers in sub-Saharan Africa and South Asia lose a substantial portion of their produce before it reaches the consumer or can be consumed by the farmers' families. Perishables (fruits, vegetables and meat) are lost more than cereals. (Source: FAO, 2011a)

Temperature sensitivity of various livestock products

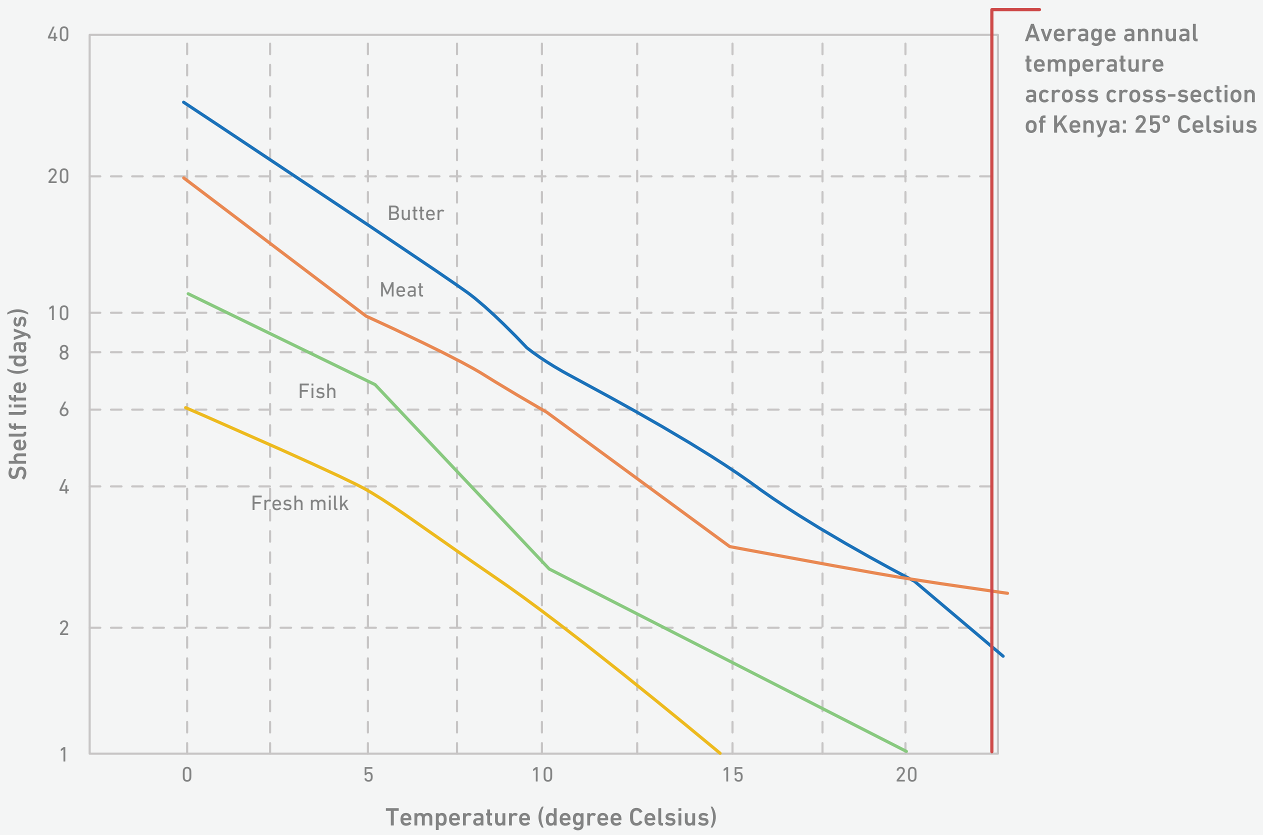


Exhibit 5: Livestock products, such as milk, fish, meat and butter, are highly temperature-sensitive. They need to be stored well below the average temperatures common to most tropical countries. Note: Vertical axis scale is logarithmic. (Source: adapted from Practical Action, 2012)

Only 14 percent of the rural population in sub-Saharan Africa has access to electricity (IEA, 2013) and only 3 to 4 percent of milk processors in countries like Ghana and Tanzania have access to refrigeration (ILRI, 2009).

Even in Kenya, Africa's largest milk producer, only 10 to 15 percent of all marketed milk is packaged or processed; most of it is consumed unpasteurized (Meridian Institute, 2012). Similarly, more than 90 percent of milk in Tanzania and Ghana, and 80 percent in India, is unprocessed (ILRI, 2009, 2011). This is equally true of all other livestock food products.

Because of their distance from markets and limited access to transportation, only a small fraction of cattle herders is able to take their milk to a sale-point.

In Ghana, for example, virtually 100 percent of milk producers and more than 70 percent of market intermediaries transport their milk by foot. As a result, almost 90 percent of milk producers sell their product at their farms or homes (ILRI, 2009). The only producers who have access to markets are those living near urban areas (World Bank, 2008).

KEY CHALLENGES

There are seven major gaps in post-harvest handling and storage, which lead to large losses in food and economic opportunity for smallholder African farmers. These have been discussed above in detail. The following is a summary of the main issues.

1. Limited access to markets

When farmers do not have access to markets for their produce, they are forced to either store the produce on (or near) their farms or sell it to intermediaries at below-market prices. Fewer than 30 percent of smallholder farmers in countries like Kenya, Ethiopia and Zambia sell higher value non-grain produce (Jayne, et al., 2005).

2. Poor grain storage facilities

Grain storage facilities need adequate temperature control and must be protected from moisture and pests. Nearly 70 percent of grain grown by African smallholder farmers is stored on-farm in structures construct by farmers from found material (Gockel, et al., 2009). Such structures provide inadequate protection against the elements and pests.

3. Lack of access to packaging materials for medium-term storage

In addition to larger storage structures, there are also no robust, affordable bags or smaller containers that African farmers can use to safely store their produce on or near their farms (Gockel, et al., 2009).

4. Lack of access to refrigeration

The optimum storage temperature for most temperate horticultural crops is close to 0 degrees Celsius (FAO, 1983). Temperature sensitive commodities like fruits, vegetables and flowers, deteriorate rapidly without refrigeration. There is no viable cold chain in the African agricultural ecosystem, near the farm, for transport or in much of the marketplace. Refrigerators, both standalone and for transport, are far too expensive for smallholder farmers. Moreover, farmers have very limited access to electricity and owning a refrigerator means the added cost of a diesel generator and fuel.

5. Limited local processing capabilities

Virtually all cash crops, as well as a sizable portion of grains, need to be processed so that they can be sold to the market in a usable or consumable form. There are currently very few commodities that can be processed fully in country. The farther the processing sites, the greater the likelihood of damage due to inadequate storage during shipping (Gockel, et al., 2009). The lack of transportation infrastructure, primarily usable roads and access to trucks, exacerbates the situation.

6. Poor transportation infrastructure and limited access to transport

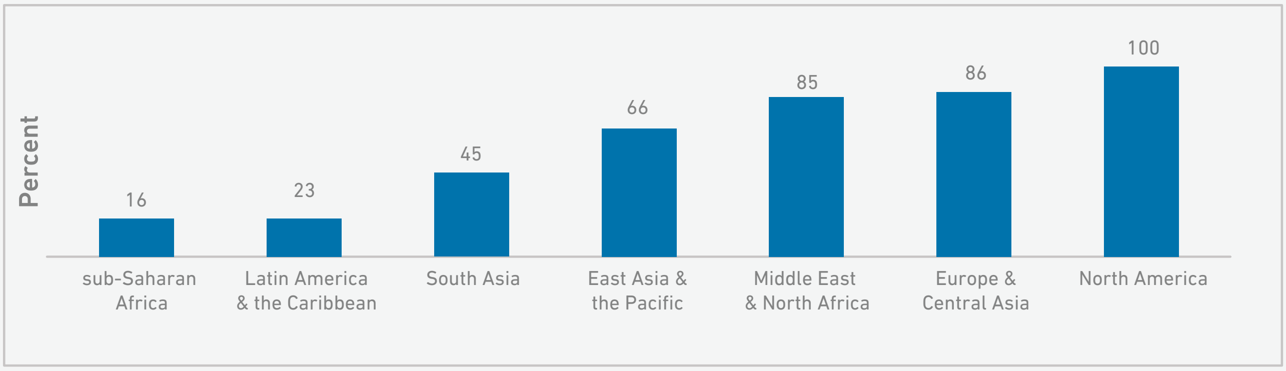
Only 16 percent of the roads in Africa are paved (**Exhibit 6**) and there are only 6.7 automobiles (cars, buses or trucks) for every kilometer of road. Smallholder farmers are often unable to transport their produce to markets that aren't in the immediate vicinity of their farms, unless they have access to a dealer, which only happens for high value cash crops.

7. Inadequate understanding of appropriate agronomic practices

In a demanding marketplace, buyers have much more negotiating power than smallholder farmers and small differences in handling can lead to major differences in the quality of produce. In such a scenario, the lack of adequate extension support and a clear understanding of subtle differences between various agronomic practices leads to considerable losses for the farmers.

Transportation infrastructure in different parts of the world

Percent of major roads that are paved



Number of vehicles (cars, buses and freight) per kilometer of road

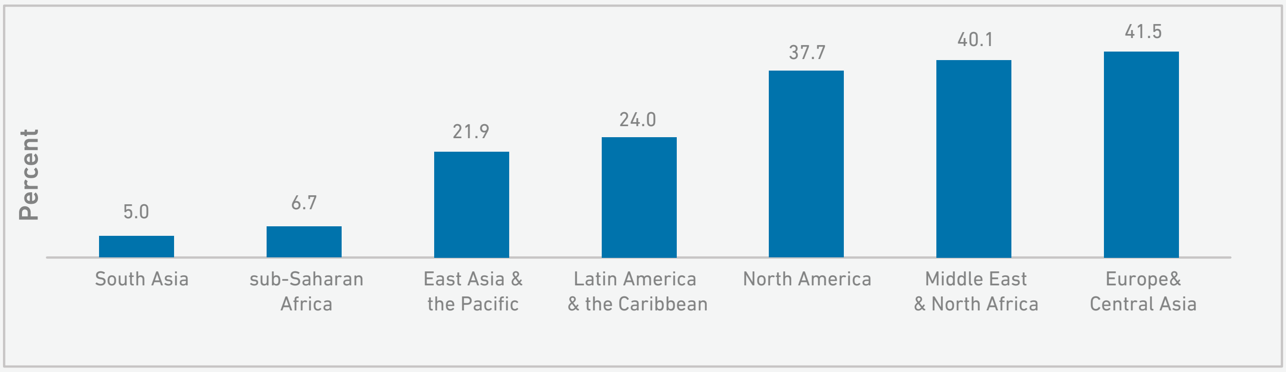


Exhibit 6: Smallholder farmers in Africa do not have any realistic means of transporting their produce to markets far from where they live. Only 16 percent of the roads are paved and there is a serious dearth of automobiles for transport. (Source: World Bank, 2014)

SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

In the absence of national-level systemic interventions like promoting agribusinesses, increasing local processing capacity, improving market access and improving transport infrastructure, agricultural losses can be reduced to some extent by training aimed at farmers. Such training can change the core handling and storage practices farmers use—especially for market-facing cash and horticulture crops delivered by others in the value chain. Keeping in mind the unique challenges that African (and, to a somewhat smaller extent, South Asian) smallholder farmers face, it is promising to see programs like the World Food Programme's Purchase for Progress (P4P) that aims to increase local procurement of aid food. Another promising sign is the emergence of technologies like low cost, ventilated solar dryers making their way into different markets. Notwithstanding these developments, we believe two technological breakthroughs and four additional innovations can make a meaningful impact on post-harvest losses.

Breakthroughs:

1 2 3 4 5 6 7 8 9 10
11 12 13 14 15 16 17 18 19 20
21 22 23 24 25 26 27 28 29 30
31 32 33 34 35 36 37 38 39 40
41 42 43 44 45 46 47 48 49 50

12 Affordable (less than $50) off-grid refrigeration for smallholder farmers and small agribusinesses

The absence of affordable refrigeration and electricity severely limits the ability of smallholder farmers to produce, preserve and sell perishable commodities like vegetables, fruits, meat and dairy. Such products are highly sensitive to temperature, and the lack of refrigeration dramatically reduces their shelf life, especially in tropical climates.

While there are some inexpensive refrigerators available in emerging markets like India and China, they still cost more than $100, need reliable electricity and are difficult to repair once damaged. A new kind of refrigerator that costs less than $50 and can run on solar power will help smallholder farmers provide better nutrition for their families, and take high-value commodities to market, thereby increasing their incomes.

There is a recent resurgence of interest of very affordable age-old traditional cooling technologies (like clay pots). While this showcases the potential demand for an affordable and durable solution, traditional options like clay are subject to biological contamination and difficult to clean. Moreover, as agricultural systems advance, there will be greater need for commodity-specific temperature control. Furthermore, it is difficult to see traditional cooling solutions leading to modern and profitable agricultural value chains.

To serve the needs of rural, low-income farmers, refrigerators need to be operable off-grid (like solar-powered), considerably less expensive than the current $100 range and easy to repair. Such technologies appear to be on the horizon.

A new generation of refrigerators using thermoelectric technology is beginning to reach the market, supplementing existing vapor-compression models. Given the broad demand for refrigeration there is reason to believe that an affordable product will gradually reach a critical mass of smallholder farmers—notwithstanding the usual problems of market fragmentation and distribution.

Current State

Development Stage: Engineering

Time to market (years): <3 | 4-6 | 7-10 | 10+

Deployment: Challenging

Associated 50BT Chapters

Food Security

SDG Alignment

Impact

Increased Access to Food (# of People): <1M | 10M+ | 100M+ | 1B+

New Income Generated (# of People): <1M | 10M+ | 100M+ | 1B+

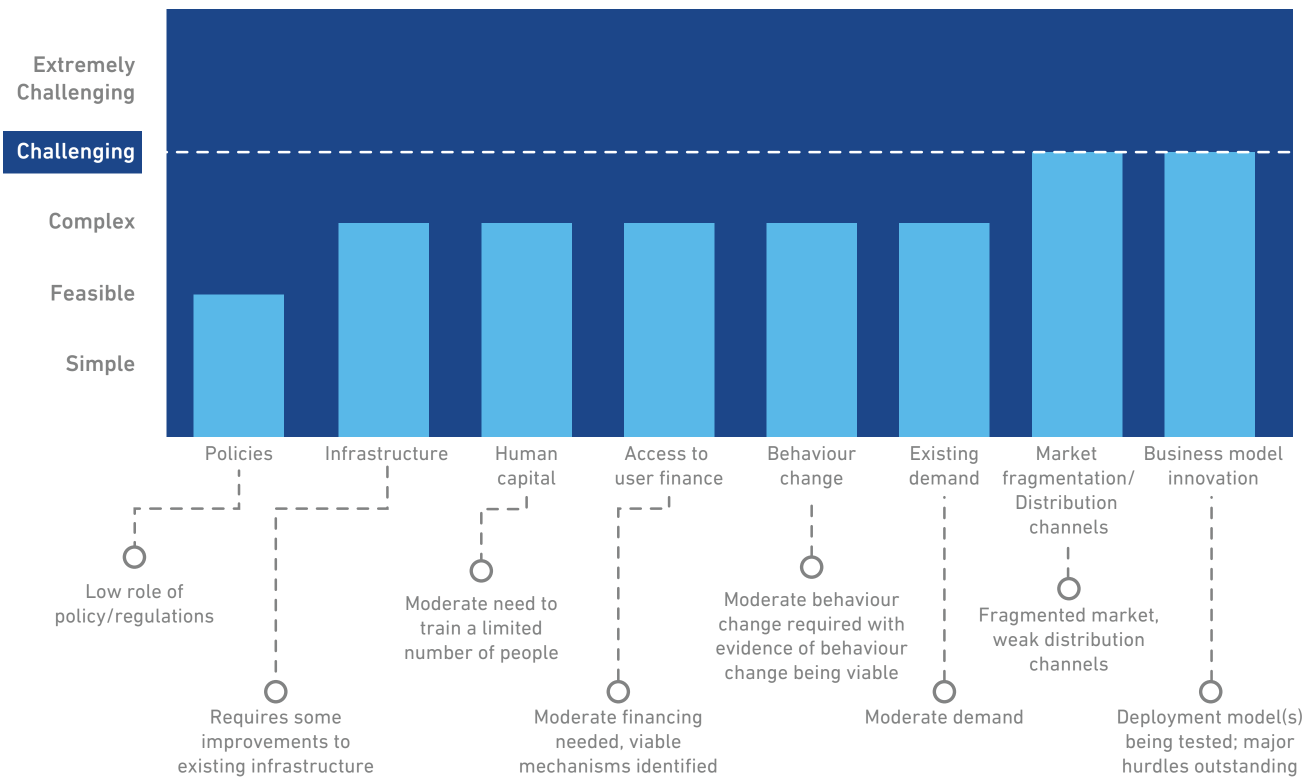
Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- **Attractive for emerging markets (lower profits)**
- Emerging markets potential; requires derisking (sustainable)
- Non-commercial (unprofitable)

Based on the above, it is likely only a matter of three to four years before low cost refrigerators become practical for rural farmers. Despite the need and expected demand, such a technology will face considerable barriers to deployment due to the fragmented nature of the market, the absence of a value chain for distribution and maintenance and the need for financing for farmers.

Hence, deployment will be CHALLENGING.

Breakthrough 12: Difficulty of deployment



13 Commercial scale, affordable and energy efficient refrigeration/cold-chain systems for agribusinesses and transport of food

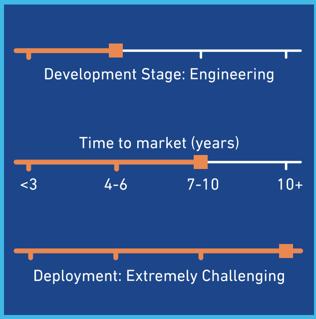
The ability to transport food to markets while preserving freshness will not only reduce post-harvest losses, but also create new value propositions for smallholder farmers. The absence of such cold chain infrastructure is one of the factors limiting access to market for higher-value produce (for example, horticulture; and as the Livestock section discusses, meat and dairy). The lack of refrigeration also reduces everyday access to a diverse base of nutrients for children and the population in general.

Refrigerated trucks available on the market today cost tens of thousands of dollars, require diesel and are built for smooth roads. To be useful to dealers and agribusiness entrepreneurs who serve smallholder farmers in remote areas, refrigerated storage chambers and transport vehicles will have to be robust and cost significantly less than $5,000. While advances in stationary refrigeration technologies can also help advance mobile refrigeration, there are a number of significant differences.

First, stationary refrigerators normally operate indoors, whereas transport refrigerators will have to operate outdoors, under much warmer ambient temperatures and harsher conditions.

Second, while a major challenge for stationary refrigeration is the absence of reliable electricity, transport refrigerators can use the fuel used to power the vehicles. Third, refrigerated vehicles will become affordable only after general-purpose vehicles become affordable. Based on the above analysis, the projected time to market for such technologies is five to seven years.

Current State

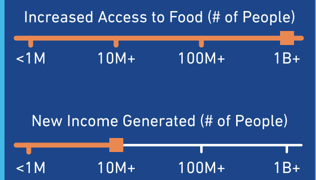


Associated 50BT Chapters

Food Security

SDG Alignment

Impact



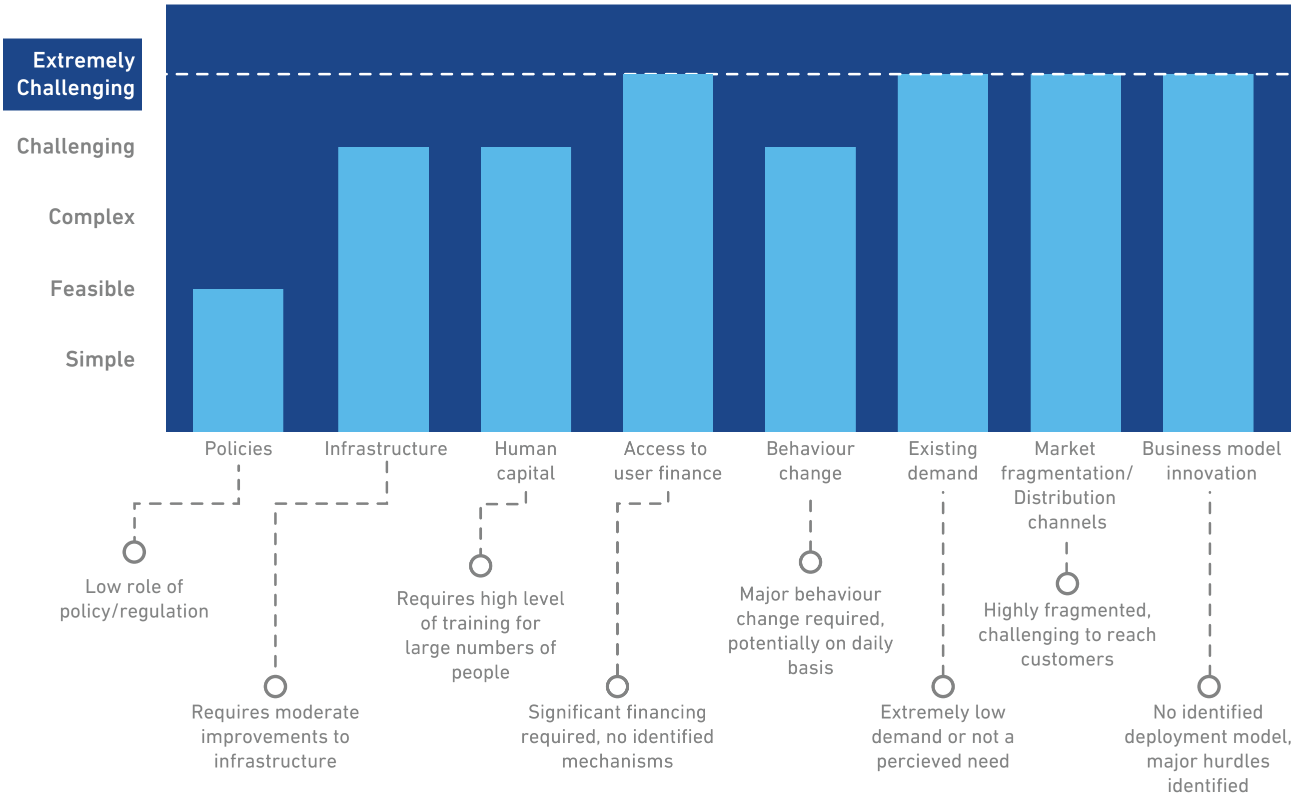
Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- **Attractive for emerging markets (lower profits)**
- Emerging markets potential; requires derisking (sustainable)
- Non-commercial (unprofitable)

Even when such a technology is developed, deployment will be difficult. The market is extremely fragmented and adoption will depend on the growth of the broader market for the relevant agricultural commodities. In addition, poor road infrastructure and the sparse presence of fueling stations will be a major hurdle in the usability of refrigerated transport.

Finally, a maintenance and repair infrastructure (currently absent) will be necessary to keep these refrigeration facilities functioning. We estimate that deployment will be EXTREMELY CHALLENGING.

Breakthrough 13: Difficulty of deployment



Innovation: Easy-to-install, low-cost structures for long-term grain storage

Most smallholder farmers in sub-Saharan Africa are subsistence farmers and primarily grow cereal crops. They have to store their produce for several months on (or near) their farm because a large portion of it is for their own consumption.

Currently, most storage structures used by such farmers are made from mud, twigs, straw and other easily and locally available raw materials and are highly vulnerable to the elements and pests. As fragile as such structures are, they do not cost the farmers much in cash terms. On the other hand, a reasonably durable structure (like with a concrete foundation, sturdy walls and roof resistant to rain and pests) could cost several thousand dollars, which is decidedly unaffordable for the farmers.

A structure made with a new type of material, which is lightweight (so it can be easily transported to remote areas that may not be connected by paved roads), easy to assemble (so it does not require the technical skill necessary to build traditional brick-and-mortar structures), durable (does not need extensive or regular maintenance) and with some form of ventilation (to prevent accumulation of internal moisture) can address this problem.

The value of such structures can be augmented by durable, low cost material for constructing medium-term storage containers (boxes or bags), which offer similar levels of protection.

Durable, lightweight materials (such as structured insulated panels and flexible PVC) as well as promising materials for short and medium-term storage exist but have not penetrated the African market yet.

These products are currently too expensive and/or untested for use at a large scale. With a lack of developed markets and scarce economic incentives to invest in R&D, it is unlikely that there is enough private investment going into adapting existing materials for use by smallholder farmers. We believe a solution is three to five years away from being market-ready for the African smallholder farmer.

Once such a product becomes available, it will face a number of major deployment challenges: the extent of market fragmentation; the likely lack of initial demand; the need for financing and the absence of established distribution channels. Based on the above factors, the difficulty of deployment is extremely challenging.

Innovation: Improved processing and storage technologies to preserve food life and reduce degradation of nutritional content

Due to the seasonal nature of agriculture, farmers experience major swings in the availability of different foods. This is often most acute with fruits and vegetables, which spoil fairly rapidly after harvesting, leading to limited availability. Drying and processing preserves the life of food and often its nutritional content, thereby reducing the seasonal nature of hunger.

Specific technological needs vary depending on the food items (for example grains versus vegetables). In general, however, drying, processing and storage technologies need to be less capital intensive and should preserve as much of the nutritional content of the crop as possible. This is an area of emerging research. Milling rice, for example, often strips away nutritional content in the germ, although it also removes phytates, which bind nutrients and can prevent their absorption. The full impact of processing on nutrition requires continued research for improved understanding.

In most cases there is no fundamental technological issue to overcome. Rather, these are technologies that have traditionally received minimal attention. While there are some technologies capable of, for example, hermetic or air tight storage, none are at a cost low enough to enable large-scale deployment. When it comes to drying and processing technologies, the primary constraint is developing a technology with a low enough cost to enable a sustainable deployment model.

The projected time to market readiness varies widely. Some new products may enter the market within one to two years, while other products have received such little attention that they will likely not be introduced for seven to 10 years. The difficulty of deployment is similarly varied, but due to low margins and the need to target remote and rural areas the expected difficulty of deployment is challenging.

Innovation: Improved storage technologies for grains and pulses to reduce development of mycotoxins

Mycotoxins are poisonous compounds that are created primarily by fungi that accumulate during harvest and post-harvest storage and processing. The FAO has estimated that as much as a quarter of the world's crops could be contaminated with mycotoxins. The problem is believed to be most acute and least understood in sub-Saharan Africa, followed by South Asia. In particular, aflatoxins are known to build up in maize and groundnuts, when crops are improperly dried and/or stored in cool, damp places in the household. Chronic exposure to mycotoxins has been linked to malnutrition, impaired immunity and various forms of cancer.

There are multiple approaches to preventing contamination from mycotoxins. Storage technologies have focused on prevention of insect infestation, which can cause exposure to fungal spores, and technologies to reduce condensation. Biological strategies include development of fungi or bacteria that can outcompete the fungi that produce mycotoxin. Chemical strategies have generally focused either on compounds that prevent insect infestation or those that prevent the growth of fungi.

Different approaches are at various stages of development. Several compounds are being tested and some are nearly market ready. However, any successful technology will face major deployment challenges. Mycotoxin poisoning is poorly understood by most smallholder farmers. Moreover, there are few distribution channels that address smallholder farmers, where most contamination occurs. While market readiness varies by technology, some technologies could be ready within two to four years. The difficulty of deployment for any technology is extremely challenging.

Innovation: Diagnostics to determine nutritional content and bioavailability of nutrients in foods

Many nutrition interventions rely on provision of fortified foods to address nutrient gaps. While there are multiple processes to fortify staple foods, it is challenging to assure quality and control safety due to the difficulty of assessing nutritional content in food. Assessments are usually made in laboratories, which are rarely sufficiently resourced to either accurately assess nutritional content of food or handle the sheer number of samples that need testing.

Due to this lack of quality assurance, a major nutrition agency has estimated that as much as half of fortified food staples do not actually contain enough supplemental nutrients to create desired health benefits. In order to address this issue, better diagnostics are needed that can assess the nutritional content and bioavailability of nutrients in food. The ideal device would produce rapid results and be usable in a field rather than lab setting.

Little applied research is underway in this area. Only a small number of universities or companies are developing rapid micronutrient testing devices, with at least one nearing market release. Further work related to precision, validation and local reagent production need continued research. Detecting vitamin B9, iodine and zinc deficiencies, in particular, require rapid diagnostic technologies.

The current market for such devices is concentrated. Only a small number of entities have an existing need for such a device. These institutions could benefit greatly from such a diagnostic and may be somewhat price insensitive, although cost is still expected to be a major barrier. A dearth of commercial demand for diagnostics and a lack of willingness within local governments to enforce micronutrient testing in food remain significant hurdles. The projected time to market readiness is about one to three years, and the difficulty of deployment is complex.

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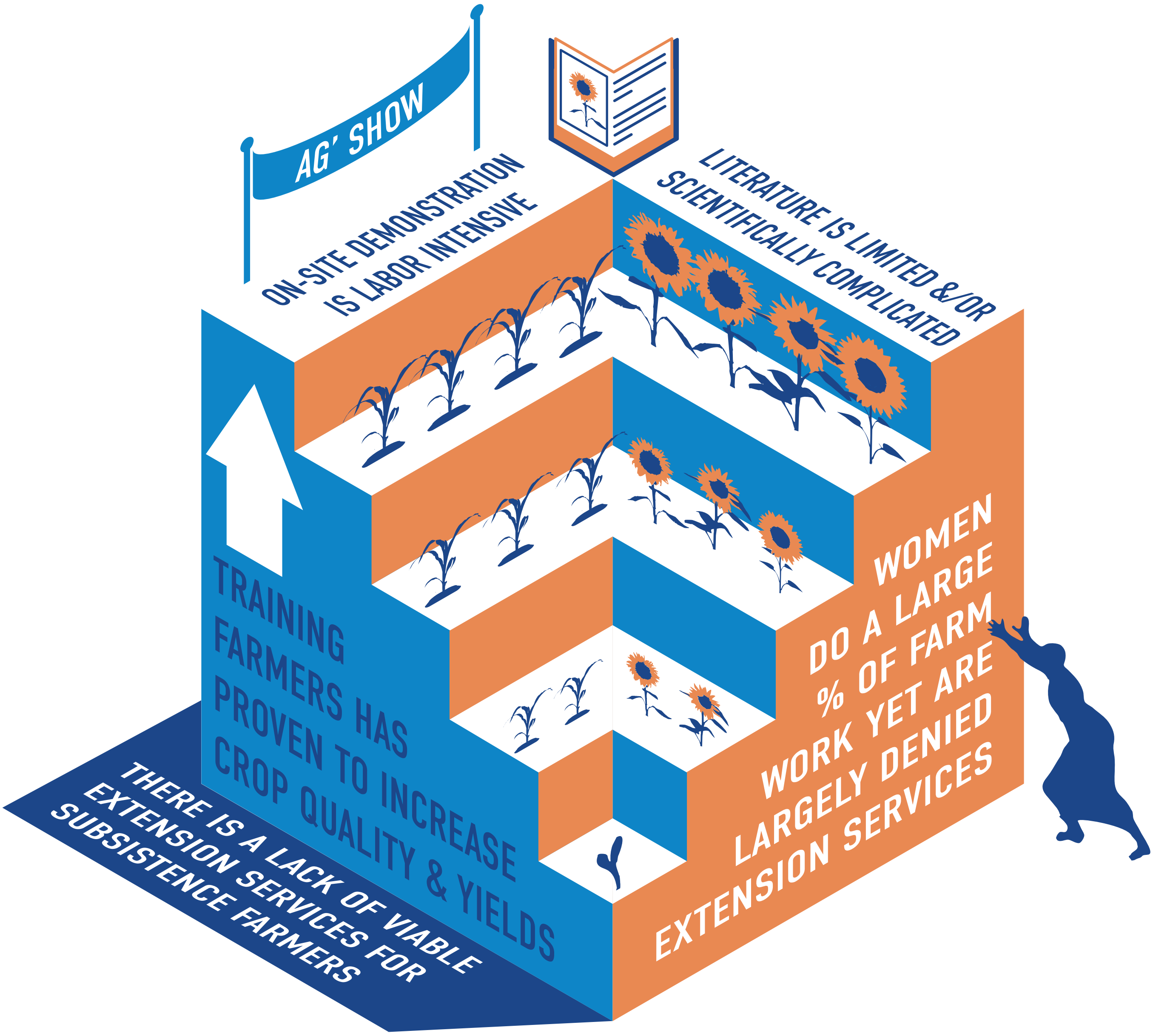


EXTENSION SERVICES

INTRODUCTION

The training and technical support provided to farmers by professional agents, collectively known as extension services, are very important for improving food security.

Farmers can significantly improve yields and quality through better management of inputs like water and fertilizers, maintaining soil health and using appropriate harvest and post-harvest techniques. Changing traditional agronomic practices is extremely difficult, particularly when the new recommendations seem counterintuitive to farmers or require more effort and investment. Bringing about such a change needs ongoing training, support and follow-up from knowledgeable and committed extension agents.

Government-provided agricultural extension services are the primary form, and usually the only form, of training available to smallholder farmers in low-income regions. In many countries, the quality, relevance and accountability of extension systems are questionable, and the meager government budgets allocated for providing these services do not offer much scope for improvement.

In recent years, ICT innovations have helped improve the content quality, reach, and efficiency of extension work. While the current state of ICT devices (like smartphones and tablets) allows the creation and dissemination of valuable information, there is still a dearth of appropriate and engaging content. Moreover, training alone is not sufficient for farmers. Extension services need to include value-added interventions for saving crops and livestock from disease and for improving quality (and hence income potential) of high-value commodities like cash crops. Two technological breakthroughs, which are both amalgams of numerous smaller advances, can enable such services.

- Breakthrough 14. An affordable and portable toolkit for extension workers, which includes a core set of devices for testing crop health, livestock health and quality of produce
- Breakthrough 40. A new generation of wireless broadband network technologies that radically cut the cost of expanding coverage to rural areas

Extension services conduct training of farmers on a range of issues like agronomic practices, appropriate use of fertilizer and other inputs, pest management, mechanisms to access financial support, natural resource management, livestock health and management, and access to markets or intermediaries. Given the low level of technical knowledge among African smallholder farmers,[11] revamping extension services constitutes a major opportunity for improving agricultural yields and food security in the region.

[11] As with other aspects of agricultural development, there has been considerable work in recent decades to strengthen extension systems in South Asia (Swanson, 2006, 2008). As such, this discussion focuses on sub-Saharan Africa.

CORE FACTS AND ANALYSIS

1. There is a wide variety of agricultural extension methods

Extension services can be characterized along three dimensions: provider type, content type and channel. In principle, a broad range of providers across the public-private spectrum deliver extension services (**Exhibit 1**).

Some are free services provided by government agencies, NGOs, or value-chain partners (like food companies, processors or intermediaries). Some services are fee-based, provided by private individuals or organizations, representatives of farmer organizations or others.

The topics cover the full range of issues relevant to crop and livestock farmers: crop management, usage of inputs like water and fertilizer, pest management, understanding of market prices and dynamics, information about weather patterns and changes, treatment and management of livestock and negotiating with value chain partners, among others.

These services can be provided in-person (individually, to a group, or to representatives of farmer organizations who can then serve as trainers to others), or through ICT tools and devices using video recordings or interactive platforms like call-in radio programs and phone messages. In short, there is no single modality for delivering extension services.

Types of extension services and models

Provider Types

- Government
- NGO (with fee-for-service)
- NGO (free service)
- Private value chain partner
- Private fee-for-service
- Farmer organization
- Community member
- Universities or research institutions

Content Type

- Inputs usage
- Plant management
- Livestock rearing
- Post-harvest processing
- Market information
- Weather information
- Farming business training
- Natural resource management

Channel

- In-person, verbal
- In-person, demonstration
- Train-the-trainer
- Peer-to-peer sharing
- Two-way ICT (Internet or mobile)
- One way ICT (radio, video)
- Written/Print

Exhibit 1: Extension services cover a broad range of topics including usage of inputs like water and fertilizer, plant management, livestock rearing and treatment, business best practices, and understanding of the market. This content can be delivered by a range of providers (like government, private for- profit or private non-profit) and through a range of channels. (Source: ITT analysis)

About 80 percent of extension services in sub-Saharan Africa are provided by local government agencies, with most of the remaining split between international and local NGOs. Private sector actors (like value chain partners or fee-for-service providers) account for less than 5 percent of the total volume of services. Funding for these services, on the other hand, comes from a broad range of sources including country governments, multilateral and bilateral donor institutions and private foundations.

Most of these services are free, with farmers paying for a very small portion of the services. **Exhibit 2** shows this data, estimated from aggregation across various sources (Interview, 2013).

Sources of funding and management of extension services in sub-Saharan Africa

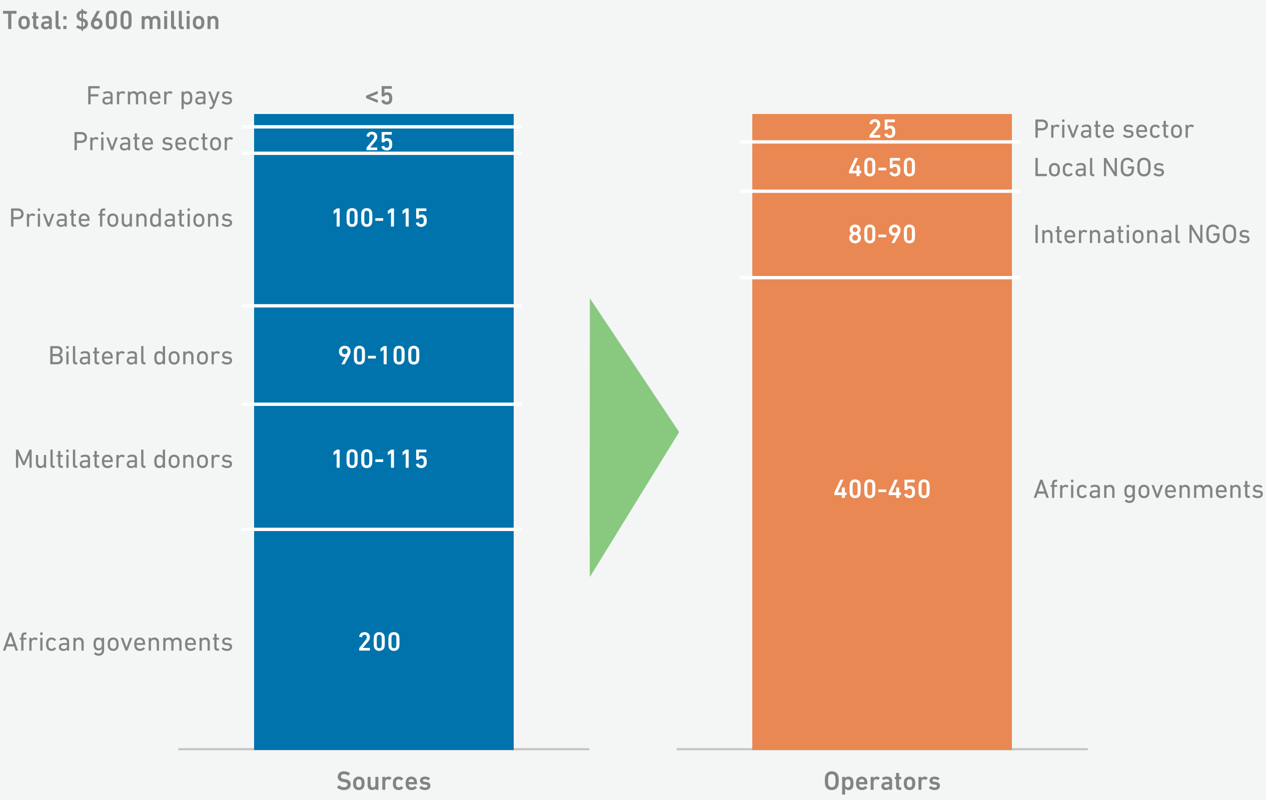


Exhibit 2: About 80 percent of the extension services for farmers in Africa is provided by their governments, with most the remainder of the services provided by NGOs. Private providers account for a very small portion of the services. About one-third of the funds for these services come from the local governments. Multilateral, bilateral and private philanthropic donors account for the bulk of funds.
(Source: Interview, 2013)

2. There are many case examples of the value of extension services in improving agronomy, and thereby, agricultural output

Perhaps the most important focus of extension services is the improvement of agronomic practices. It is very difficult to conclusively determine the contribution of improved agronomy—in exclusion of other factors—on improvements in yield and quality of produce.

There are, however, some prominent examples. In Ethiopia, farmers of teff (the national grain) have traditionally broadcast their seeds (manually scattered) to sow them. Conventional belief was that more seed would result in more teff.

Five years ago, researchers in Ethiopia showed that teff seeds that were planted in rows (rather than being scattered all over the field) showed a 50 to 80 percent yield improvement with 90 percent reduction in the amount of seeds needed for sowing (which represent a significant cost for the farmer).

The teff also exhibited stronger stalks and bigger leaves (ATA, 2012; IFPRI, 2013). There are many other similar examples of the value of extension services (Swanson, 2006, 2008).

A recent innovation in extension services is the use of digital technology to help farmers identify and overcome agricultural pests and disease. A leader in this field is the Plantwise Knowledge Bank developed by the Centre for Agriculture and Bioscience International (CABI, 2018).

This online resource to help combat plant health problems includes a diagnostic tool with country- or region-specific information that farmers and extension workers can use to find out what problem might be affecting crops.

A search function allows them to find information on management of pests and diseases, and maps are available to view the distribution of pest species. The platform contains more than 10,000 factsheets, which are short, practical guides that can be taken offline into the field to identify a plant pest and find an effective solution.

Plantwise works with national implementing partners to organize plant clinics in 34 countries, which are analogous to health clinics where human ailments are diagnosed and treated. In plant clinics, local plant health extension officers provide diagnoses and management advice to farmers.

The system is also useful to policymakers, as information collected at plant clinics is aggregated and analyzed to better respond to emerging and crop problems (Powell, 2017).

3. Despite the evident need and opportunity, African farmers receive little in the way of quality extension services

The predominant form of extension service delivery is in-person verbal advice, also known as travel-and-visitation or T&V (Swanson, 2008). This is a labor-intensive process and heavily dependent on the ability of the extension workers to spend adequate time with farmers. However, as **Exhibit 3** shows, low government budgets (about $13 per farm per year) mean that a very small force of extension agents has to cover a large number of farmers, with an average annual coverage capacity of 0.9 days per agent per farm, including travel to and from the farms.

Hence, barely 30 percent of the farmers receive any extension service support (Interview, 2013). Crucially, extension workers have little in the way of on-farm tools to help farmers diagnose or address questions specific to their farms in real-time. They do not have access to devices that can quickly test soil quality to recommend appropriate fertilizer use or to diagnose livestock or crops for particular diseases.

Coverage of extension services across Africa

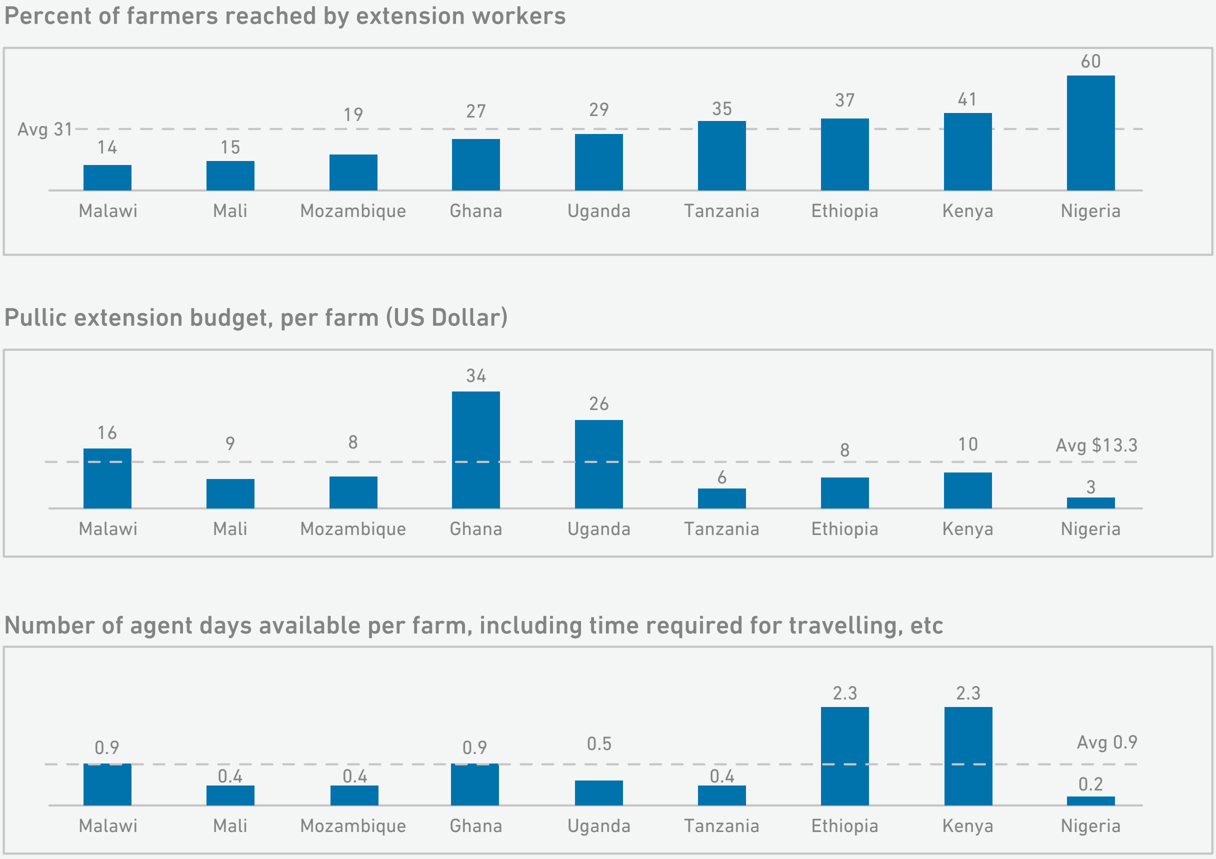


Exhibit 3: Extension workers reach a small percentage of African farmers—barely 30 percent across a sample of countries. With an annual extension budget of $13 per farm, and average availability of less than 1 day per extension agent per farm, few farmers receive any quality advice. This is particularly true since the predominant mode of extension is travel-and-visitation. (Source: Swanson, 2008)

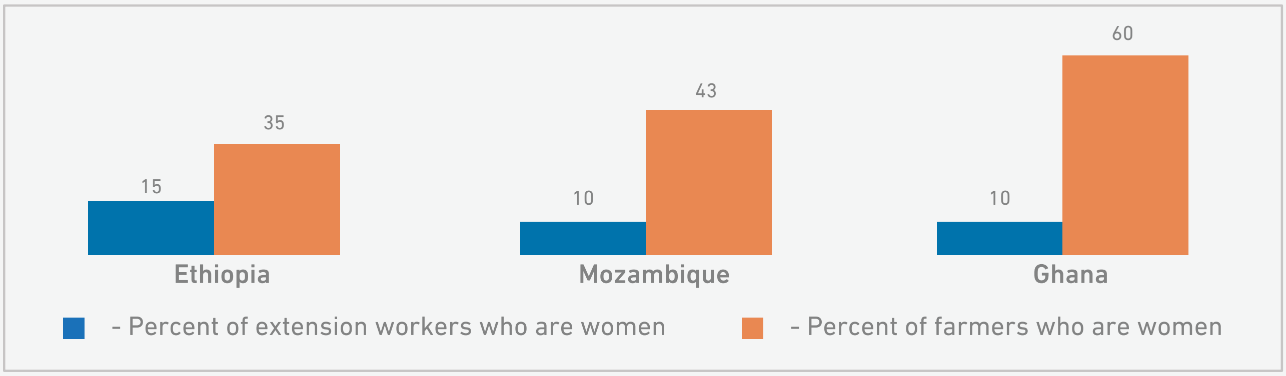
4. Extension services are not geared towards women farmers, even though women perform a substantial portion of the agricultural work

As pointed out in the Overview section of this chapter, women are responsible for a significant portion of agricultural work, which constitutes the single largest type of economic activity undertaken by women (World Bank, 2012, 2018). In countries like Ghana, available data suggests that women perform a greater share of the work across a broad range of on-farm and post-harvest functions (**Exhibit 4**).

Still, only a small fraction (10 to 15 percent) of extension workers are women. The traditional gender dynamics of agricultural extension in Africa lead to a gross exclusion of women (Due, et al., 1997). Male extension agents interact very little with women and male farmers do not typically share their learnings with their wives or other women in the family. As a result, the volume and quality of extension support that women farmers get is significantly worse than that received by their male counterparts (which is itself very little).

Gender disparity in extension services

Number of women farmers versus number of extension workers



Share of agricultural work done by women

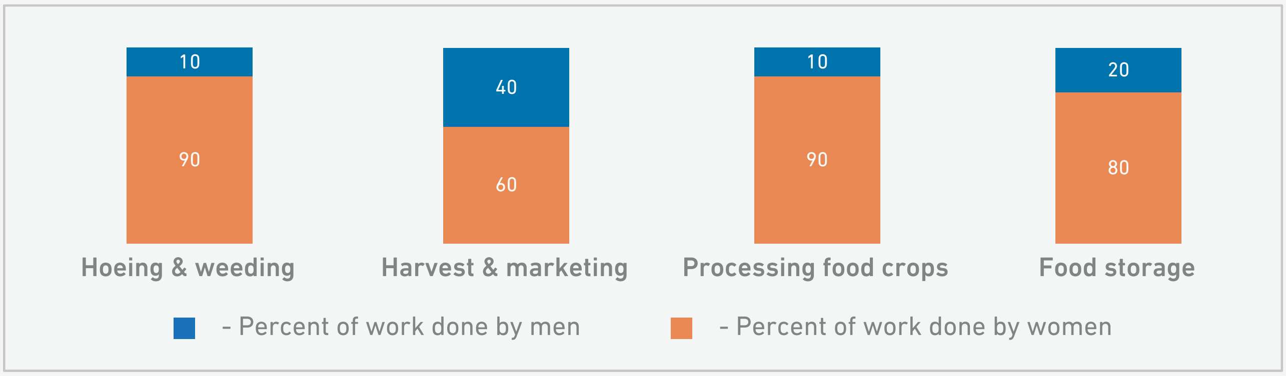


Exhibit 4: Even though women perform a substantial portion—in many countries more than half—of agricultural work, extension agents are primarily men. As a result, the quality of extension support women receive does not address the needs and constraints of women farmers. (Source: Swanson, 2008)

KEY CHALLENGES

Based on the above discussion, there are two main reasons why smallholder farmers in Africa do not receive adequate extension support.

1. The predominant mode of providing extension services in Africa is travel-and-visitation, which is labor-intensive and largely ineffective

Most extension agents conduct their work in-person, either on an individual farm, or at group events organized by farmer organizations. Given the low government budgets, there simply aren't enough agents to cover a critical mass of farmers, even through group events.

ICT channels to improve reach and efficiency, while rapidly emerging, are still far from achieving scale. The labor-intensive nature of current extension models is a fundamental hurdle to reaching enough farmers with quality, relevant and updated content during every planting cycle.

2. While public extension systems suffer from limited capacity accountability and few incentives, there is scant scope for developing private services, especially for staple crops and subsistence farmers

The vast majority of extension programs are free of cost to farmers and run by government agencies. Unfortunately, this often means that the farmers have very limited leverage on the quality and frequency of service, and there is very limited accountability in the system to ensure that whatever services do exist are actually helping farmers.

At the same time, the low demand from farmers—and their meager capacity to pay for services—meant there has been very limited scope for private services to enter the picture (which are, presumably, more accountable to the farmers). This has proven particularly true for subsistence farmers and staple crops. Unlike cash crops, staple crops do not have value chain partners with an interest in improving quality and output.

SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

Extension workers need to add tangible value to farmers' food production and livelihoods. Currently, there is neither an adequate supply of effective extension services, nor strong demand for it. Without adequate government budgets to employ and train a critical mass of extension workers, and adequate measures to ensure accountability, it will be extremely challenging to provide the necessary support to farmers. It is also clear that extension services in Africa have to make a fundamental shift towards being more relevant to women farmers.

Even as efforts are made to develop standardized training packages and strengthen farmer organizations, two technological breakthroughs can help advance the quality of extension services.

Breakthroughs:

1 2 3 4 5 6 7 8 9 10
11 12 13 14 15 16 17 18 19 20
21 22 23 24 25 26 27 28 29 30
31 32 33 34 35 36 37 38 39 40
41 42 43 44 45 46 47 48 49 50

14 An affordable and portable toolkit for extension workers, which includes a core set of devices for testing crop health, livestock health and quality of produce

Training farmers, while helpful, is often not sufficient on its own to add tangible value. Extension workers should also be able to provide specific on-farm products and services to help farmers improve the volume and quality of their produce. The most important of such on-farm services include:

- Testing crops for particular, common pathogens and providing information about appropriate remedies. If combined with the provision of appropriate remedies, such a tool can help prevent potentially devastating losses for farmers.
- Diagnosing livestock at the point-of-care for particular diseases and providing appropriate medication and disease management advice. As discussed in the Livestock section, disease is a significant contributor to livestock losses. Hence, an effective veterinary service, enabled by such a toolkit, combined with regular extension support, can prove invaluable.
- Testing the composition (like chemical and water) of high-value cash crops and produce to provide real time advice on maximizing the quality of the output. This, in turn, can lead to higher market prices.

Such a toolkit does not currently exist in developing countries. Even in industrialized countries such tests are typically performed at labs and other centralized locations, or carried out using expensive portable equipment. Even though there is nothing fundamentally complex about the underlying science for developing such a toolkit, it will take considerable effort to build a practical product. While our research found that there is some interest in such technologies (especially from buyers of cash crop and livestock output), it is not clear that the necessary R&D and product development is being conducted. As such, we believe such a toolkit is four to six years from being available in the market.

Current State

Development Stage: Engineering

Time to market (years)

<3 4-6 7-10 10+

Deployment: Complex

Associated 50BT Chapters

Food Security

SDG Alignment

2 ZERO HUNGER

8 DECENT WORK AND ECONOMIC GROWTH

Impact

Increased Access to Food (# of People)

<1M 10M+ 100M+ 1B+

New Income Generated (# of People)

<1M 10M+ 100M+ 1B+

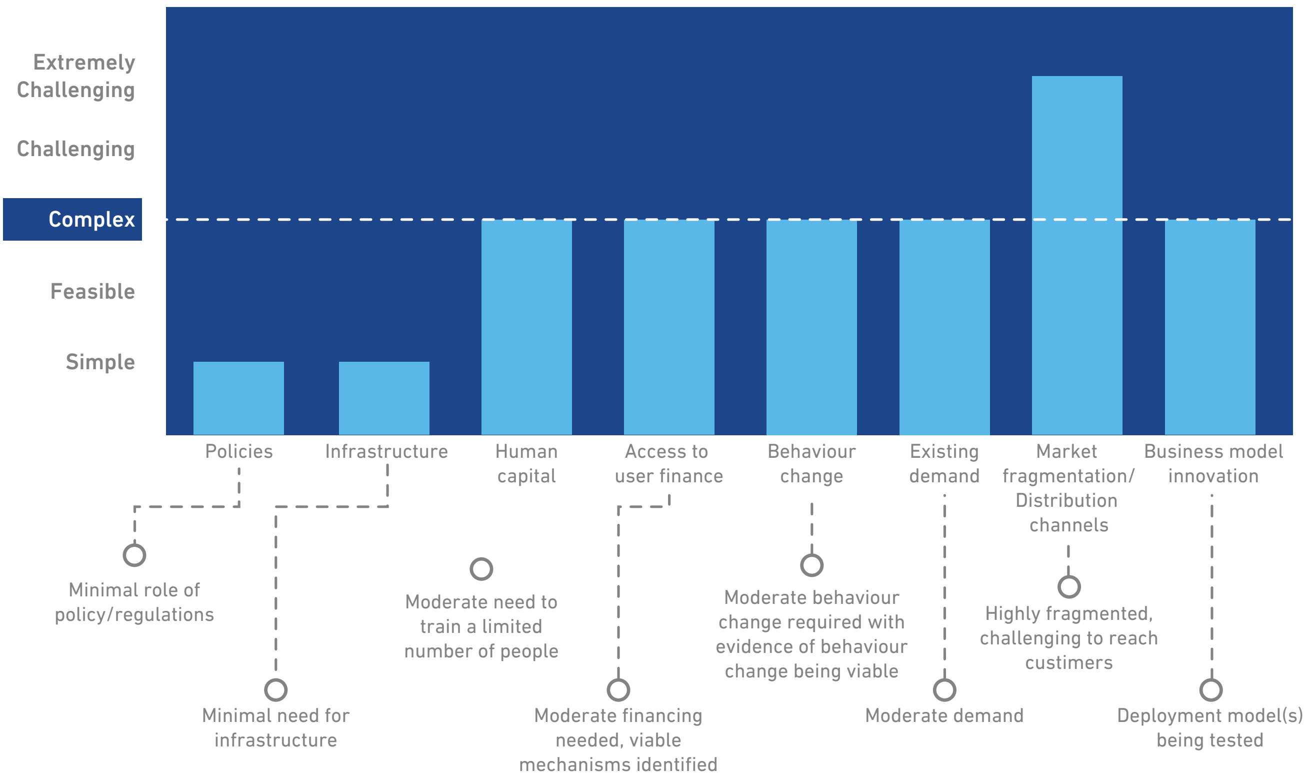
Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

When such a technology becomes available, it has the potential to catalyze a range of valuable services for farmers. This, in turn, can help spawn private service providers who will intrinsically be more accountable to their customers. However, it will face many of the familiar challenges: overcoming a lack of demand, the need for user finance and training.

On the whole, we believe such a toolkit can gain significant traction because it can demonstrate value within a short time frame. We expect deployment in this case will be COMPLEX.

Breakthrough 14: Difficulty of deployment



40 A new generation of wireless broadband network technologies that radically cut the cost of expanding coverage to rural areas

There is substantial opportunity for providing improved learning tools for farmers using existing ICT devices like smartphones and tablets. Creative, gender inclusive multimedia content produced in local languages, combined with other interactive media platforms (like call-in radio), can significantly increase the relevance, timeliness and quality of disseminated information.

In addition, tools for providing feedback on the responsiveness and effectiveness of individual extension agents—with creative mechanisms to escalate feedback to appropriate decision-makers—can help increase the entire system's accountability.

However, in most developing countries, ground-based networks are challenged to provide ICT-enabled service in rural areas, because the network economics of conventional wired or cellular technologies that work for urban areas, which are typically densely populated, do not translate well to sparsely populated rural areas.

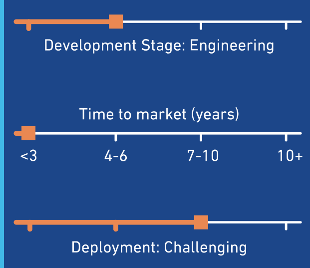
Ground-based technologies require disproportionately more infrastructure to providing connectivity to rural inhabitants than for the same number of people in urban areas, including towers, base stations, backhaul and electricity provision (through the grid or off-grid options like diesel generators). Aerial platforms, whether based on satellites or atmospheric vehicles, could radically improve the economics of rural broadband coverage. A high platform allows greater spans of the network, and operates wirelessly over large distances with equipment that costs less and uses less energy.

A growing alternative for digital communication is to use satellites in orbit around the Earth. A large number of such satellites are required to provide continuous coverage. Although low- and medium-Earth orbit (LEO and MEO) services are becoming increasingly commercially available, they are still too expensive for widespread use.

In 2018, SpaceX received approval from the United States Federal Communications Commission to deploy 4,425 low-Earth orbit broadband satellites, as well as 7,518 very-low Earth orbit (VLEO) non-geostationary broadband satellites. Once deployed, these satellites are expected to boost capacity and reduce latency.

However, the business model regarding these SpaceX satellites, and their relevance to digital inclusion for low-income populations, remain unclear.

Current State

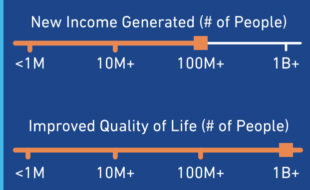


Associated 50BT Chapters

Digital Inclusion Food Security

SDG Alignment

Impact



Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- **Attractive for emerging markets (lower profits)**
- Emerging markets potential; requires derisking (sustainable)
- Non-commercial (unprofitable)

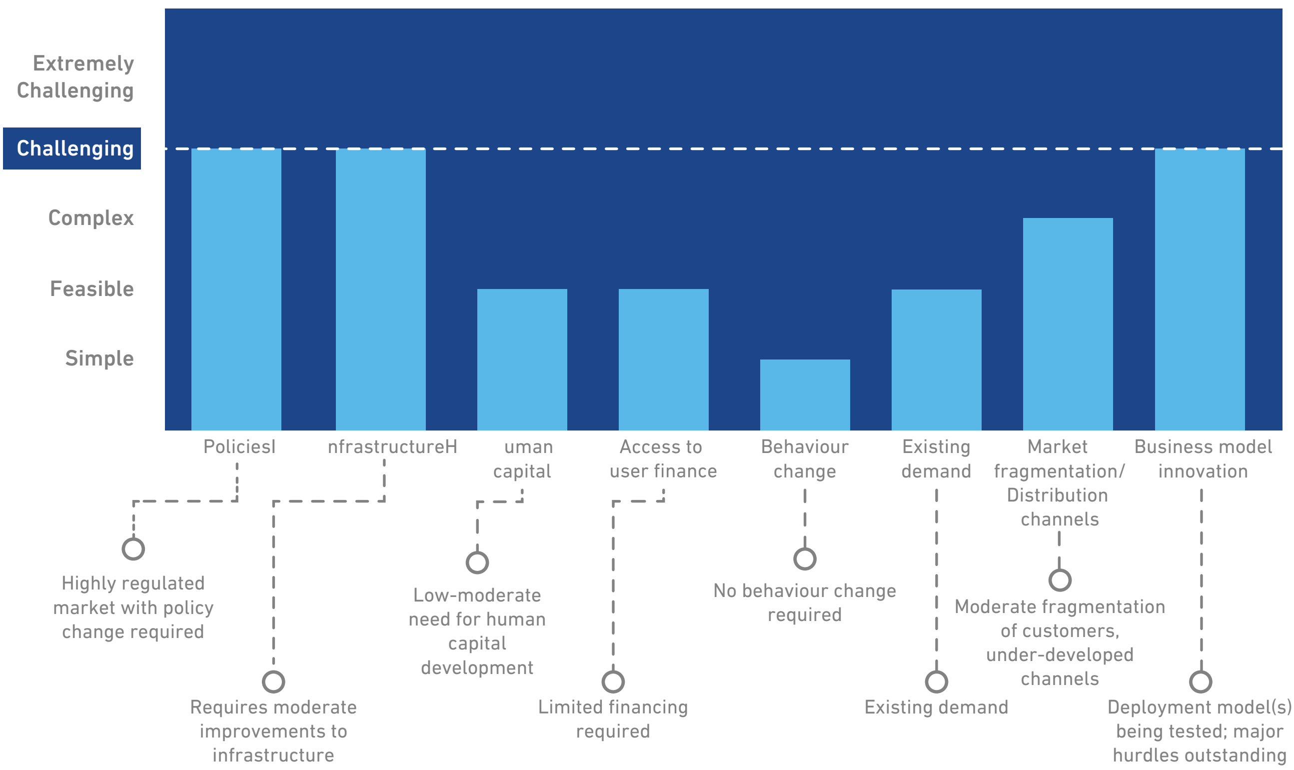
Yet another approach is to use aerial equipment in the stratosphere, for example with balloons or drones. Using balloons at altitudes of 18 to 25 kilometers to provide internet connectivity to rural areas via wireless links is the goal of Loon LLC, a subsidiary of Alphabet Inc. Apart from short pilots in Brazil, Peru and elsewhere, the technology has not reached the desired scale of impact.

Facebook has also experimented with solar-powered drones at altitudes of about 20 kilometers to provide data connectivity using infrared lasers. Their aircraft Aquila had a successful first test flight in 2016, powered by onboard solar cells. The drone has a wingspan of 42 meters but weighs only 450 kilograms. However, despite successful technology demonstrations, the project has not been implemented in practice at any locations so far.

Even as such technologies are becoming market-ready, there will be a number of deployment challenges. Many countries have regulatory constraints on the use of the radio frequency spectrum. Some technologies are very capital intensive, with significant risk of failure and loss.

Regardless of which technology is used, there is clear need for scaling up the infrastructure and human resources. In addition, even as the technologies are being developed, there are no proven business models. Therefore, deployment will be CHALLENGING.

Breakthrough 40: Difficulty of deployment



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2/3 OF LOW-INCOME RURAL LIVESTOCK KEEPERS ARE WOMEN
ASSETS
SAVINGS
FOOD
TRACTION
FERTILIZER
FUEL/MATERIAL
LIVESTOCK CONTRIBUTE 30-50% OF LOW INCOME FARMERS INCOME
IMPROVING GENETICS OFFERS THE BIGGEST BOOST TO LIVESTOCK PRODUCTIVITY
...BUT IS HARD FOR FARMERS TO ACCESS
GLOBAL MEAT CONSUMPTION PER CAPITA IS EXPECTED TO MORE THAN DOUBLE BY 2050

LIVESTOCK

INTRODUCTION

Livestock farming is a primary source of food and income for 900 million smallholder farmers in sub-Saharan Africa and South Asia.

That accounts for more than 60 percent of all smallholder farmers in sub-Saharan Africa and more than 40 percent in South Asia. Livestock farming provides income to farmers that increases their resilience to economic and environmental shocks, and also serves as an important asset for financing.

The vast majority of livestock farmers in sub-Saharan Africa practice pastoral, agro-pastoral or extensive mixed crop-livestock systems, all of which are characterized by limited inputs for animal health, grazing on whatever forage is available and very little access to markets for any produce from the livestock. Climate heavily influences the productivity of livestock in all three systems, as a result of which climate change and related environmental stresses are posing major challenges to traditional practices (Thornton, et al., 2002).

Inputs considered essential for productive and profitable livestock farming, such as nutrient-rich fodder, selected germplasm, appropriate cold storage for artificial insemination, and drugs to prevent and treat diseases, are largely absent in such systems.

As a result, animal health and productivity are very poor, and 25 percent of livestock in sub-Saharan Africa die from preventable conditions. These livestock production systems also leave a very high environmental footprint. Systemic interventions are required to encourage a shift towards more intensive systems, broad provision of veterinary and extension services and the development of local value chains for processing and preserving meat, dairy and other animal products.

Six technological breakthroughs and one innovation can help facilitate these systemic interventions.

- Breakthrough 12. Affordable (less than $50) off-grid refrigeration for smallholder farmers and small agribusinesses
- Breakthrough 13. Commercial scale, affordable and energy efficient refrigeration/cold-chain systems for agribusinesses and transport of food
- Breakthrough 14. An affordable and portable toolkit for extension workers, which includes a core set of devices for testing crop health, livestock health and quality of produce
- Breakthrough 15. A low-cost mechanism to preserve animal semen (including new methods to produce liquid nitrogen or alternatives to liquid nitrogen)
- Breakthrough 16. Alternative meat production system that is affordable, desirable and environmentally sustainable
- Breakthrough 38. Low cost off-grid refrigerators for preserving vaccines (and other temperature sensitive pharmaceuticals) in remote settings
- Innovation: Low cost stall-side diagnostics for the major livestock diseases

Livestock is often the highest value asset for rural households. In arid and semiarid settings in particular, livestock is often the only major viable agricultural commodity. It provides income-generating produce, serves as a key source of nutrition for the household (protein, vitamin B12, calcium, zinc, and riboflavin) and provides byproducts with economic value, such as manure used for fertilizer and animal hide that is sold as raw material for various products.

CORE FACTS AND ANALYSIS

Nearly 900 million low-income people in sub-Saharan Africa and South Asia rear livestock as a primary source of income (McDermott, et al., 2010; BMGF, 2010). Livestock can have a high return-on-investment and therefore represents a major opportunity to increase smallholder incomes.

1. There are three major types of livestock production, each employing very different rearing practices

The most common mode of livestock production in both Sub-Saharan Africa and South Asia is extensive mixed crop-livestock farming, which is characterized by limited labor, rain-fed agriculture and few inputs. Mixed crop-livestock farming accounts for 85 percent and 62 percent of smallholder livestock farmers in sub-Saharan Africa and South Asia, respectively (Herrero, et al., 2012) (**Exhibit 1**).

However, because of its reliance on limited inputs to improve animal health and productivity, this is also the least productive form of livestock farming. The animals are used for food, manure for fuel and fertilizers, draft power to facilitate agriculture and a buffer against the price volatility, which other agricultural commodities are often subject to. In an extensive mixed crop-livestock system, cattle manure could account for up to 70 percent of all fertilizer use (Smith, 2012) and crop residues provides up to 70 percent of all animal feed (Smith, 2013).

Intensive mixed crop-livestock systems are usually concentrated in agriculturally productive regions with established supply chains to urban markets. About 35 percent of livestock farmers in South Asia practice intensive mixed crop-livestock farming, but the practice is negligible in sub-Saharan Africa (Herrero, et al., 2012).

In such a system, production tends to involve access to irrigation and other farming inputs, a dense population of smallholder farmers and a reasonably developed agricultural infrastructure.

Pastoral and agro-pastoral livestock farming is practiced by 15 percent of livestock farmers in sub-Saharan Africa and 3 percent in South Asia, almost all on marginal lands. Pastoralists focus only on livestock, whereas agro-pastoralists also grow crops to varying degrees. These systems are characterized by high number of animals, limited use of purchased inputs and weak linkages to markets.

In pastoral systems, livestock form the bulk of protein consumption, and are the main sources of food and income. Despite accounting for only 15 percent of all low-income livestock holders in sub-Saharan Africa, agro-pastoralists provide 36 percent of the region's cattle meat production and almost half of its milk (Herrero, et al., 2012). Climate heavily influences the choice and productivity of livestock systems.

Exhibit 2 shows a map of production systems across various agro-climatic zones (Thornton, et al., 2002).

Distribution of livestock production systems in South Asia and Sub-Saharan Africa

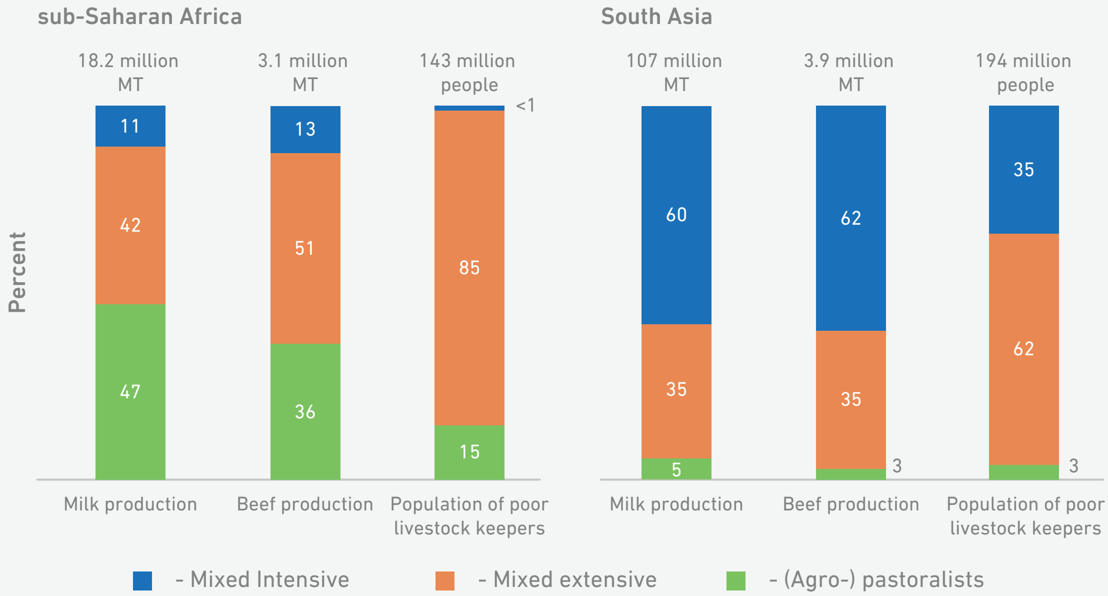


Exhibit 1: There are three major forms of livestock production. Extensive mixed crop-livestock farming is the most common both in sub-Saharan Africa and South Asia. Agro-pastoral and pastoral farming is primarily an African phenomenon, and mixed intensive farming is common in South Asia. Currently, mixed extensive systems are the most prevalent in both regions. (Source: Herrero, et al., 2012)

Livestock production systems across agroclimatic zones

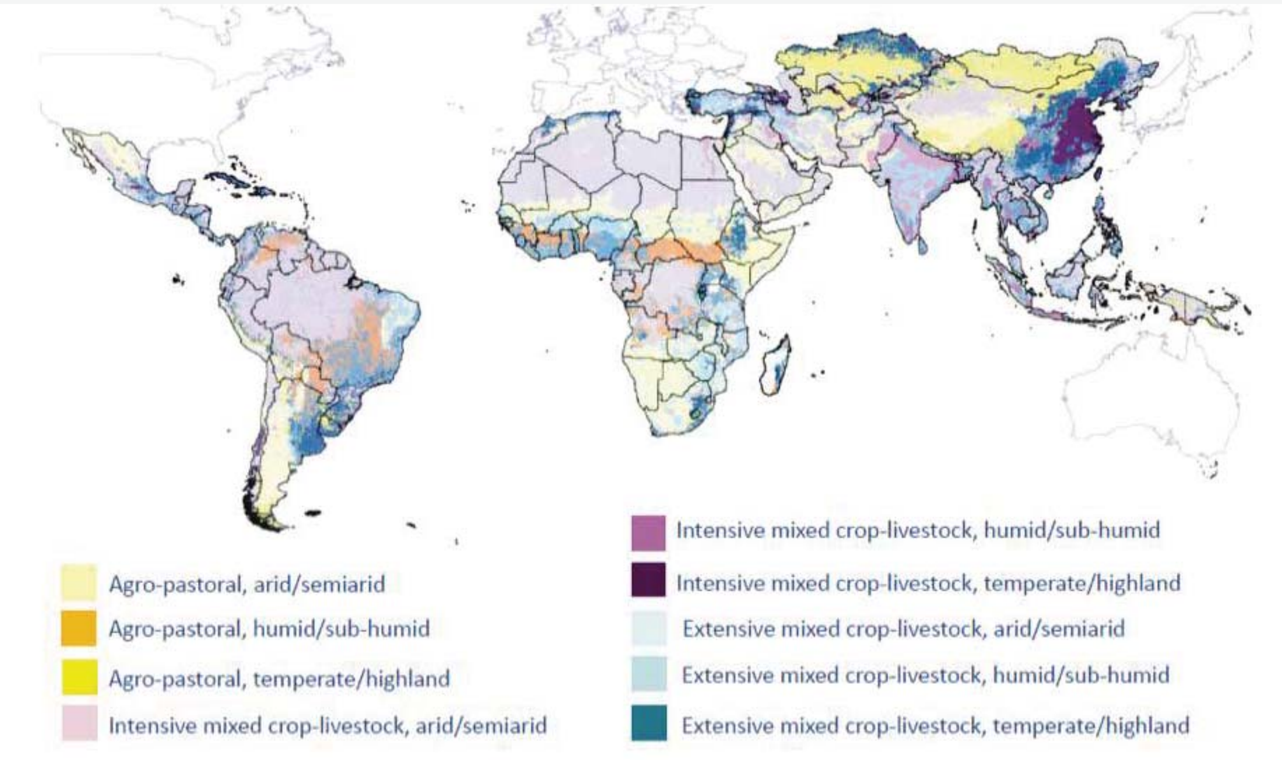


Exhibit 2: Livestock production practices and output are heavily influenced by agroclimatic zones. (Source: Thornton, et al., 2002)

Since the adoption of animal husbandry as a food security strategy long ago, sources of wild animal food have become less important for humans. Meat from wild land animals, or bushmeat, continues to form only a minor part of the human diet in select countries. For example, bushmeat was reported in 1997 to contribute about 8 percent of total protein consumption in several African countries including DR Congo, Liberia and Ghana (FAO, 1997). More recent figures are unavailable, but overall consumption is expected to have decreased since 1997. Most animal protein for humans now comes from domesticated land animals such as cattle and poultry. Wild fish is still an important source of food, and is discussed in the Fisheries and Aquaculture section.

2. Most livestock farmers keep a small number of animals, which serve as a source of food and an asset

The most important livestock animals in sub-Saharan Africa and South Asia are cattle, small ruminants (sheep and goats) and poultry. Water buffalo are reared as livestock in South Asia (**Exhibit 3**). About 90 percent of all livestock keepers also raise chickens (BMGF, 2012).

Most livestock keepers—especially those practicing mixed-intensive and mixed-extensive livestock farming— maintain a very small number of animals. In India, for example, the world's largest producer of dairy products by volume, farmers with three or fewer dairy cows produce 70 percent of milk (ILRI, 2011). In Kenya, the largest milk producing country in sub-Saharan Africa, the average dairy farmer only owns two cows (ILRI, 2009).

Such farmers sell only 20 to 40 percent of their output, while the rest is consumed in the farmer's household (FAO, 2009). For most farmers engaged in mixed crop-livestock systems, a few units of livestock are used for crop-tending activities like plowing the fields and hauling, and some are sold if the need for supplemental income emerges. Agro-pastoralists tend to have more animals, which contribute to the bulk of their income (McDermott, et al., 2010).

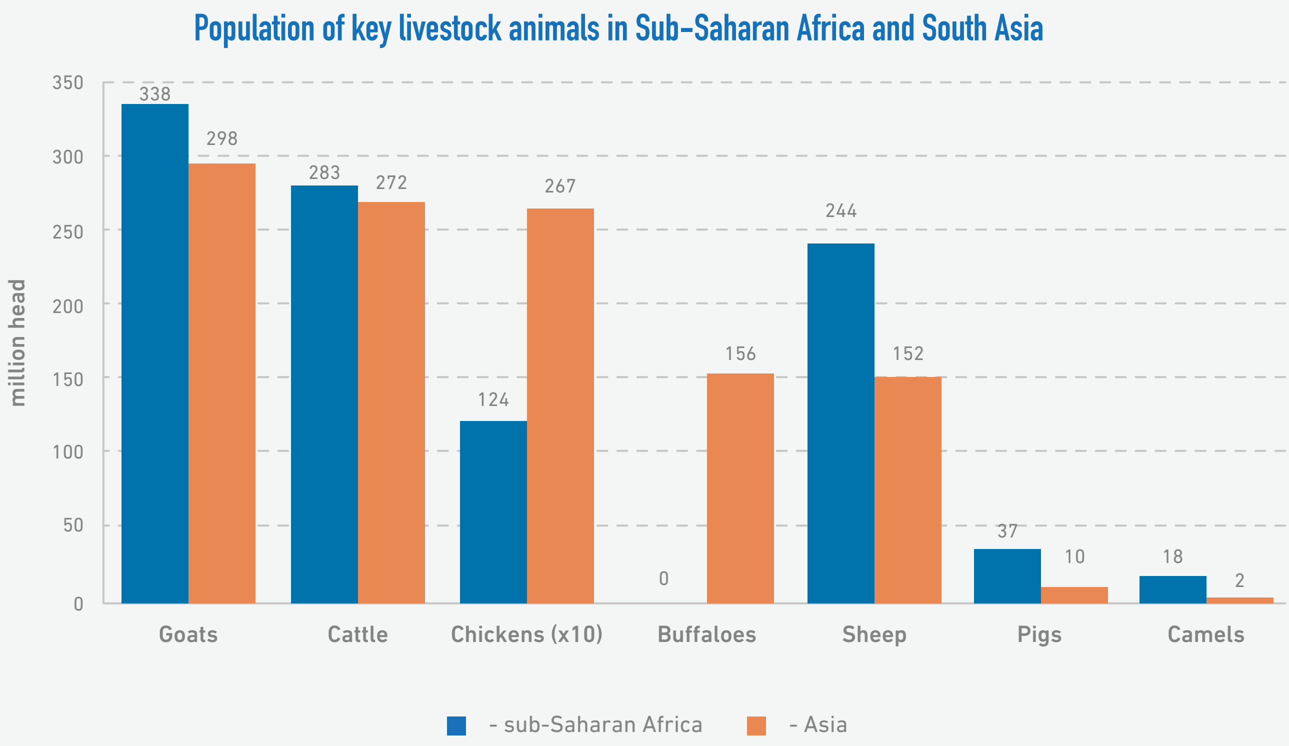


Exhibit 3: Chickens, goats, cattle and sheep constitute the majority of livestock in Sub-Saharan Africa and South Asia. Water buffaloes are kept primarily in South Asia. (Source: FAO, 2018)

3. Livestock are valuable to farmers in several ways

Livestock not only provide direct value as a source of food for agrarian households, but are also an asset and source of income for farmers.

Owned livestock animals and dairy products are the key source of protein among smallholder livestock farmers. Livestock provides sustenance to 830 million food insecure people around the world, where it constitutes 6 to 36 percent of total protein intake and 2 to 12 percent of total caloric intake (Smith, 2013).

Livestock products (meat, milk and eggs), along with fish, are the main sources of protein and other essential micronutrients like vitamin B-12, calcium, zinc and riboflavin (not available from other crops) for human nutrition.

There is some regional variation in food preferences though. For example, milk accounts for 30 to 40 percent of all proteins from livestock product consumption in South Asia (FAO, 2002).

Globally, four out of the five highest value agricultural commodities are livestock, which consistently provide higher profit margins than crops. Livestock contributes approximately 30 to 50 percent to the overall income of low-income farmers (**Exhibit 4**), providing a major opportunity for poverty alleviation.

Some studies found that diversification into livestock farming is among the most commonly cited reason among Kenyan farmers for measurably increasing their incomes and escaping poverty (BMGF, 2010). Livestock serves as a means of savings and insurance, which can be sold in times of crisis, unlike crops that are subject to seasonal and economic cycles (BeVier, 2010; Heffernan, et al., 2008; Tjanson, et al., 2004).

Economic importance of livestock for low-income farmers

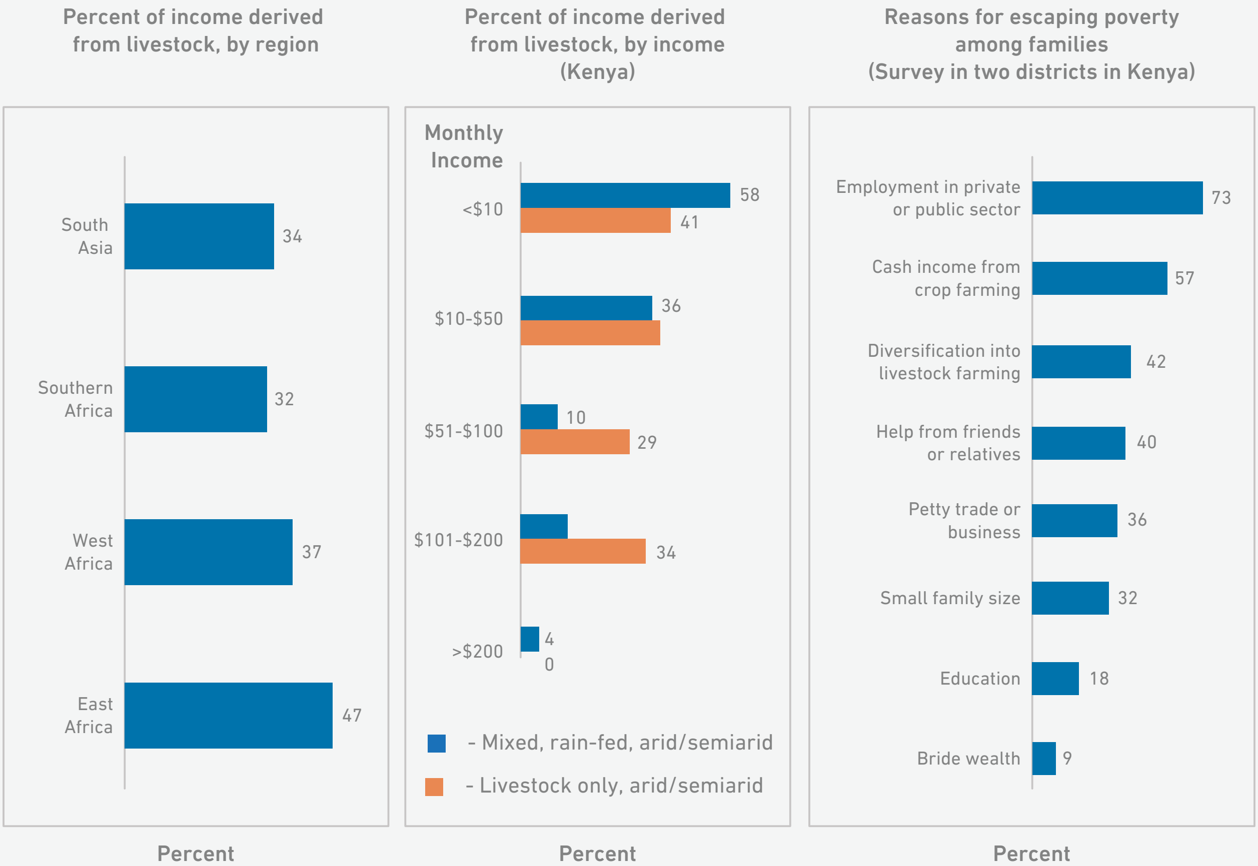


Exhibit 4: Livestock is a major source of income for smallholder farmers and accounts for 30 to 50 percent of total income for farmers in different parts of sub-Saharan Africa and South Asia. Revenue from livestock is particularly important for lower income farmers, a greater portion of whose overall income depends on livestock. (Source: BMGF, 2010, converted from Kenyan Shillings to US Dollars)

Beyond direct value, livestock also provides considerable indirect value to farmers.

The International Livestock Research Institute (ILRI, 2011) estimates that up to 40 percent of the value of livestock may be due to indirect products and benefits, such as manure, animal labor for traction, as well as insurance and savings. In developing countries, cattle manure is the main source of soil fertilizer, accounting for 70 percent of all soil amendments (Smith, 2012).

It is important to remember that livestock are regularly transferred between members of extended families and clans as a buffer against food shocks. These non-monetary transactions are extremely significant during times of disaster, as was seen during the 1984 Sahel drought, where livestock transfers accounted for 60 percent of all food aid to the poorest households (Fafchamps, et al., 1998).

Demand for livestock products is growing around the world, including developing countries, driven by urbanization and increasing incomes (Smith, 2013). By 2030, demand for milk products is expected to double and demand for beef products is expected to increase by 75 to 100 percent in sub-Saharan Africa and South Asia.

In the same time period, demand for poultry products will increase eightfold in South Asia and three-fold in sub-Saharan Africa. Global meat consumption per capita is expected to more than double by 2050, leading to an increase in world trade in meat products of a factor of five (Rosegrant, 2009). These growing domestic and export markets provide a significant opportunity for profitable income.

Crucially, the status and living standards of women are closely linked to the number of livestock units they control. Two-thirds of low-income rural livestock keepers are women. In sub-Saharan Africa, women tend to manage poultry and small ruminants, while men manage cattle. In India, on the other hand, women perform 70 percent of dairy-related labor (ILRI, 2011). Recent research has found that the greater a woman's assets at the time of marriage, the larger the share of wealth the household tends to invest in children's education (Kristjanson, et al., 2010).

4. Livestock output in sub-Saharan Africa and South Asia is extremely low, compared to industrialized countries

Livestock output in sub-Saharan Africa and South Asia is a fraction of that in industrialized countries (**Exhibit 5**). The annual beef output in the two regions is 0.06 and 0.04 kilograms per kilogram of biomass, respectively, compared with 0.2 kilograms per kilogram of biomass in industrialized countries.

The per-cow milk output in sub-Saharan Africa and South Asia is only 6 percent and 14 percent that of industrialized countries, respectively. Output from chicken and pigs is slightly more favorable. Chicken meat production per kilogram of biomass, in sub-Saharan Africa and South Asia, is 46 percent and 76 percent that of industrialized countries, respectively. Pig meat output stands at 48 percent and 56 percent that of industrialized countries, respectively, in sub-Saharan Africa and South Asia.

Livestock output in South Asia, Sub-Saharan Africa and industrialized countries

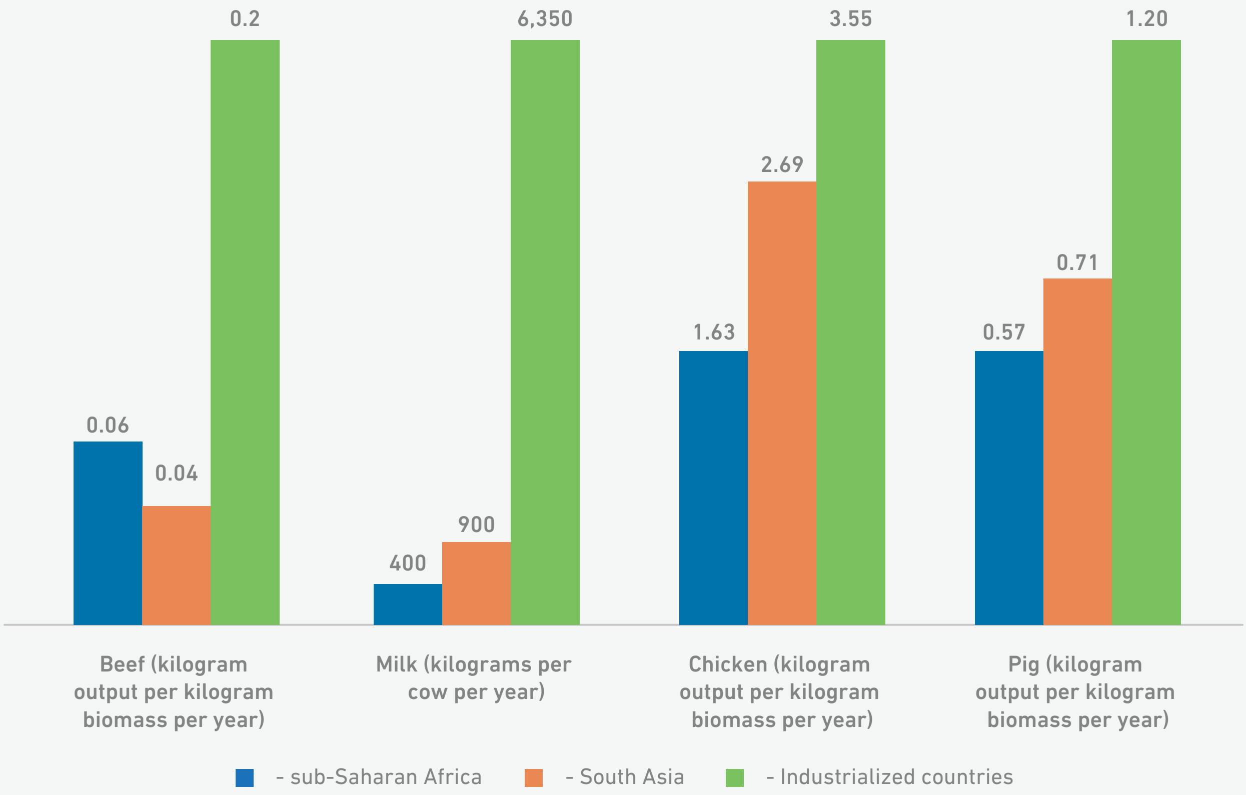


Exhibit 5: Livestock output in sub-Saharan Africa and South Asia is a fraction of that in industrialized countries. Beef and milk output, in particular, lag far behind. (Source: FAO, 2006)

Three main drivers of livestock productivity: nutrition, health and genetics

Nutrition: Quality and quantity of food for the animals

In mixed-extensive, pastoral and agro-pastoral systems, animals forage on whatever feedstock and water is naturally available. This can vary significantly, depending on the area's natural vegetation and how denuded the land is. Inadequate food and nutrition weaken animals, reduces yield and increases vulnerability to disease.

In arid and semiarid regions, such as the Sahel belt and the Horn of Africa, marginalized populations—already entirely dependent on whatever little is naturally available—are feeling increasing stresses from land degradation and water scarcity, caused by livestock farming, other human activities and climate change. As **Exhibit 6** shows, a significant portion of livestock systems across sub-Saharan Africa is facing current and future degradation (Thornton, et al., 2002; Herrero, et al., 2012).

Regions in sub-Saharan Africa where livestock farming is threatened by environmental degradation

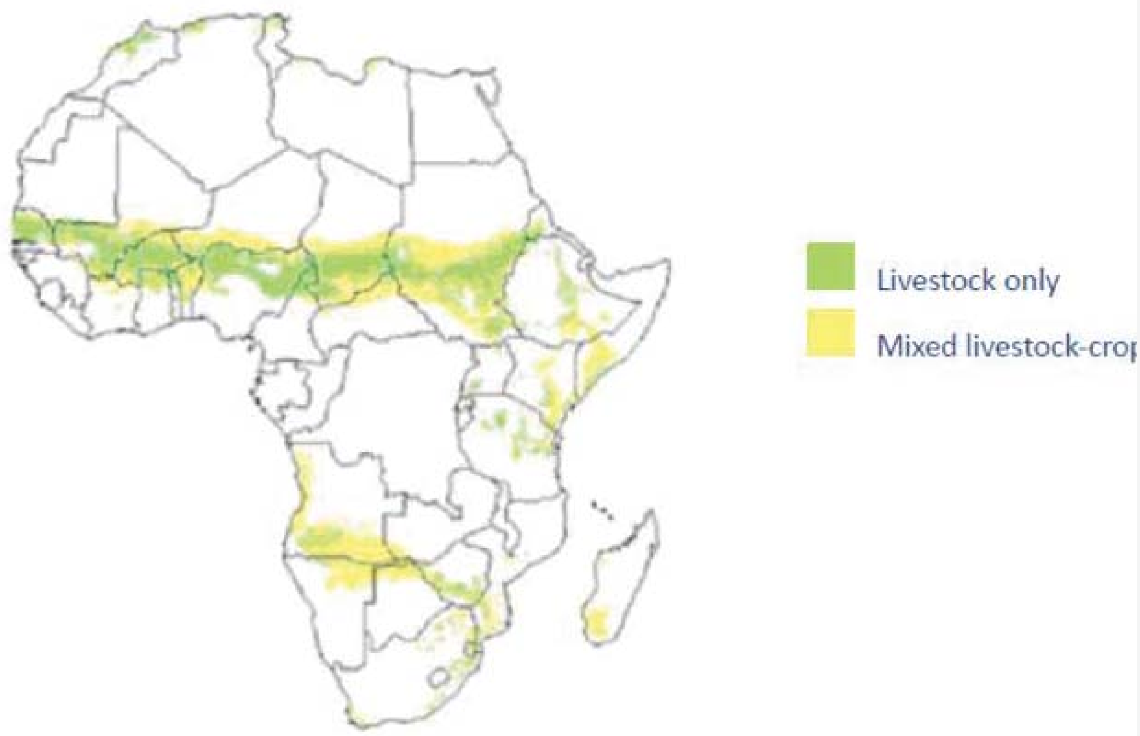


Exhibit 6: A large portion of the agro-pastoral, pastoral and extensive mixed-crop systems in sub-Saharan Africa is facing serious threats due to environmental degradation (current and projected). These stresses deplete the already meager food and water sources for livestock.
(Source: Thornton, et al., 2002; Herrero, et al., 2012)

Health: Protection from disease
Across the various types of livestock in sub-Saharan Africa and South Asia, a total of 14 major diseases—all of which are preventable and/or treatable—collectively cause $33.5 billion in economic losses. In sub-Saharan Africa, treatable diseases prematurely kill a quarter of all animals owned by poor livestock keepers and represent the single largest driver of economic losses (BMGF, 2012).

Animal mortality in South Asia is also significant, although considerably less than in sub-Saharan Africa. **Exhibit 7** lists the 14 predominant diseases, the economic damage they cause and the animals they commonly affect (World Organization for Animal Health, 2009). They include:

- A highly diverse range of indigenous endoparasites (which live inside the host) and ectoparasites (which live outside the host).
- Peste des Petits Ruminants (PPR), or goat plague, which is spread by a virus through airborne animal discharges. The virus spreads before sheep or goats exhibit symptoms (with an incubation period as long as 21 days), making it difficult to isolate animals in time. Morbidity can be as high as 90 to100 percent and mortality up to 50 to100 percent. No medication exists to treat the disease. Although vaccines exist, they require cold storage and are not accessible to many livestock keepers.
- Contagious Bovine Pleuropneumonia (CBPP), which involves multiple strains of mycoplasma bacteria spread through airborne animal discharges. The incubation period can be longer than four months.

- Contagious Caprine Pleuropneumonia (CCPP) are mycoplasma bacteria that affect goats in a similar manner. Although there is no treatment, several vaccines exist. However, their efficacy and side- effects on local breeds of livestock and local strains of pleuropneumonia vary.
- Foot and mouth disease (FMD), which is caused by a virus with seven different serotypes that do not confer cross-immunity. The virus is spread through airborne animal discharges and is highly contagious. While mortality among adult animals is low, it can be 20 percent or higher among young animals. Quarantining is extremely important for controlling this disease. One important factor in sub-Saharan Africa is the prevalence of FMD in wildlife, as a result of which spillover to livestock populations requires intensive control through vaccinations. A number of FMD vaccines exist.

Major livestock diseases in South Asia and Sub-Saharan Africa

Diseases	Economic value lost (US$ billions): sub-Saharan Africa	Economic value lost (US$ billions): South Asia	Total losses (US$ billions)	Cattle	Small ruminants	Poultry
Endoparasites	4.4	3.3	7.7	✓	✓	✓
Peste des Petits Ruminants (PPR)	4.8		4.8		✓	
Contagious Bovine Pleuropneumonia (CHPP)	4.4		4.4	✓		
Ectoparasites	2.5	1.8	4.3	✓	✓	✓
Contagious Caprine Pleuropneumonia (CCPP)	3.7		3.7	✓	✓	
Foot and Mouth Disease	1.2	1.1	2.3	✓	✓	
Trypanosomiasis	1.6	0.5	2.1	✓	✓	
Newcastle Disease	0.6	0.6	1.2			✓
Sheep/Goat Pox	0.7	0.5	1.2		✓	
Brucellosis	0.5	0.6	1.1	✓	✓	
Bovine Tuberculosis	0.3	0.4	0.7	✓		
Rift Valley Fever (RVF)	0.6		0.6	✓	✓	
Lumpy Skin Disease	0.6		0.6	✓		
East Coast Fever	0.4		0.4	✓		

■ - sub-Saharan Africa ■ - South Asia

Exhibit 7: Fourteen livestock diseases collectively cause $33.5 billion in losses to smallholder farmers in sub-Saharan Africa and South Asia. In sub-Saharan Africa, these diseases kill a quarter of livestock animals owned by low-income farmers. (Source: World Organization for Animal Health, 2009)

Genetics: Genetic improvement through cross-breeding

Superior genetic inputs through crossbreeding of animals have led to significant increases in livestock production efficiency in middle and high-income countries.

For example, crossbreeding of cattle in South Africa has shown a 26 percent increase in cattle weight, with minimal increase in feed requirements (Scholtz & Theunissen, 2010). In other developing countries, between 1980 and 2005, increases in yield output per animal—54 percent for chicken and 135 percent for pigs—occurred due to successful North-South genetic transfers (World Bank, 2008). Throughout developing regions, 100 million cattle and pigs are bred annually using artificial insemination, but this is mostly outside of sub-Saharan Africa and South Asia (World Bank, 2008).

Only 12 percent of dairy cattle in India are crossbred (ILRI, 2011). Across both regions, improved genetic inputs are seldom used and improvements in livestock health and productivity remain stagnant.

It is important to note that crossbreeding and improving genetics should be site-specific. One example of a common mistake due to lack of understanding of site-specific issues is in Ethiopia, where AI with Hereford cattle are in demand due to their high milk production; however, since these cattle do not have strong parasitic resistance, the crossbred animals often suffer heavy morbidity and mortality (Interview, 2014).

While each of the above drivers is important to all the major types of livestock, they have different levels of impact on different animals (**Exhibit 8**). Cattle productivity—with respect to both beef and milk—will require improved genetics (through crossbreeding), along with healthcare and nutrition (BeVier, 2010).

Genetics can be valuable in poultry farming as well, as can better health and nutrition. Such improvements could collectively add US $11.5 billion in economic value for the smallholder livestock farmers of sub-Saharan Africa.

Contribution of various drivers to potential livestock productivity gains in Sub-Saharan Africa

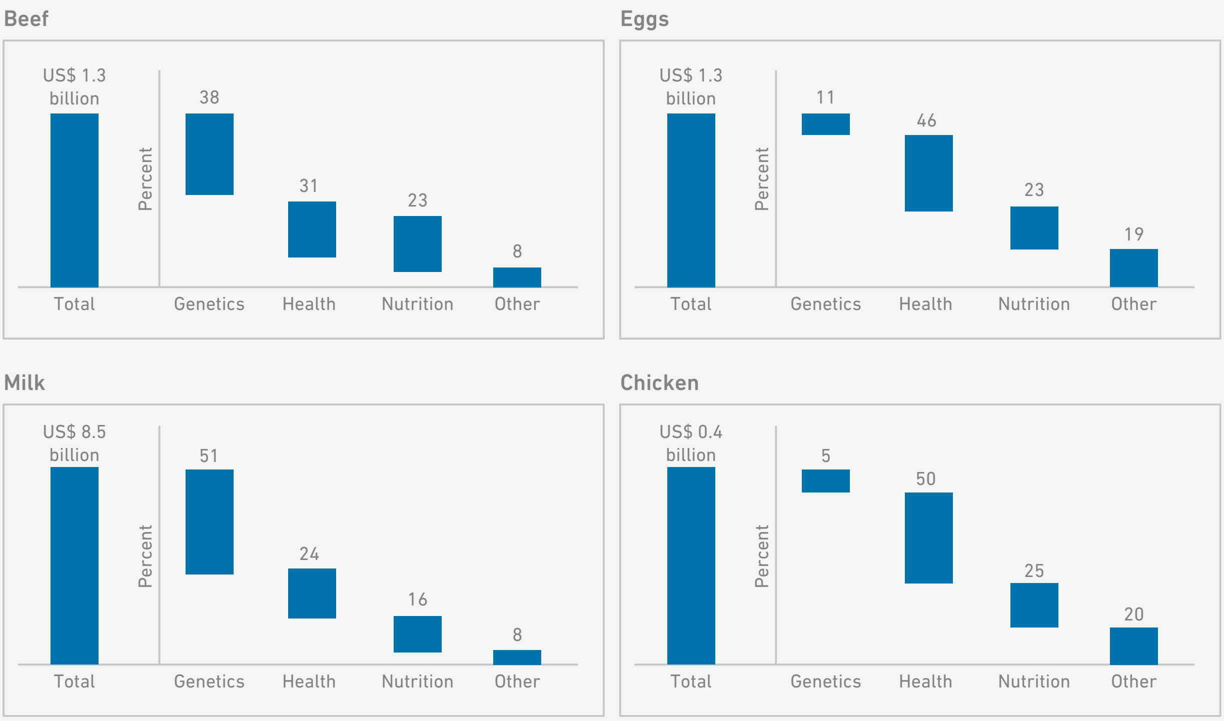


Exhibit 8: Improvements in animal genetics are the single largest driver of productivity for cattle products (beef and milk). Improvements to animal health (through both vaccines and treatment) can also have significant impact. For poultry (chicken meat and eggs), the primary driver is improvement in health (through vaccines and treatment for parasites and Newcastle Disease) and nutrition. In aggregate, this represents $11.5 billion in incremental value for the farmers. (Source: BeVier, 2010)

5. Livestock production causes significant environmental damage

Livestock systems occupy 30 percent of the planet's ice-free terrestrial surface (Thornton, 2010) and contribute to 18 percent of all global greenhouse emissions (McMichael, et al., 2007). The primary drivers of these emissions are deforestation or desertification due to grazing, manure (which releases nitrous oxide) and enteric (digestive) fermentation in cattle and small ruminants, which leads to methane release through belching and flatulence (**Exhibit 9**).

Pastoral and extensive systems contribute to more than twice as much greenhouse gases to the atmosphere as intensive livestock systems (McMichael, et al., 2007) because of free grazing and the ever-increasing need for more land to graze on.

While most of the environmental damage from livestock production is concentrated in industrialized countries, deforestation and desertification—caused by a number of factors including livestock rearing—are a major problem in sub-Saharan Africa and South Asia. A future decoupling of livestock production from land use may occur if industrial-scale feed production can be developed based on, for example, microbial proteins (Pikaar, et al., 2018). However, such technology is unlikely to be available to smallholders in developing countries.

Greenhouse gas emissions from different elements of livestock production

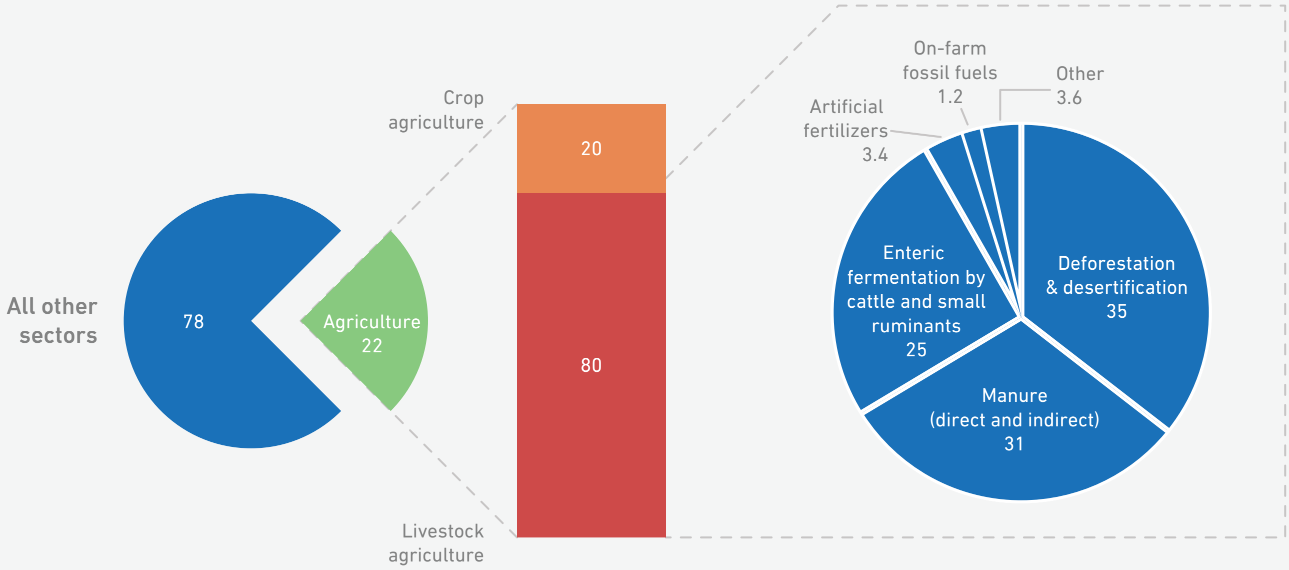


Exhibit 9: Agriculture accounts for 22 percent of all greenhouse gas emissions, and 80 percent of the agriculture-related emissions—18 percent of all GHG emissions—are from livestock rearing. While this predominantly comes from industrialized countries, desertification and deforestation are a major concern in parts of sub-Saharan Africa and South Asia. (Source: McMichael, et al., 2007)

6. Alternative meat production techniques are being developed, such as in vitro cultivation and insect farming

The environmental consequences of large-scale conventional meat production systems are increasingly evident, such as deforestation and polluted water ways (described in detail in the Resilience to Global Change chapter).

Alternative meat production techniques are being developed, that if successful could satisfy our growing meat demand with reduced environmental impacts. Such products are potentially healthier and more efficient alternatives to conventional meat, with lower use of land, water and agricultural inputs (Tuomisto & de Mattos, 2011; Mattick, et al., 2015).

There are two primary avenues for alternative meat production. The first avenue, often called substitute meat or meat analog, involves the conversion of non-animal biomass to have the characteristics of actual meat. This begins with the conventional agricultural production of feedstocks such as soybean, wheat or peas, followed by industrial conversion into a material with texture and taste similar to meat.

A notable example is Impossible Foods, which is primarily made of soybean protein concentrate and vegetable oils, with additional plant-based additives to mimic the flavor of meat. Impossible Foods products were initially introduced in 2016, and in 2019 the firm partnered with Burger King to serve alternative meat burgers in fast-food restaurants throughout the US.

The second avenue, often described as cultured meat, cellular meat or in-vitro meat, involves the managed growth of actual animal cells. This tissue engineering process begins with collection of stem cells from living animals, which are then allowed to grow and reproduce in a bioreactor, a device for carrying out biochemical processes.

The living cells are provided with nutrients in a suitable culture medium, typically composed of water, glucose, amino acids, lipids, vitamins and salts (Mattick, et al., 2015). If the cultured meat is to match or exceed the nutritional value of conventional meat, any nutrients found in meat that are not synthesized by the growing cells must be supplied in the culture medium.

There are however many technical challenges to sustainable in vitro meat culturing system on a large scale (Bhat & Fayaz, 2011). The technology now exists to produce in vitro meat on very small scales, as its major use to date has been regenerative medicine of a variety of tissues and organs (Bhat, et al., 2017).

Current cultured meat processes require large energy input for industrial processes, as biological functions such as digestion and nutrient circulation are replaced by industrial equivalents (Mattick, et al., 2015). The climate implications of cultured meat are complex, and depend on emissions of carbon dioxide, methane and other greenhouse gases from the cultured and reference animal-based systems (Lynch & Pierrehumbert, 2019).

Numerous other non-traditional foods show varying levels of potential, such as cultivated mycoprotein, insect larvae and aquatic foods like chlorella and spirulina (Parodi, et al., 2018). Insects in particular appear to be quite nutritious, as they are rich in proteins with healthy amino acid composition, and also provide fat, minerals and vitamins (Bukkens, 1997).

Feeding such organisms with waste products, such as agricultural residues, can create significant added value. Nevertheless, scaling such technologies as a global food security solution will depend on many economic, cultural and technical factors. Widespread deployment of cultured meat and non-traditional species will face a number of hurdles, primarily along acceptance by consumers and regulators, and limited current demand for alternative meat products.

KEY CHALLENGES

There are four major hurdles preventing smallholder livestock farmers from developing productive and profitable systems. These hurdles are much more prevalent in sub-Saharan Africa than in South Asia.

1. Healthcare services for livestock are extremely limited

There is strong evidence to show that cattle losses from disease are directly related to public expenditures on livestock health (World Bank, 2008). However, access to health services, particularly for the majority of agro-pastoral, pastoral and mixed-extensive livestock keepers in remote areas, is heavily constrained due to poor infrastructure and a lack of properly trained animal health workers.

Only a fraction of livestock farmers (such as 20 percent in Uganda) have access to any extension services (CGIAR, 2013), let alone quality advisory services. While animal health inputs are sometimes offered free of cost through government programs, such services tend to be limited to intensive and industrial livestock production systems (Upton, 2004).

Similarly, even private animal health practices have only proven viable for intensive livestock production systems where veterinary service providers have a dense market. In addition, vaccines and veterinary pharmaceuticals in low-income markets are often of poor quality, leading to a vicious cycle in which farmers from remote and rural areas, who only occasionally use pharmaceutical products for animals, lose further confidence in the value of such interventions when they don't see dramatic or immediate results (Upton, 2004; IFAD, 2011).

Animal vaccines require refrigeration to remain viable, and the absence of a cold chain for animal pharmaceuticals makes delivery of vaccines very difficult. Beyond pharmaceuticals, the lack of a veterinary infrastructure means that there is very limited diagnosis, monitoring or reporting for timely disease control. Lastly, the low investment in animal health research is inhibiting the production of new vaccines, diagnosis tools and drugs (World Bank, 2008).

2. Smallholder farmers have very limited access to genetic material for crossbreeding

Smallholder farmers usually procure animals through informal networks and markets, equipped with limited knowledge—or means—of strengthening their herd with animals with the appropriate genetic composition. Successful livestock breeding programs rely on artificial insemination (AI) with appropriate superior breeds. While AI has made some headway in South Asia, its use has been extremely limited in sub-Saharan Africa. The three main reasons are:

- Animal semen must be stored at extremely low temperatures (well below -100 degrees Celsius) using liquid nitrogen. While the process has become fairly standardized over the decades in much of the world, it has not reached rural farmers in sub-Saharan Africa because of its reliance on liquid nitrogen (for freezing) and the need for specific AI training.
- Successful AI requires a high number of genetically distinct livestock variants, to preserve genetic diversity over time. This is not possible with small herds in extensive or pastoral settings, where the number of livestock units is too low to allow for diversification. It also takes technical skill to conduct artificial insemination.
- Livestock in tropical areas face very different stresses from those in more temperate climates. In industrialized countries (most of which are in temperate areas), animals are reared in clean surroundings, have access to high-nutrition feed and are adequately protected from major diseases. This means that these animals often do not develop resistance to tropical diseases, and their genetic material may have limited usefulness in tropical countries.

3. Limited access to appropriate local storage, processing or markets

Livestock food products are highly temperature sensitive and need to be consumed, processed, or refrigerated very soon after production. With milk, for instance, most of the losses occur post-harvest, during the processing and distribution stages (**Exhibit 10**) because rural smallholder farmers have little to no access to refrigeration and find it difficult to reach markets within the short shelf life of the product (FAO, 2011).

The lack of access to affordable, off-grid refrigeration is especially challenging for livestock farmers, since products deteriorate rapidly in warm temperatures.

As **Exhibit 11** shows, fresh milk can last up to a day in 15 degrees Celsius but needs to be kept at 10 degrees Celsius to last two days and at 5 degrees Celsius to last three days. Fish needs to be at 10 degrees Celsius to last three days, while meat and butter can last longer in sub 20 degrees Celsius temperatures (Practical Action, 2012).

However, daily ambient temperatures routinely get over 20 degrees Celsius in many tropical countries. In Kenya for example, the average daily temperature over the course of the year, across a nationwide cross-section of locations, is nearly 25 degrees Celsius. In many other countries, the average temperature is higher. Only 14 percent of the rural population in sub-Saharan Africa has access to electricity (IEA, 2013), and only 3 to 4 percent of milk processors in countries like Ghana and Tanzania have access to refrigeration (ILRI, 2009). Even in Kenya,

Africa's largest milk producer, only 10 to 15 percent of all marketed milk is packaged or processed; most of it is consumed unpasteurized (Meridian Institute, 2012). Similarly, more than 90 percent of milk in Tanzania and Ghana, and 80 percent in India, is unprocessed (ILRI, 2009, 2011). This is equally true of all other livestock food products.

Because of their distance from markets and limited access to transportation, only a small fraction of livestock farmers is able to take their milk to a sale-point. In Ghana, for example, virtually 100 percent of milk producers and more than 70 percent of market intermediaries transport their milk by foot. As a result, almost 90 percent of milk producers sell their product at their farms or homes itself (ILRI, 2009). The only producers who have access to markets are those living near urban areas (World Bank, 2008; ILRI, 2009).

As a consequence, the majority of livestock products from smallholder farmers are used in the farmers' households and both sub-Saharan Africa and South Asia import livestock products from higher income countries to satisfy urban consumer demand, despite a very large population of local livestock farmers.

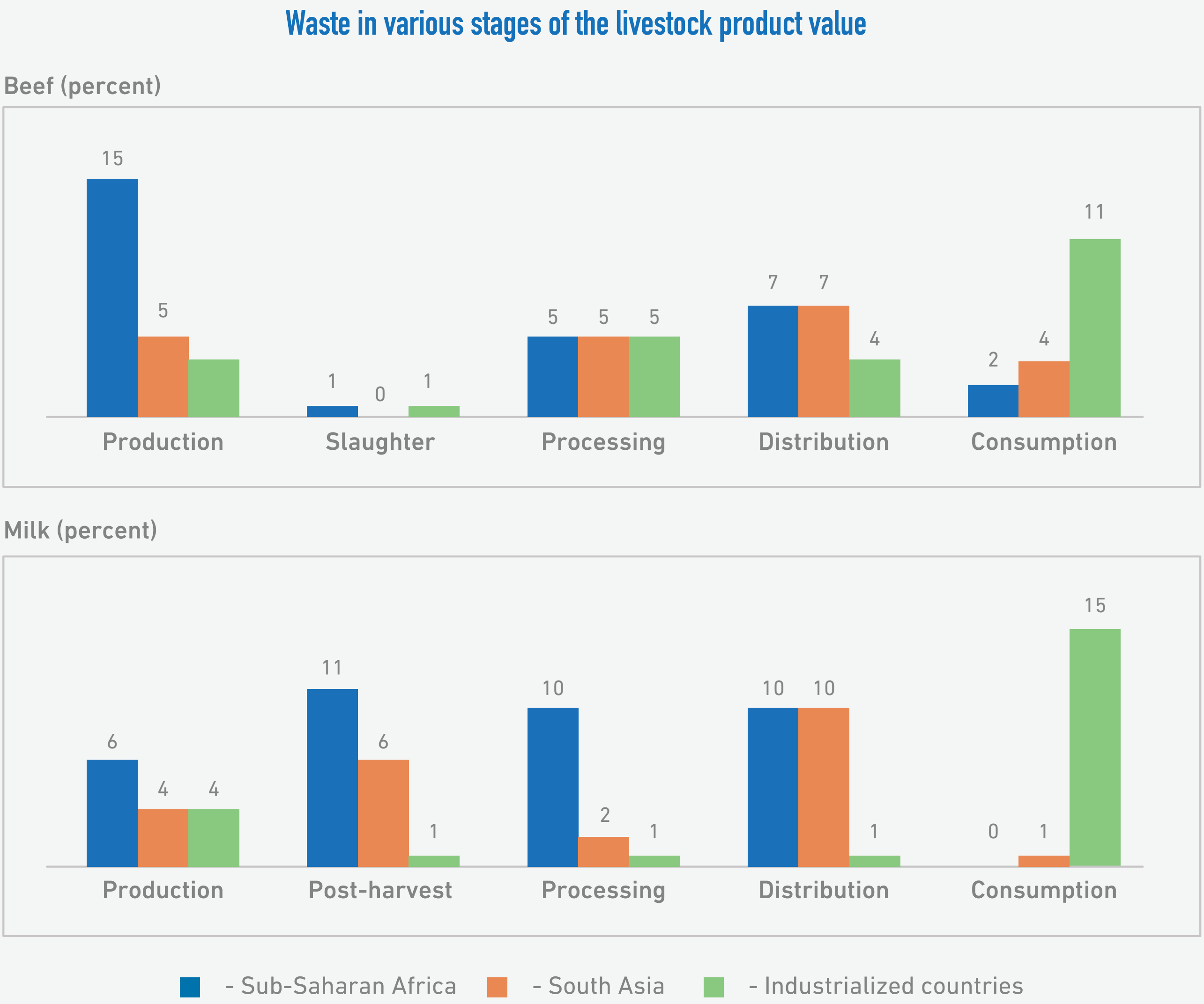


Exhibit 10: The most significant losses in beef (and other meat products) occur in the production phase due to animal death from diseases or other causes. For milk, on the other hand, greater losses occur post-production, due to the absence of processing and storage infrastructure on route to the market. (Source: FAO, 2011)

Temperature sensitivity of various livestock products

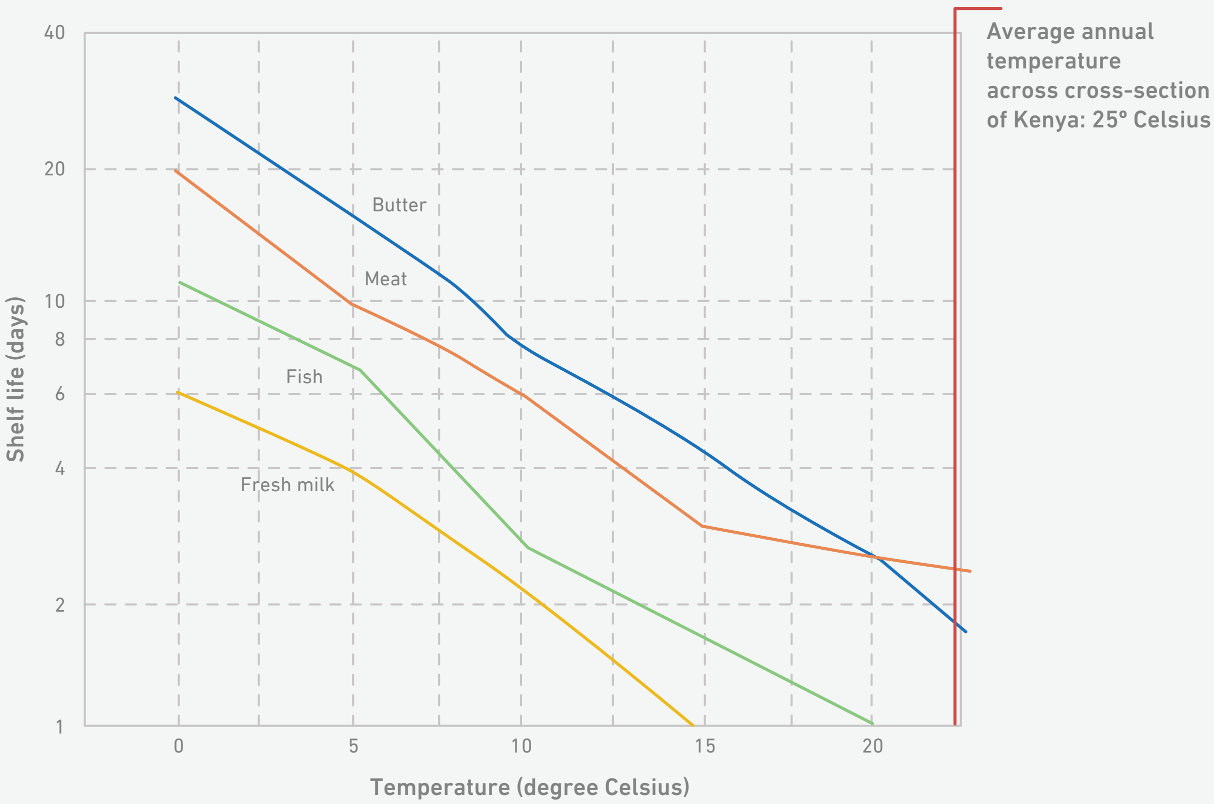


Exhibit 11: Livestock products such as milk, fish, meat and butter are highly temperature-sensitive. They need to be stored well below the average temperatures common to most tropical countries. Note: The vertical axis scale is logarithmic. (Source: adapted from Practical Action, 2012)

4. The cost of inputs is a significant barrier for pastoral, agro-pastoral and mixed-extensive farmers to convert to intensive farming

The cost of animal feed has traditionally prevented the transition from pastoralism to intensive livestock systems (World Bank, 2008). For example, feed accounts for 70 percent of the production cost of dairy in India (ILRI, 2011). Consequently, most poor livestock producers, particularly pastoralists, rely on public grazing lands to keep animal production costs low.

However, due to shrinking land resources and alternative feed crop demand, feed prices are expected to increase at a faster rate than livestock product prices (Thornton, 2010). Water for livestock accounts for 30 percent of all water used in agriculture (Herrero, et al., 2009). Affordable access to water is especially critical to mixed crop-livestock systems, where both plant and animal water needs must be met.

In arid and semiarid regions, access to water is the main reason for not transitioning to more intensive livestock production systems. Climate change and changing weather patterns are further eroding pastoralists' ability to convert to intensive systems, by reducing the amount of water in the dry seasons, and decreasing the availability of forage.

SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

Livestock are not only a source of food for smallholder farmers, but also a valuable asset. Recent research proves that owning livestock can help smallholder farmers escape poverty. Yet, in the absence of functioning markets and value chains for livestock produce, smallholder farmers can derive only limited economic benefits. This lack of income in turn impacts livestock production and yield—no genetic diversification through artificial insemination, little protection against diseases and high wastage of produce because of a lack of on-farm refrigeration facilities.

While broader systemic interventions including increasing local processing capacity, incentivizing a shift to more intensive systems, improving market access and improving transport infrastructure are necessary to make fundamental long-term changes, six technological breakthroughs and one further innovation can drive significant targeted improvements in animal health and productivity.

Breakthroughs:

1 2 3 4 5 6 7 8 9 10
11 12 13 14 15 16 17 18 19 20
21 22 23 24 25 26 27 28 29 30
31 32 33 34 35 36 37 38 39 40
41 42 43 44 45 46 47 48 49 50

12 Affordable (less than $50) off-grid refrigeration for smallholder farmers and small agribusinesses

The absence of affordable refrigeration and electricity severely limits the ability of smallholder farmers to produce, preserve and sell perishable commodities like vegetables, fruits, meat and dairy. Such products are highly sensitive to temperature, and the lack of refrigeration dramatically reduces their shelf life, especially in tropical climates.

While there are some inexpensive refrigerators available in emerging markets like India and China, they still cost more than $100, need reliable electricity and are difficult to repair once damaged. A new kind of refrigerator that costs less than $50 and can run on solar power will help smallholder farmers provide better nutrition for their families, and take high-value commodities to market, thereby increasing their incomes.

There is a recent resurgence of interest of very affordable age-old traditional cooling technologies (like clay pots). While this showcases the potential demand for an affordable and durable solution, traditional options like clay are subject to biological contamination and difficult to clean. Moreover, as agricultural systems advance, there will be greater need for commodity-specific temperature control. Furthermore, it is difficult to see traditional cooling solutions leading to modern and profitable agricultural value chains.

To serve the needs of rural, low-income farmers, refrigerators need to be operable off-grid (like solar-powered), considerably less expensive than the current $100 range and easy to repair. Such technologies appear to be on the horizon.

A new generation of refrigerators using thermoelectric technology is beginning to reach the market, supplementing existing vapor-compression models. Given the broad demand for refrigeration there is reason to believe that an affordable product will gradually reach a critical mass of smallholder farmers—notwithstanding the usual problems of market fragmentation and distribution.

Current State

Development Stage: Engineering

Time to market (years)

<3 4-6 7-10 10+

Deployment: Challenging

Associated 50BT Chapters

Food Security

SDG Alignment

Impact

Increased Access to Food (# of People)

<1M 10M+ 100M+ 1B+

New Income Generated (# of People)

<1M 10M+ 100M+ 1B+

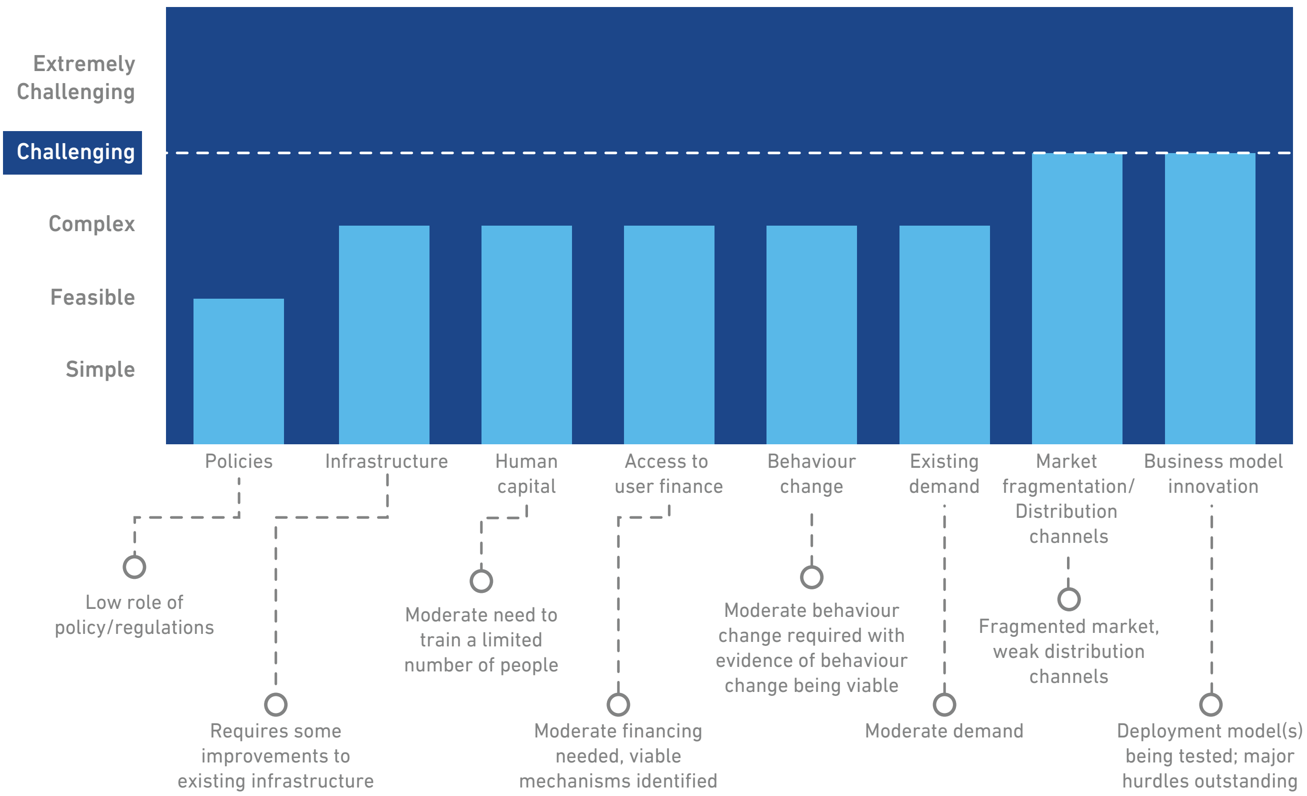
Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- **Attractive for emerging markets (lower profits)**
- Emerging markets potential; requires derisking (sustainable)
- Non-commercial (unprofitable)

Based on the above, it is likely only a matter of three to four years before low cost refrigerators become practical for rural farmers. Despite the need and expected demand, such a technology will face considerable barriers to deployment due to the fragmented nature of the market, the absence of a value chain for distribution and maintenance and the need for financing for farmers.

Hence, deployment will be CHALLENGING.

Breakthrough 12: Difficulty of deployment



13 Commercial scale, affordable and energy efficient refrigeration/cold-chain systems for agribusinesses and transport of food

The ability to transport food to markets while preserving freshness will not only reduce post-harvest losses, but also create new value propositions for smallholder farmers. The absence of such cold chain infrastructure is one of the factors limiting access to market for higher-value produce (for example, horticulture; and as the Livestock section discusses, meat and dairy). The lack of refrigeration also reduces everyday access to a diverse base of nutrients for children and the population in general.

Refrigerated trucks available on the market today cost tens of thousands of dollars, require diesel and are built for smooth roads. To be useful to dealers and agribusiness entrepreneurs who serve smallholder farmers in remote areas, refrigerated storage chambers and transport vehicles will have to be robust and cost significantly less than $5,000. While advances in stationary refrigeration technologies can also help advance mobile refrigeration, there are a number of significant differences.

First, stationary refrigerators normally operate indoors, whereas transport refrigerators will have to operate outdoors, under much warmer ambient temperatures and harsher conditions.

Second, while a major challenge for stationary refrigeration is the absence of reliable electricity, transport refrigerators can use the fuel used to power the vehicles. Third, refrigerated vehicles will become affordable only after general-purpose vehicles become affordable. Based on the above analysis, the projected time to market for such technologies is five to seven years.

Current State

Development Stage: Engineering

Time to market (years)
<3 4-6 7-10 10+

Deployment: Extremely Challenging

Associated 50BT Chapters

Food Security

SDG Alignment

2 ZERO HUNGER
8 DECENT WORK AND ECONOMIC GROWTH

Impact

Increased Access to Food (# of People)
<1M 10M+ 100M+ 1B+

New Income Generated (# of People)
<1M 10M+ 100M+ 1B+

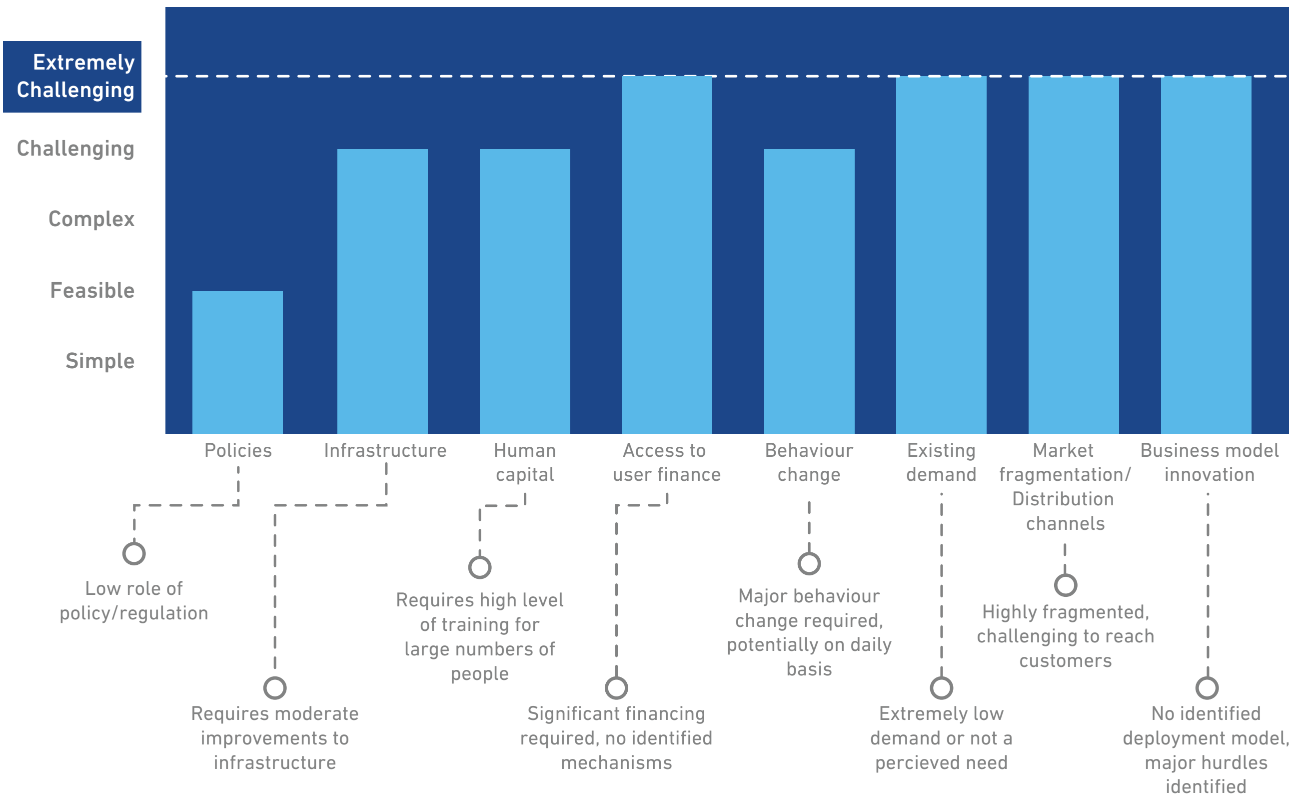
Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- **Attractive for emerging markets (lower profits)**
- Emerging markets potential; requires derisking (sustainable)
- Non-commercial (unprofitable)

Even when such a technology is developed, deployment will be difficult. The market is extremely fragmented and adoption will depend on the growth of the broader market for the relevant agricultural commodities. In addition, poor road infrastructure and the sparse presence of fueling stations will be a major hurdle in the usability of refrigerated transport.

Finally, a maintenance and repair infrastructure (currently absent) will be necessary to keep these refrigeration facilities functioning. We estimate that deployment will be EXTREMELY CHALLENGING.

Breakthrough 13: Difficulty of deployment



14 An affordable and portable toolkit for extension workers, which includes a core set of devices for testing crop health, livestock health and quality of produce

Training farmers, while helpful, is often not sufficient on its own to add tangible value. Extension workers should also be able to provide specific on-farm products and services to help farmers improve the volume and quality of their produce. The most important of such on-farm services include:

- Testing crops for particular, common pathogens and providing information about appropriate remedies. If combined with the provision of appropriate remedies, such a tool can help prevent potentially devastating losses for farmers.
- Diagnosing livestock at the point-of-care for particular diseases and providing appropriate medication and disease management advice. As discussed in the Livestock section, disease is a significant contributor to livestock losses. Hence, an effective veterinary service, enabled by such a toolkit, combined with regular extension support, can prove invaluable.
- Testing the composition (like chemical and water) of high-value cash crops and produce to provide real time advice on maximizing the quality of the output. This, in turn, can lead to higher market prices.

Such a toolkit does not currently exist in developing countries. Even in industrialized countries such tests are typically performed at labs and other centralized locations, or carried out using expensive portable equipment. Even though there is nothing fundamentally complex about the underlying science for developing such a toolkit, it will take considerable effort to build a practical product. While our research found that there is some interest in such technologies (especially from buyers of cash crop and livestock output), it is not clear that the necessary R&D and product development is being conducted. As such, we believe such a toolkit is four to six years from being available in the market.

Current State

Development Stage: Engineering

Time to market (years): <3 | 4-6 | 7-10 | 10+

Deployment: Complex

Associated 50BT Chapters

Food Security

SDG Alignment

Impact

Increased Access to Food (# of People): <1M | 10M+ | 100M+ | 1B+

New Income Generated (# of People): <1M | 10M+ | 100M+ | 1B+

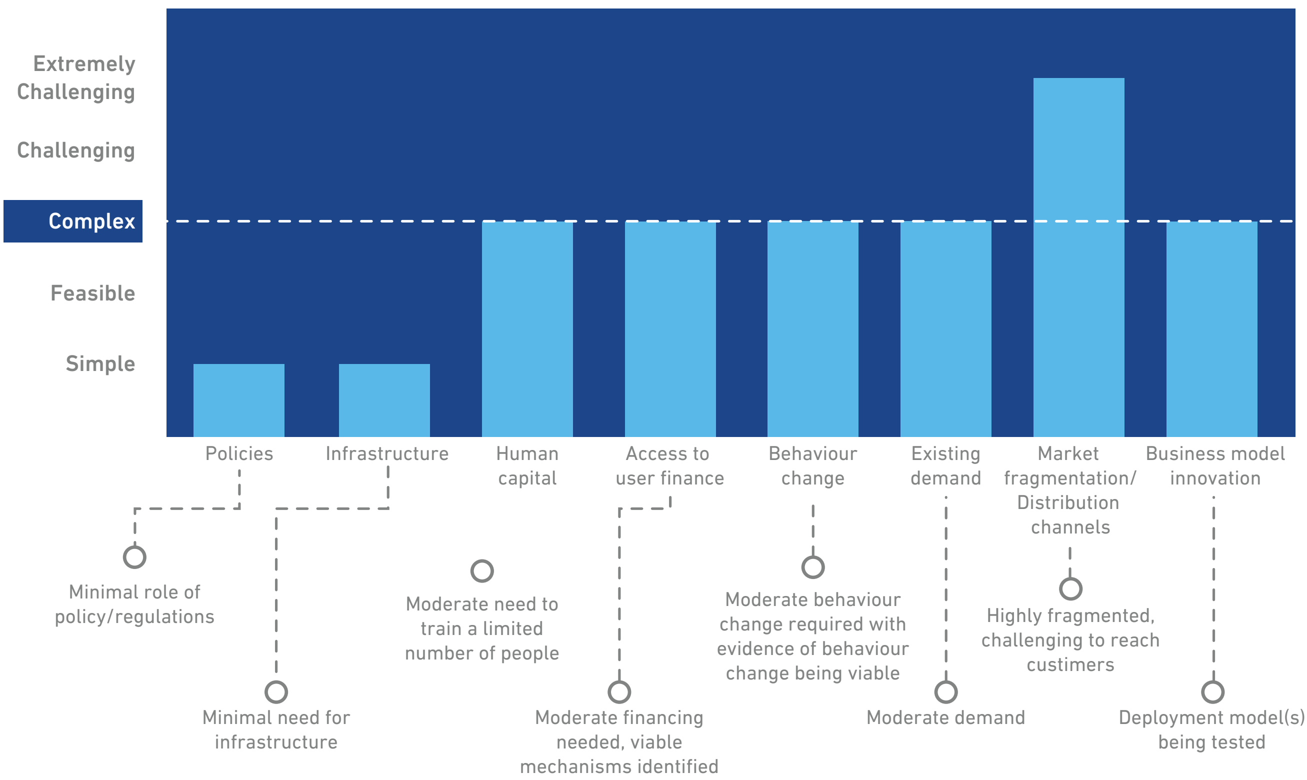
Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

When such a technology becomes available, it has the potential to catalyze a range of valuable services for farmers. This, in turn, can help spawn private service providers who will intrinsically be more accountable to their customers. However, it will face many of the familiar challenges: overcoming a lack of demand, the need for user finance and training.

On the whole, we believe such a toolkit can gain significant traction because it can demonstrate value within a short time frame. We expect deployment in this case will be COMPLEX.

Breakthrough 14: Difficulty of deployment



15 A low-cost mechanism to preserve animal semen (including new methods to produce liquid nitrogen or alternatives to liquid nitrogen)

Selective breeding has proven to be one of the most effective mechanisms for continuously improving the stock of animals. Artificial insemination is the only realistic means of selective breeding for most farmers.

Preservation and transport of animal semen requires temperatures colder than minus 100 degrees Celsius, currently achieved only with liquid nitrogen. While it is possible to build small-scale liquid nitrogen production units with limited investment (for example, cryogenics enthusiasts have built 1 liter per day production units for about $500 to $1,000), large-scale production facilities are expensive.

A less expensive mechanism to produce liquid nitrogen, or an alternative to liquid nitrogen as the means of preserving semen, can be a significant enabler of germplasm delivery.

Nitrogen liquefaction is intrinsically energy-intensive and hence, expensive. At the same time, there is no proven mechanism to preserve a particularly thermosensitive substance like animal semen. Currently, limited R&D is underway for such technologies. It is likely that such a breakthrough will take at least 10 years to materialize.

Current State

Development Stage: R&D

Time to market (years)
<3 4-6 7-10 10+

Deployment: Extremely Challenging

Associated 50BT Chapters

Food Security

SDG Alignment

2 ZERO HUNGER

9 INDUSTRY, INNOVATION AND INFRASTRUCTURE

Impact

Increased Access to Food (# of People)
<1M 10M+ 100M+ 1B+

New Income Generated (# of People)
<1M 10M+ 100M+ 1B+

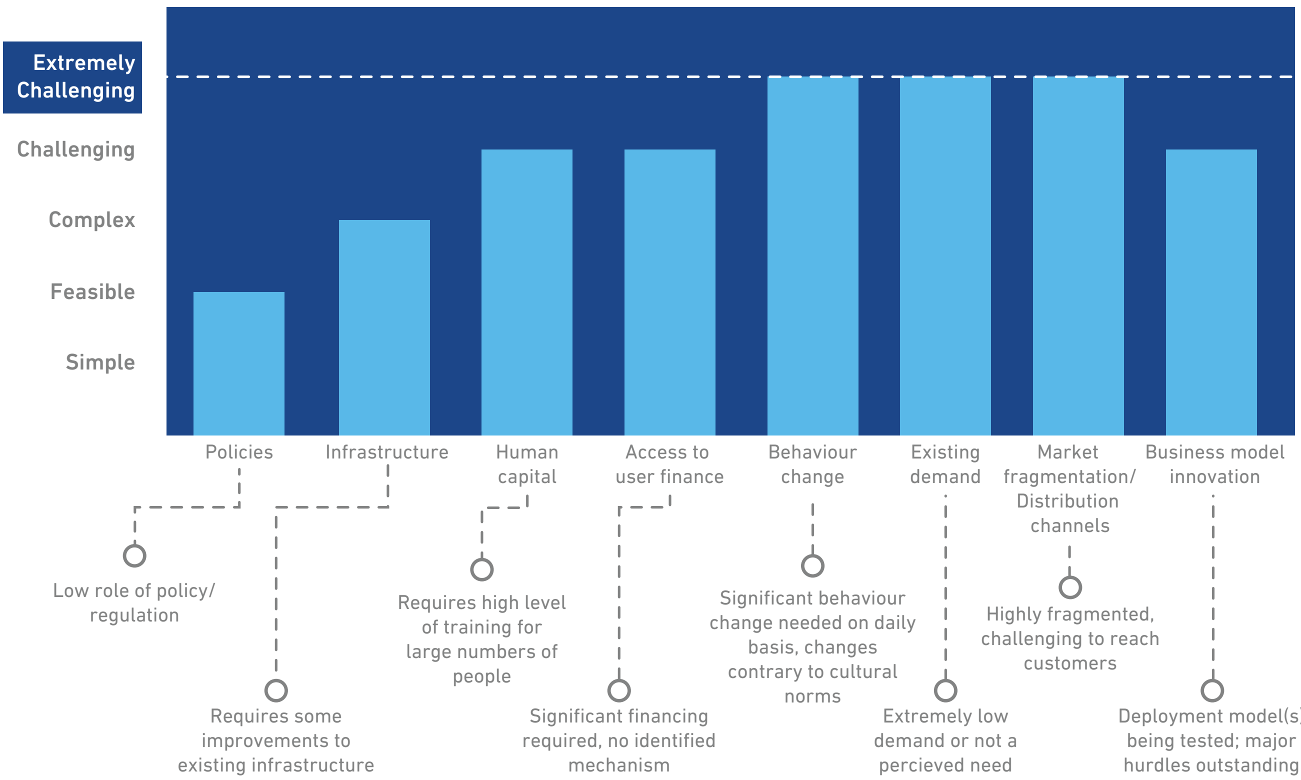
Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

Such a technology will face significant deployment challenges: there is very limited demand for artificial insemination from smallholder livestock farmers and the highly fragmented nature of the market means that distribution will be very difficult.

Moreover, collection and administration of AI takes a certain amount of technical knowledge. Overall, deployment will be EXTREMELY CHALLENGING.

Breakthrough 15: Difficulty of deployment



16 Alternative meat production system that is affordable, desirable and environmentally sustainable

The environmental consequences of large-scale conventional meat production systems are increasingly evident, such as deforestation and polluted waterways.

Alternative meat production techniques are being developed, that if successful could satisfy our growing meat demand with reduced environmental impacts. Such products are potentially healthier and more efficient alternatives to conventional meat, with lower use of land, water and agricultural inputs.

If the conditions for alternative meat production could be sufficiently controlled and manipulated at industrial scale, it would offer safe and affordable food with a healthy nutritional profile, to improve food security and quality of life.

There are two primary avenues for alternative meat production. The first avenue, often called substitute meat or meat analog, involves the conversion of non-animal biomass to have the characteristics of actual meat. This begins with the conventional agricultural production of feedstocks such as soybean, wheat or peas, followed by industrial conversion into a material with texture and taste similar to meat.

A notable example is Impossible Foods, which is primarily made of soybean protein concentrate and vegetable oils, with additional plant-based additives to mimic the flavor of meat. Impossible Foods products were initially introduced in 2016, and in 2019 the firm partnered with Burger King to serve alternative meat burgers in fast-food restaurants throughout the US.

The second avenue, often described as cultured meat, cellular meat or in-vitro meat, involves the managed growth of actual animal cells. This tissue engineering process begins with collection of stem cells from living animals, which are then allowed to grow and reproduce in a bioreactor, a device for carrying out biochemical processes.

The living cells are provided with nutrients in a suitable culture medium, typically composed of water, glucose, amino acids, lipids, vitamins and salts.

If the cultured meat is to match or exceed the nutritional value of conventional meat, any nutrients found in meat that are not synthesized by the growing cells must be supplied in the culture medium.

Current State

Development Stage: In-Market Small Scale

Deployment: Challenging

Associated 50BT Chapters

Food Security

Global Change

SDG Alignment

2 ZERO HUNGER

12 RESPONSIBLE CONSUMPTION AND PRODUCTION

Impact

Increased Access to Food (# of People)

<1M 10M+ 100M+ 1B+

New Income Generated (# of People)

<1M 10M+ 100M+ 1B+

Commercial Attractiveness

- **Attractive for industrialized markets (high profits)**
- Attractive for emerging markets (lower profits)
- Emerging markets potential; requires derisking (sustainable)
- Non-commercial (unprofitable)

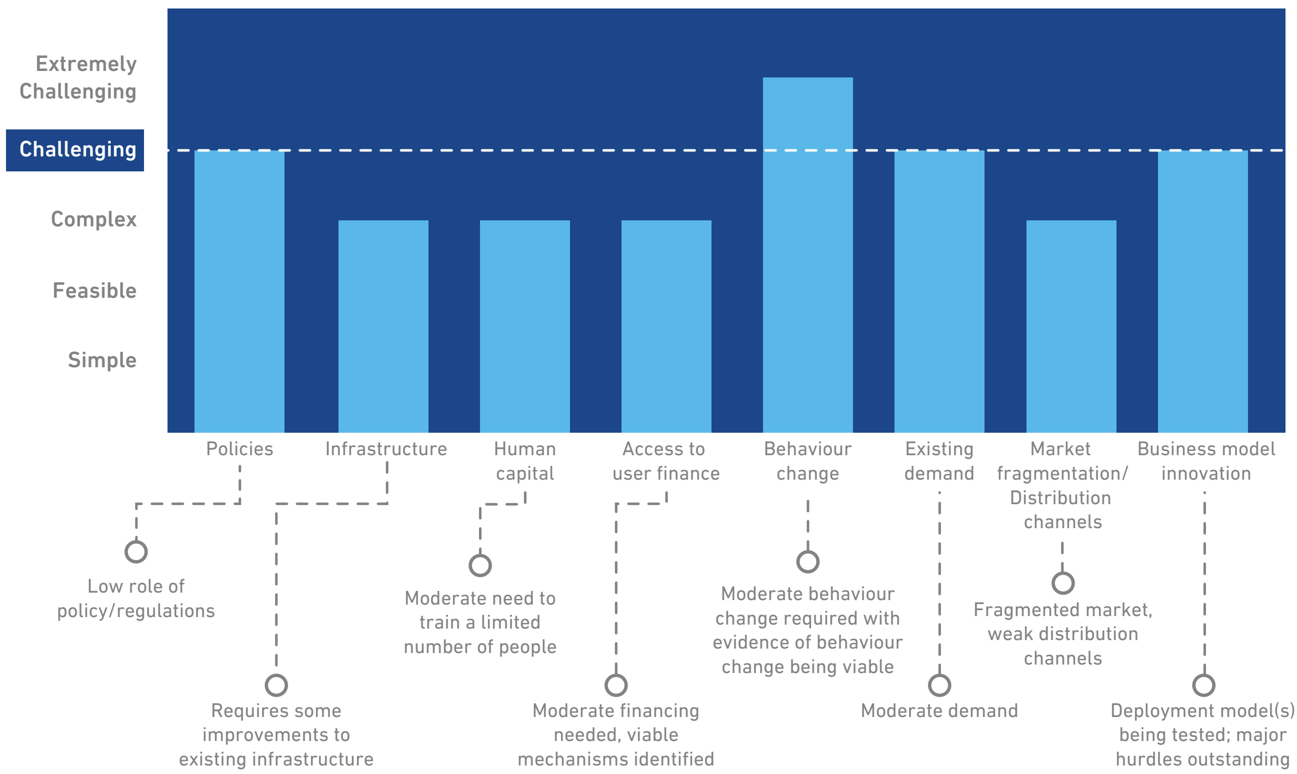
There are many technical challenges to sustainable in vitro meat culturing system on a large scale. The technology now exists to produce in-vitro meat on very small scales, as its major use to date has been regenerative medicine of a variety of tissues and organs.

Current cultured meat processes require large energy input for industrial processes, as biological functions such as digestion and nutrient circulation are replaced by industrial equivalents. The climate implications of cultured meat are complex, and depend on emissions of carbon dioxide, methane and other greenhouse gases from the cultured and reference animal-based systems.

Scaling alternative meat technologies as a global food security solution will depend on many economic, cultural and technical factors. Widespread deployment will face a number of hurdles, primarily along acceptance by consumers and regulators, and limited current demand for alternative meat products.

Initial substitute meat products are already on the market, and cultured meat products are likely to be market-ready in three to five years. Large-scale deployment is projected to be CHALLENGING.

Breakthrough 16: Difficulty of deployment



38 Low cost off-grid refrigerators for preserving vaccines (and other temperature sensitive pharmaceuticals) in remote settings

Vaccines and a number of other pharmaceuticals are highly temperature sensitive. Thermostable mechanisms likely represent the long-term solution for deploying these life-saving pharmaceuticals to remote parts of the world. In the meantime, refrigeration will continue to play a critical role in preserving and delivering them to those in need.

Larger storage and health facilities tend to have access to reliable refrigerators powered by grid electricity or diesel-powered generators. Smaller, rural facilities, however, have neither the necessary funding, nor access to reliable power sources.

Existing refrigeration technologies have proven unreliable or unaffordable for small, remote health centers, and for last-mile outreach. Currently, most remote health centers use mechanical compression (requiring high levels of energy, environmentally questionably coolants, and/or batteries) or absorption (requiring kerosene or gas as the fuel); these technologies are energy-intensive, heavy, and difficult to maintain.

As a result, a large number of such refrigerators are non-functioning. While there are reliable technologies for larger-scale clinics, these refrigerators are too large and too expensive for small health centers; and they still do not address the problem of last-mile outreach. Outreach campaigns have no access to active refrigerators, and have to use ice-lined cooler boxes which often lead to freezing and keep the vaccines cold only as long as the ice does not melt. As such, an affordable, portable, solar-powered refrigerator will be crucial, especially for outreach campaigns to remote areas.

In recent years new refrigeration technologies like smaller-scale vapor compressors and solid-state thermoelectric cooling mechanisms have been introduced, and are beginning to be used for small refrigerators. One such technology is a vaccine storage device called Arktek™ that can keep vaccines at appropriate temperatures for a month or more.

The super-insulated device uses only ice—no propane, batteries, electricity, solar panels or other power sources are necessary at the point of use. Arktek™ can handle travel over rough roads and use in harsh environments, making it ideal for rural areas and for outreach work, or as a stationary device at rural health posts.

Clinical trials of Arktek™ have been conducted in Senegal and Ethiopia, and the device has received positive feedback from users. In another initiative, the UNICEF is conducting drone delivery trials of vaccines in Vanuatu. Although this is innovative, viability of a scale up plan is yet to be proven.

Current State

Development Stage: Engineering

Time to market (years): <3 | 4-6 | 7-10 | 10+

Deployment: Challenging

Associated 50BT Chapters

Global Health

SDG Alignment

Impact

Lives Saved (# of People/Year): <1M | 10M+ | 100M+ | 1B+

Health Improved (# of People): <1M | 10M+ | 100M+ | 1B+

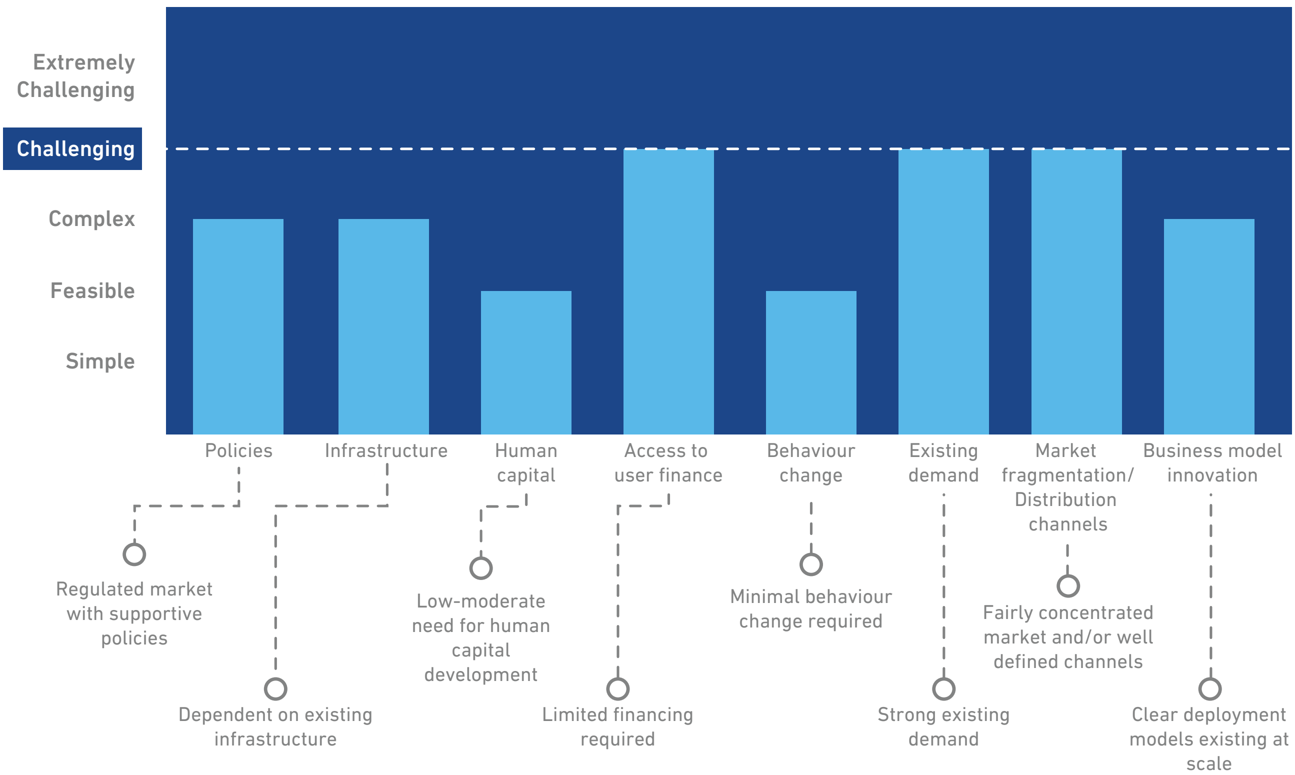
Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

While this is positive news, there is still no affordable market-ready technology available, nor proven refrigeration method at the scale needed for sustained outreach campaigns. A number of emerging approaches have been validated and the technology is being actively developed in research institutions and industrial facilities.

Once developed, the deployment challenges for these technologies will include a highly fragmented market with limited access to finance, sparse distribution channels, limited technical capacity along the value chain and a difficult path to creating demand. Hence, deployment will be CHALLENGING.

Breakthrough 38: Difficulty of deployment



Innovation: Low cost stall-side diagnostics for the major livestock diseases

Farmers, and the few service providers they usually have access to, are typically not able to diagnose a sick animal. This prevents them from seeking timely treatment, even if available. More importantly, it keeps farmers from preventing the disease from spreading to the rest of the herd.

A simple low-cost stall-side[13] diagnostic that can be used by an extension worker or veterinarian—for the deadliest diseases specific to animal type and geography—can be a powerful tool to reduce livestock losses. Given the range of potential diseases and a lack of laboratory facilities to test samples, a point-of-care suite of diagnostics would be required.

Existing reliable diagnostics are expensive, highly technical and involve culturing (which takes time). There is limited R&D and product development activity because the private sector does not find the market for animal diagnostics attractive. At the same time, there is limited public or philanthropic funding because animal health—unlike human health or crop health—has not been a major donor priority.

Advances in animal diagnostics will likely build on similar point-of-care platforms for human health diagnostics, many of which are still several years from becoming a reality. Given these facts, low cost and reliable point-of-care animal health diagnostics are likely seven to 10 years away from being market ready.

Once ready, such technologies will face a highly fragmented market and limited demand from smallholder livestock keepers, who understand little about the tools and are likely unable to afford them. This is particularly true in extensive and pastoral systems. as such, deployment will be extremely challenging. Diagnostic devices are discussed in detail in the Diagnostics section of the Global Health chapter.

[13]Stall-side diagnostics are those that can be used where the animals are located, rather than requiring the transport of samples to a veterinary center or lab.

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FISHERIES AND AQUACULTURE

INTRODUCTION

Fish are an important and fast-growing component of human diet. The average person now eats over 20 kilograms of fish per year, and in numerous countries fish comprise over half of all animal protein consumed.

Fish have traditionally been obtained by catching wild fish from oceans, lakes and rivers, though fish stocks from these sources have become increasingly depleted during recent decades. Per unit of fish caught, fishers must now work harder and travel longer distances compared to years past. Trends toward increasing overexploitation of global fish stocks suggest that it will become increasingly difficult to catch significant quantities of wild fish.

Aquaculture production, or fish farming, has increased rapidly in the last two decades. Aquaculture is now on par with capture fishery as a source of fish for human consumption, and continues to grow. China is, by far, the country with the greatest annual fish production from both aquaculture and wild capture fisheries.

Despite the increasing importance of aquaculture to human food supply, current models of aquaculture production are largely unsustainable, and their ability to substantially scale up is questionable. Most aquaculture production requires feeding the farmed fish, and the most common feed is fish meal made from wild caught fish. Such fish meal is increasingly difficult to obtain in sufficient quantities due to overexploitation of wild fisheries. Current aquaculture production is also vulnerable to disease and changing environmental conditions. One technological breakthrough and one other innovation have the potential to overcome these challenges and enable the growing consumption of meat and fish in human diets.

- Breakthrough 16: Alternative meat production system that is affordable, desirable and environmentally sustainable
- Innovation: A scalable method for sustainable integrated aquaculture

Fish are an important part of a healthy human diet, but wild fish stocks are increasingly overexploited. The global catch of wild fish has remained roughly constant since the late 1980s, while the effort needed to catch the same amount of fish has increased. Aquaculture, or fish farming, has made up the gap in fish supply and has allowed us to increase our consumption of fish. Despite the increasing importance of aquaculture to human food supply, current models of aquaculture production are largely unsustainable and are unlikely to scale up sufficiently to meet growing demand.

CORE FACTS AND ANALYSIS

1. Fish are an important and growing part of the human diet

Global food fish consumption increased by an average 3.2 percent annually between 1961 and 2016, making it the fastest growing source of animal-based food, outpacing the 2.8 percent annual increase in consumption of meat from all terrestrial animals combined (FAO, 2018). Both of these consumption growth metrics exceeded the 1.6 percent average population growth rate during the period.

Per capita food fish consumption increased from 9 kilogram in 1961 to 20 kilogram in 2015, at an average annual rate of about 1.5 percent. In 2015, fish accounted for about 17 percent of animal protein and 7 percent of all proteins consumed by the global population (FAO, 2018). Fish contribute 50 percent or more of total animal protein intake in countries including Bangladesh, Cambodia, the Gambia, Ghana, Indonesia, Sierra Leone and Sri Lanka.

Fish play an important role in nutrition and global food security, providing a valuable source of nutrients and micronutrients that are important for diversified and healthy diets. Fish provide amino acids, fats and micronutrients such as iron, iodine, vitamin D and calcium, which are often lacking in vegetable-based diets. An estimated 845 million people are at risk of micronutrient deficiency due to insufficient consumption of zinc, iron or vitamin A, as a result of declines in wild fish catch in equatorial regions (Golden, et al., 2016).

Exhibit 1 shows global fish production from 1950 to 2016. The global catch of wild fish has remained roughly level since the late 1980s. The gap has been made up by aquaculture production, allowing expanded human consumption of fish. The global catch shown includes only reported catches, predominately industrial scale but also small-scale fishing. Not included in these official figures are illegal, unregulated and unreported catch, as well as unwanted bycatch that is discarded at sea (Pauly & Zeller, 2016; Watson, 2017).

Total fish production in 2016 was about 171 million tons. Direct human consumption accounted for about 88 percent, or 151 million tons, of fish. The percentage that is directly consumed has increased significantly in recent decades. The other 12 percent, or about 20 million tons, was mainly reduced to fishmeal and fish oil. Fishmeal and fish oil are in demand for aquaculture, as they are among the most nutritious and most digestible ingredients for farmed fish feeds.

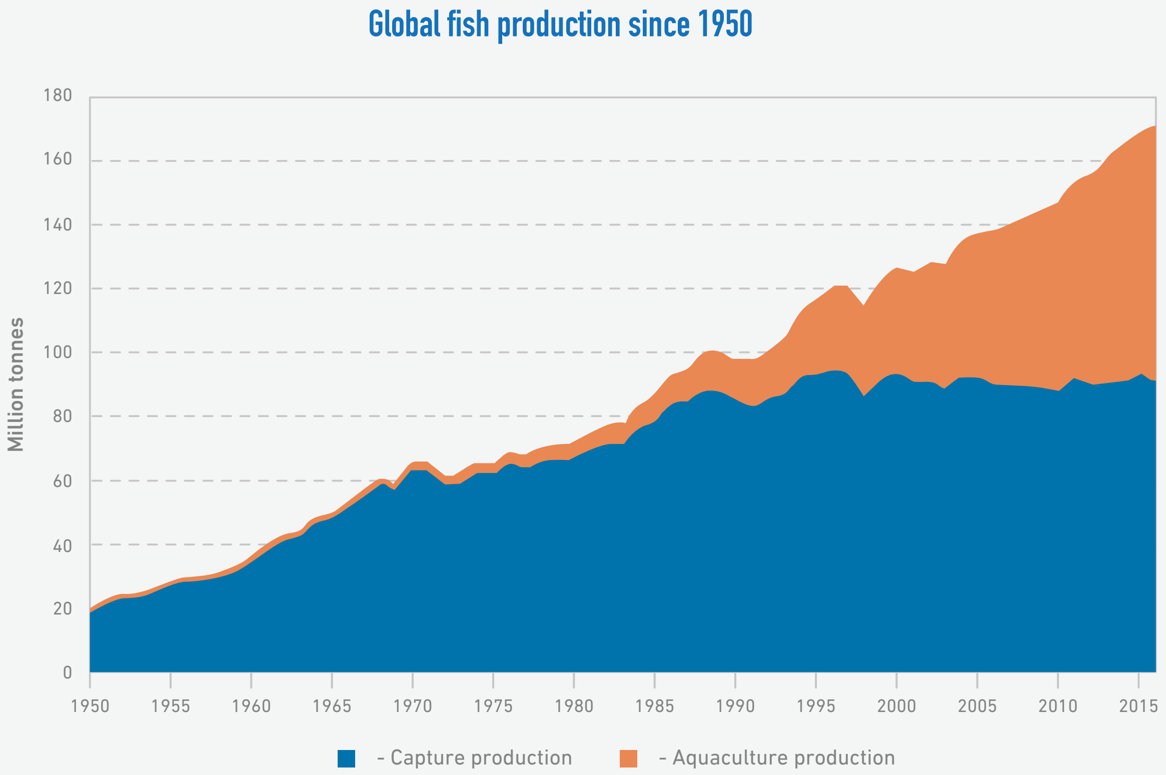


Exhibit 1: Global fish consumption has increased steadily since the 1950s. Capture of wild fish has remained roughly level since the 1990s, while aquaculture fish production has increased significantly and now provides a large share of all fish. (Source: FAO, 2018)

2. Wild fish capture is increasingly unsustainable and incapable of growth

World capture fishery production totals about 91 million tons per year. Of that amount, 87 percent is from marine waters and 13 percent is from inland waters.

The marine and inland fish catch of several major countries are detailed in **Table 1** and **Table 2**. China is, by far, the largest producer country of both marine and inland fish.

Marine capture fishery production		
Country	**2016 production (1000 tons)**	**Percent change from 2005 to 2014 average**
China	15,250	+15.6
Indonesia	6,110	+20.4
USA	4,900	+2.9
Russia	4,470	+24.0
Peru	3,780	-41.4
India	3,600	+11.9
Japan	3,170	-20.7
Vietnam	2,680	+28.7
Norway	2,030	-13.4
Philippeans	1,870	-13.5
All other countries	31,440	

Table 1: Top ten countries with the largest marine capture fisheries production. (Source: data from FAO, 2018)

Inland capture fishery production		
Country	**2016 production (1000 tons)**	**Percent change from 2005 to 2014 average**
China	2,320	+2.9
India	1,460	+34.4
Bangladesh	1,050	+2.9
Myanmar	890	+19.0
Cambodia	510	+20.5
Indonesia	430	+24.7
Uganda	390	-6.7
Nigeria	380	+31.2
Tanzania	310	+2.1
Russia	290	+20.3
All other countries	3,610	

Table 2: Top ten countries with the largest inland capture fisheries production. (Source: data from FAO, 2018)

Although the total annual catch has remained roughly the same since the 1980s (**Exhibit 1**), substantially more work is now required to maintain these catch levels (Watson, et al., 2013). **Exhibit 2** shows the clear trends of increasing fishing effort per unit of global fish catch (Bell, et al., 2017) and longer fishing distance that must be traveled per unit of catch (Tickler, et al., 2018). This growing difficulty of catching wild fish is due to the increasing overexploitation of global marine fish stocks (**Exhibit 3**).

In the 1970s, most global marine fish stocks were exploited sustainably and very few were overfished. Since that time, we have progressively exploited marine fisheries more intensively and are overfishing a larger share of global stocks (FAO, 2018). As noted above, these figures likely underestimate the problem, as they do not include illegal, unregulated and unreported catch, as well as unwanted bycatch that is discarded at sea (Pauly & Zeller, 2016; Watson, 2017). Reduction of illegal fishing is a strong lever for sustainable fisheries management (Cabral, et al., 2018).

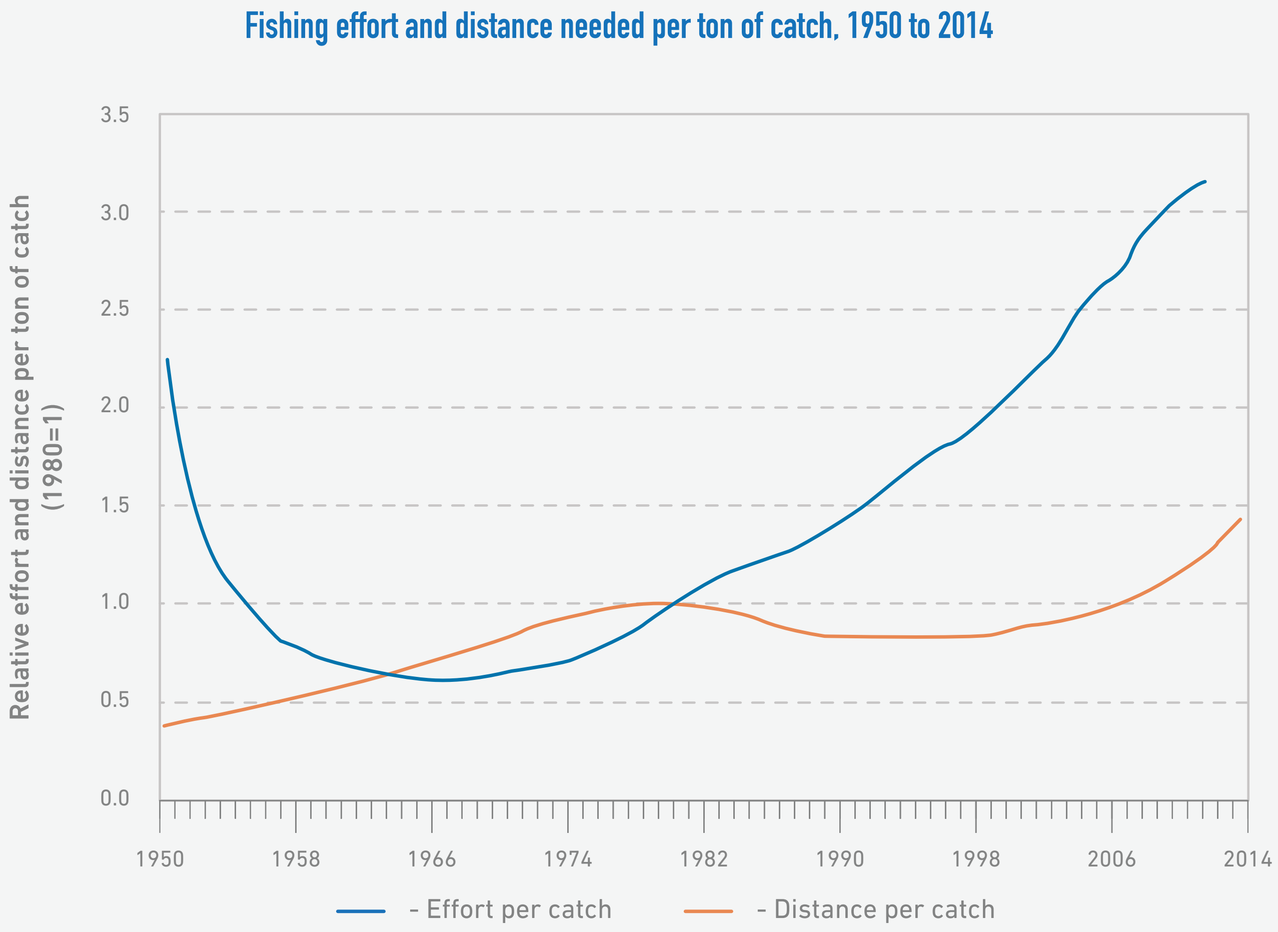


Exhibit 2: Globally, catching wild fish today requires more effort and distance than before. Fishing effort per ton dropped sharply in the 1950s due to technological improvement, but has been rising since then due to depleting stocks. Fishing effort is measured in watt-days of effort per ton of catch, based on data from Bell, et al. (2017). Fishing distance is measured in kilometers travelled per ton of catch, based on data from Tickler, et al. (2018). Both indicators are scaled so values in 1980 equal one.

Exploitation of global marine fish stocks, 1974 to 2015

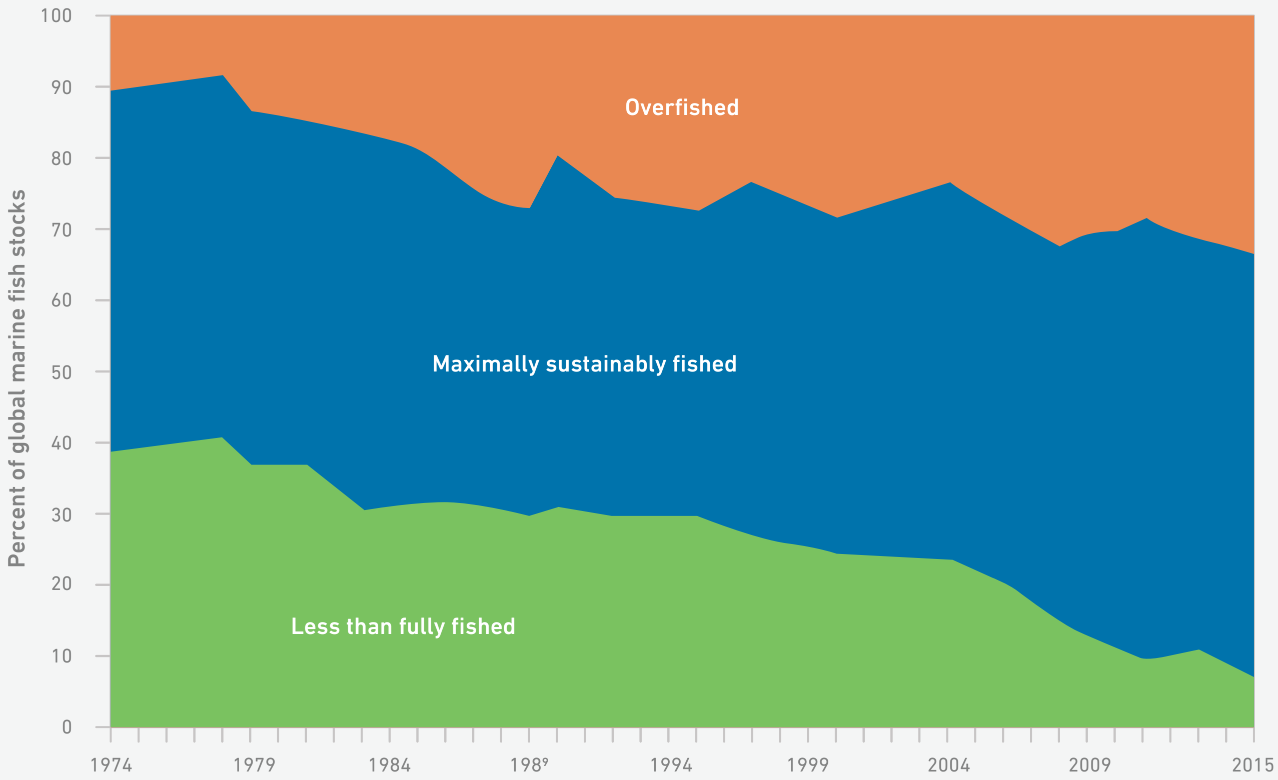


Exhibit 3: Exploitation of global marine fish stocks is becoming less sustainable, with more stocks being overfished. (Source: FAO, 2018)

3. Aquaculture production is growing rapidly to meet rising demand

Global aquaculture production has increased rapidly in the last two decades, reaching 80 million tons of food fish and 30 million tons of aquatic plants (FAO, 2018). Characteristics of the farmed food fish production in 2016 are shown in Exhibit 4. Production included 54 million tons of finfish, 17 million tons of mollusks and 8 million tons of crustaceans.

China is by far the largest producer of farmed food fish, having produced more than the rest of the world combined every year since 1991. Other major producers in 2016 were India, Indonesia, Vietnam, Bangladesh, Egypt and Norway. The 30 million tons of farmed aquatic plants included mostly seaweeds and a much smaller production volume of microalgae. China and Indonesia were by far the major producers of aquatic plants in 2016.

Characteristics of global aquaculture production

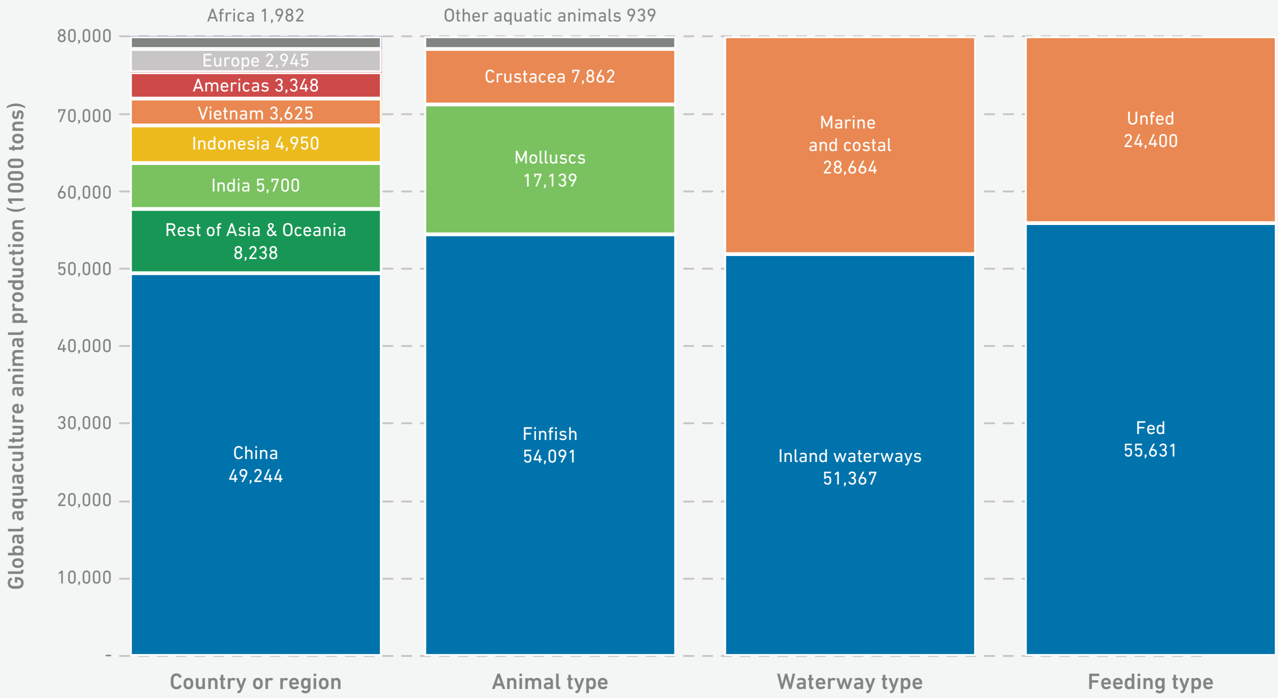


Exhibit 4: Characteristics of global aquaculture production in 2016, excluding aquatic plants. China is the location of 62 percent of global production. Finfish is the animal type produced in 68 percent of production. Inland waterways account for 64 percent of production. Animals are fed in 70 percent of production (Source: FAO, 2018)

About 64 percent of all farmed food fish production occurs in inland waters, while 36 percent occurs in marine and coastal waters. In 2016, 51 million tons of food fish were produced by inland aquaculture. Inland aquaculture is dominated by finfish farming, which accounts for 93 percent, the remaining 7 percent being crustaceans such as shrimp, crayfish and crabs.

Mariculture and coastal aquaculture produced 29 million tons of food fish in 2016. Marine and coastal aquaculture is dominated by mollusk production (59 percent), followed by finfish and crustaceans.

The practice of feeding farmed aquatic animal species has grown faster than that of unfed aquaculture, though both continue to expand. Unfed aquaculture production totaled 24 million tons in 2016, or 30 percent of all farmed food fish.

Of this, 9 million tons were filter feeding finfish raised in inland aquaculture, such as silver carp and bighead carp. Almost 16 million tons of self-feeding aquatic invertebrates, mostly marine bivalve mollusks, were raised in seas, lagoons and coastal ponds in 2016. Such marine bivalves and seaweeds are sometimes described as extractive species, and they can benefit the environment by removing waste materials and lowering the nutrient load in the water.

KEY CHALLENGES

1. Current models of aquaculture are largely unsustainable

Despite the increasing importance of aquaculture to the human food supply, current models of aquaculture production are largely unsustainable, and their ability to substantially scale up is questionable.

Almost two-thirds of all farmed food fish production currently relies on artificial feeding. This share has increased from less than half in 1980. Artificial feeding requires prepared fish feed, and results in relatively faster growth rates compared to non-fed species.

Fishmeal has been the preferred feed for aquaculture production, and is made by cooking, pressing, drying, and grinding fish or fish byproducts. Small pelagic species of fish, such as anchoveta, are typically caught and used for fishmeal production. A substantial portion, roughly one-third, of all wild-caught fish is used for non-food uses including fishmeal production.

Fishmeal production peaked in 1994 at about 30 million tons (live weight equivalent) and has fluctuated since then, dropping to 15 million tons in 2010 due to reduced anchoveta catches (FAO, 2012). While fishmeal was once a cheap commodity used widely as animal feed, demand has increased strongly while supply has fluctuated (Olsen & Hasan, 2012).

The current reliance of aquaculture on fishmeal feeding is unscalable and untenable in the long term. Some aquaculture trends are heading in the right direction; for example, the ratio of wild fisheries inputs to farmed fish output has gradually decreased to 0.63 for the aquaculture sector as a whole.

However, the ratio remains as high as 5.0 for Atlantic salmon, meaning that 5 kilograms of wild fish must be caught to produce a single kilogram of farmed salmon (Naylor, et al., 2009) Plant- and animal-based alternative feeds are increasingly used for industrial aquaculture, depending on relative prices and consumer acceptance.

However, sourcing large quantities of fish feed from land-based agriculture has important implications for the sustainability of farming and global food security (Blanchard, et al., 2017).

Nevertheless, the potential for marine aquaculture far exceeds the space required to meet seafood demand. The current total landings of all wild-capture fisheries could be produced using less than 0.015 percent of the global ocean area (Gentry, et al., 2017).

Several actions can increase the sustainability of fisheries, such as reduced use of wild-captured forage fish as feed for non-carnivorous aquaculture and agricultural species and greater use of fish by-products. Alternative feed sources that are nutrient-equivalent are needed for aquaculture sustainability (Froehlich, et al., 2018).

Current aquaculture production is also vulnerable to disease and changing environmental conditions. Disease outbreaks in recent years have affected aquaculture in numerous countries around the globe, resulting in significant loss of production (FAO, 2012).

In 2010 in China, aquaculture production suffered losses of 1.7 million metric tons caused by natural disasters, disease and pollution. Disease outbreaks almost eliminated marine shrimp farming production in Mozambique in 2011.

SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

Fish are an important part of a healthy human diet, but wild fish stocks are increasingly overexploited. Aquaculture, or fish farming, has made up the gap in fish supply and has allowed us to increase our consumption of fish.

Despite the increasing importance of aquaculture to human food supply, current models of aquaculture production are largely unsustainable and are unlikely to scale up sufficiently to meet growing demand.

One technology breakthrough and one further innovation can help overcome current limitations of wild-catch and aquaculture fish production.

Breakthroughs:

1 2 3 4 5 6 7 8 9 10
11 12 13 14 15 16 17 18 19 20
21 22 23 24 25 26 27 28 29 30
31 32 33 34 35 36 37 38 39 40
41 42 43 44 45 46 47 48 49 50

16 Alternative meat production system that is affordable, desirable and environmentally sustainable

The environmental consequences of large-scale conventional meat production systems are increasingly evident, such as deforestation and polluted waterways.

Alternative meat production techniques are being developed, that if successful could satisfy our growing meat demand with reduced environmental impacts. Such products are potentially healthier and more efficient alternatives to conventional meat, with lower use of land, water and agricultural inputs.

If the conditions for alternative meat production could be sufficiently controlled and manipulated at industrial scale, it would offer safe and affordable food with a healthy nutritional profile, to improve food security and quality of life.

There are two primary avenues for alternative meat production. The first avenue, often called substitute meat or meat analog, involves the conversion of non-animal biomass to have the characteristics of actual meat. This begins with the conventional agricultural production of feedstocks such as soybean, wheat or peas, followed by industrial conversion into a material with texture and taste similar to meat.

A notable example is Impossible Foods, which is primarily made of soybean protein concentrate and vegetable oils, with additional plant-based additives to mimic the flavor of meat. Impossible Foods products were initially introduced in 2016, and in 2019 the firm partnered with Burger King to serve alternative meat burgers in fast-food restaurants throughout the US.

The second avenue, often described as cultured meat, cellular meat or in-vitro meat, involves the managed growth of actual animal cells. This tissue engineering process begins with collection of stem cells from living animals, which are then allowed to grow and reproduce in a bioreactor, a device for carrying out biochemical processes.

The living cells are provided with nutrients in a suitable culture medium, typically composed of water, glucose, amino acids, lipids, vitamins and salts.

If the cultured meat is to match or exceed the nutritional value of conventional meat, any nutrients found in meat that are not synthesized by the growing cells must be supplied in the culture medium.

Current State

Development Stage: In-Market Small Scale

Deployment: Challenging

Associated 50BT Chapters

Food Security

Global Change

SDG Alignment

2 ZERO HUNGER

12 RESPONSIBLE CONSUMPTION AND PRODUCTION

Impact

Increased Access to Food (# of People)

<1M | 10M+ | 100M+ | 1B+

New Income Generated (# of People)

<1M | 10M+ | 100M+ | 1B+

Commercial Attractiveness

- **Attractive for industrialized markets (high profits)**
- Attractive for emerging markets (lower profits)
- Emerging markets potential; requires derisking (sustainable)
- Non-commercial (unprofitable)

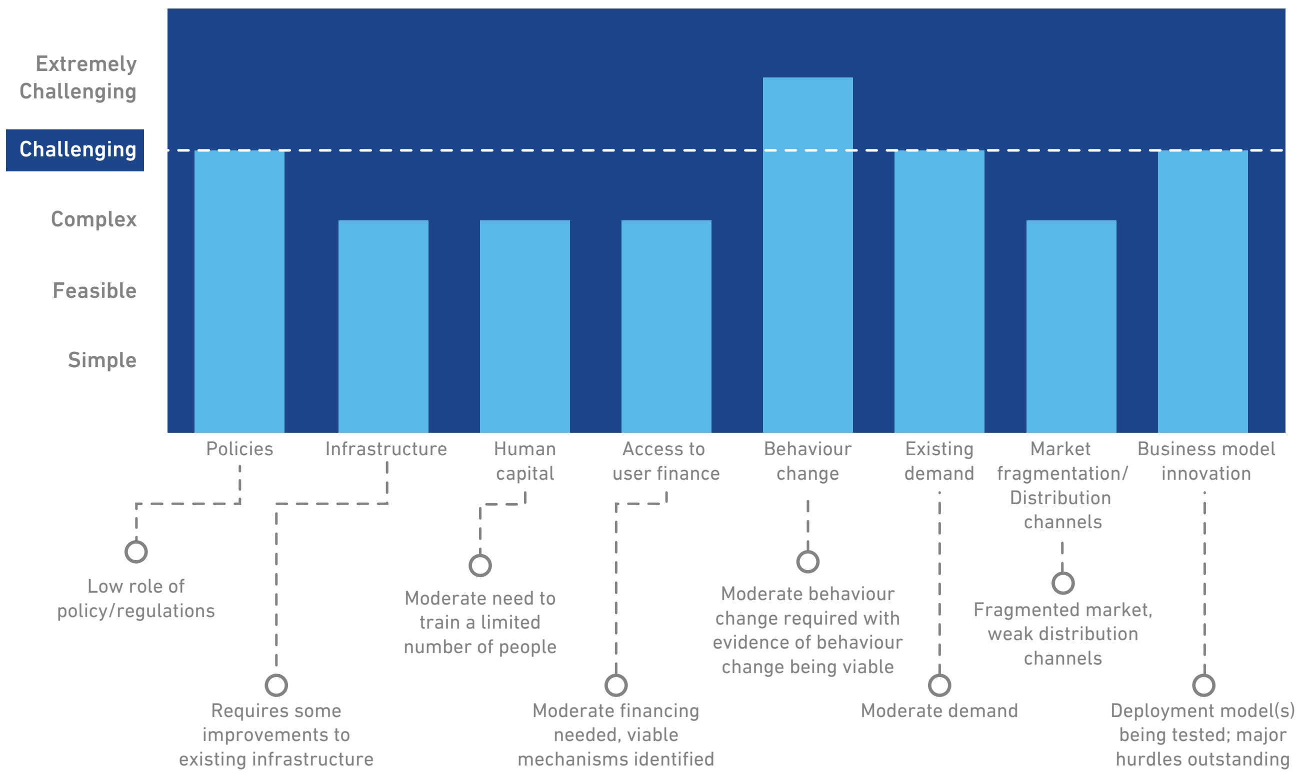
There are many technical challenges to sustainable in vitro meat culturing system on a large scale. The technology now exists to produce in-vitro meat on very small scales, as its major use to date has been regenerative medicine of a variety of tissues and organs.

Current cultured meat processes require large energy input for industrial processes, as biological functions such as digestion and nutrient circulation are replaced by industrial equivalents. The climate implications of cultured meat are complex, and depend on emissions of carbon dioxide, methane and other greenhouse gases from the cultured and reference animal-based systems.

Scaling alternative meat technologies as a global food security solution will depend on many economic, cultural and technical factors. Widespread deployment will face a number of hurdles, primarily along acceptance by consumers and regulators, and limited current demand for alternative meat products.

Initial substitute meat products are already on the market, and cultured meat products are likely to be market-ready in three to five years. Large-scale deployment is projected to be CHALLENGING.

Breakthrough 16: Difficulty of deployment



Innovation: A scalable method for sustainable integrated aquaculture

As shown earlier in **Exhibit 1** and **Exhibit 2**, the global catch of wild fish has remained roughly constant since the late 1980s, and yet the effort necessary to catch the same amount of fish has increased. Aquaculture has made up the gap in fish supply, which allowed humans to increase their consumption of fish. Aquaculture, the farming of aquatic organisms such as fish, crustaceans and aquatic plants, is currently the fastest growing animal food-producing sector.

Despite the increasing importance of aquaculture to human food supply, current models of aquaculture production are largely unsustainable, and their ability to substantially scale up is questionable. Two-thirds of all farmed food fish production currently relies on artificial feeding. This share has increased from less than half in 1980. Artificial feeding requires prepared fish feed and results in relatively faster growth rates compared to non-fed species. Fishmeal has been the preferred feed for aquaculture production and is made by cooking, pressing, drying and grinding fish or fish byproducts. Small pelagic species of fish, such as anchoveta, are typically caught and used for fishmeal production. A substantial portion, roughly one-third, of all wild-caught fish is used for non-food uses including fishmeal production. Fishmeal production peaked in 1994 at about 30 million tons (live weight equivalent) and has fluctuated since then, dropping to 15 million tons in 2010 due to reduced anchoveta catches.

While fishmeal was once a cheap commodity used widely as animal feed, demand has strongly increased while supply fluctuated. The current reliance of aquaculture on fishmeal feeding is unscalable and untenable in the long term. Current aquaculture production is also vulnerable to disease and changing environmental conditions. Disease outbreaks in recent years have affected aquaculture in numerous countries around the globe, resulting in significant loss of production. In 2010 in China, aquaculture production suffered losses of 1.7 million metric tons caused by natural disasters, diseases and pollution. Disease outbreaks almost eliminated marine shrimp farming production in Mozambique in 2011.

An important innovation is the development of a scalable method of sustainable integrated aquaculture. About 71 percent of the earth's surface is covered by water, and a large share of sunlight received by the planet falls on water. A successful aquaculture technique that directly captures this sunlight through managed photosynthesis processes and converts the accumulated biomass into various food products could greatly enhance global food security. An ecologically appropriate system would focus on integrating flows of energy, nutrients and biomass through the system. This may include integrating aquatic and terrestrial food production, for example, by using waste material from land as food and nutrients.

Important constraints of current generation aquaculture systems will need to be overcome. Advances are needed in hatchery systems, feeds and feed-delivery systems and disease management. Other potential improvements may come from better stock selection, optimizing scale of production technologies and the culture of a wider and synergistic range of species. Other important issues are disease resistance and tolerance to temperature and salinity variation, to enable a broader range of production options. To avoid unintended consequences, a scalable system would avoid discharge of organic effluents or disease treatment chemicals and being a source of diseases or genetic contamination among wild species.

Substantial research and development work is required for this innovation. We expect that it will take more than 10 years for this to be market ready, given adequate resources. Concurrent with technology development, appropriate business models must be developed to allow wide scale-up in developing regions. Deployment challenges include access to finance and policies regarding land and water use.

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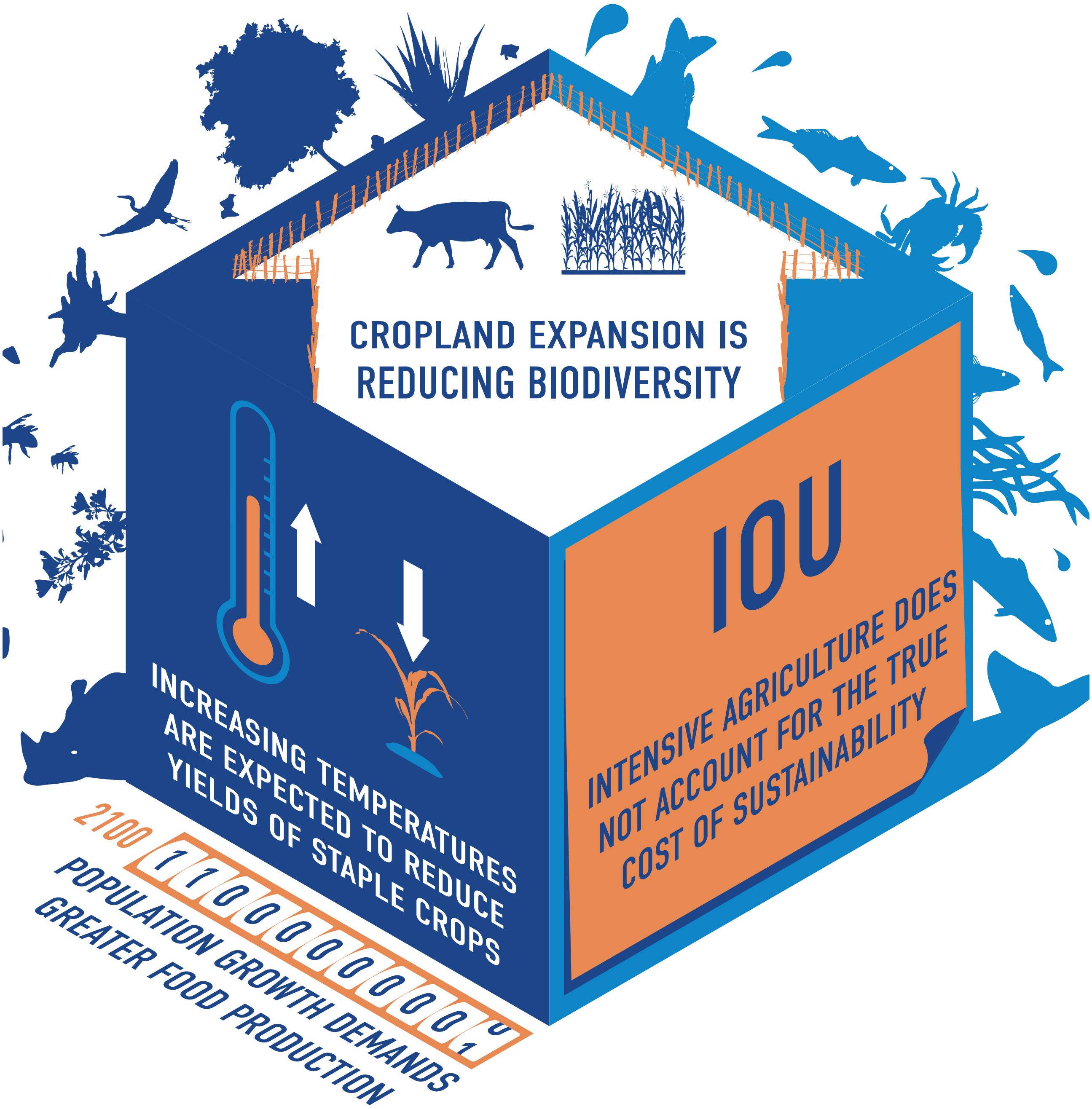


AGRICULTURAL SUSTAINABILITY

INTRODUCTION

Current global food production systems leave unsustainable environmental footprints.

Collectively, they are causing soil erosion, deforestation, greenhouse gas emissions, depletion of non-renewable groundwater, fertilizer runoff leading to dead zones in waterways, environmental toxicity from the use of chemical pesticides and herbicides, and a range of other problems.

Population growth exacerbates all of these challenges, as do increased consumption levels due to rising prosperity. Each of the various methods of food production, such as large-scale industrial, Green Revolution intensified and resource-constrained smallholder, imposes a different set of challenges.

Under business-as-usual conditions, the pressure on smallholder farmers in sub-Saharan Africa and South Asia to increase yields will likely lead to significantly greater damage to the environment. New forms of food production, facilitated by a new generation of technologies and tools to help farm profitability and sustainability, will be required to preserve the global ecological integrity.

Eight technological breakthroughs can help make this possible.

- Breakthrough 1. A low-cost system for precision application of agricultural inputs, ideally combining water and fertilizer
- Breakthrough 2. A very low-cost scalable technique for desalinating brackish water
- Breakthrough 8. New processes of nitrogen fixation that are less capital intensive than current (Haber-Bosch) processes
- Breakthrough 9. A low-cost, point-of-use device to evaluate soil nutrient content and recommend tailored use of fertilizers for specific crops
- Breakthrough 10. New generation of affordable herbicides that are specific to most destructive weeds and are safe for humans
- Breakthrough 11. Novel, low-cost, environmentally friendly pest control mechanisms (chemical or spatial), specifically targeting the most destructive insects
- Breakthrough 16. Alternative meat production system that is affordable, desirable and environmentally sustainable
- Breakthrough 17. New seed varieties that are tolerant to drought, heat, salinity and/or other emerging environmental stresses (ideally using cis-genetic modification)

A commonly used definition of sustainable development is "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (UNWCED, 1987). With respect to agriculture, sustainable development requires that adequate food supplies (in terms of both quantity and quality) be made available to all people now, and also that the systems used to produce this food be sufficiently resilient such that adequate food supplies will continue to be available indefinitely without compromising the environment.

CORE FACTS AND ANALYSIS

1. Agriculture faces various challenges to long-term sustainability

Based on the above definition of sustainable development by UNWCED (1987), prevalent forms of food production are not sustainable. Not only are fixed resources for agriculture, such as groundwater, steadily shrinking, but food production systems are also causing several other negative externalities in the broader environment (Pretty, et al., 2018). For the purpose of discussion, consider four major agricultural systems:

- Large-scale industrial agriculture is practiced in the United States and much of Europe. This is characterized by heavy mechanization, sophisticated agronomic practices and heavy use of inputs like groundwater irrigation, chemical fertilizers, chemical pesticides and GMOs (genetically modified organisms).[14]

- Green Revolution intensive agriculture, practiced in South Asia, Southeast Asia, much of Latin America and parts of China. This is characterized by smallholder animal-assisted farming, but with heavy use of inputs like groundwater irrigation, chemical fertilizers and chemical pesticide. GMOs are rare in such systems, but are likely to become more common in the near future.

- Resource-constrained smallholder systems, restricted primarily to sub-Saharan Africa and same parts of South Asia (such as the lower Gangetic Indian states of Orissa and Bihar). These smallholder systems exist without access to inputs like irrigation and fertilizer and without adequate extension services support.

- High-cost organic systems that have grown in recent years to a profitable niche market, mostly in industrialized countries.

To illustrate the relative prevalence of each of these systems, **Exhibit 1** shows the yield, cost and total output for maize from India, Africa, US conventional (industrial) systems, and US organic systems.[15] Of these systems, US conventional farms constitute the largest share, producing about 328 million tons, African farmers produce 65 million tons, Indian farmers produce 21 million tons and US organic farms produce 0.65 million tons.

Per-hectare yields of African and Indian farmers is a small fraction of US conventional and US organic systems. The cost of production also varies dramatically. The low cost of labor in India and Africa leads to relatively lower production costs, while US organic systems are significantly more expensive than all the other systems.

[14]Genetic modification is discussed in detail in the Emerging Technologies chapter.
[15]Note that this data is not fully representative of typical food production systems in the three regions, for two reasons. First, maize is a major crop in Africa and the United States, but only a minor crop in India; hence, this may be representative of the cost of typical cereals. Second, US maize is heavily subsidized, and a large portion is used to produce ethanol (rather than food). This illustration shows data for total maize production. Please also note that 'US organic' is defined by the US Department of Agriculture as an ecological production system that fosters resource cycling, promotes ecological balance and conserves biodiversity. Organic farmers are required to avoid most synthetic chemicals and must adopt practices that maintain or improve soil conditions and minimize erosion.

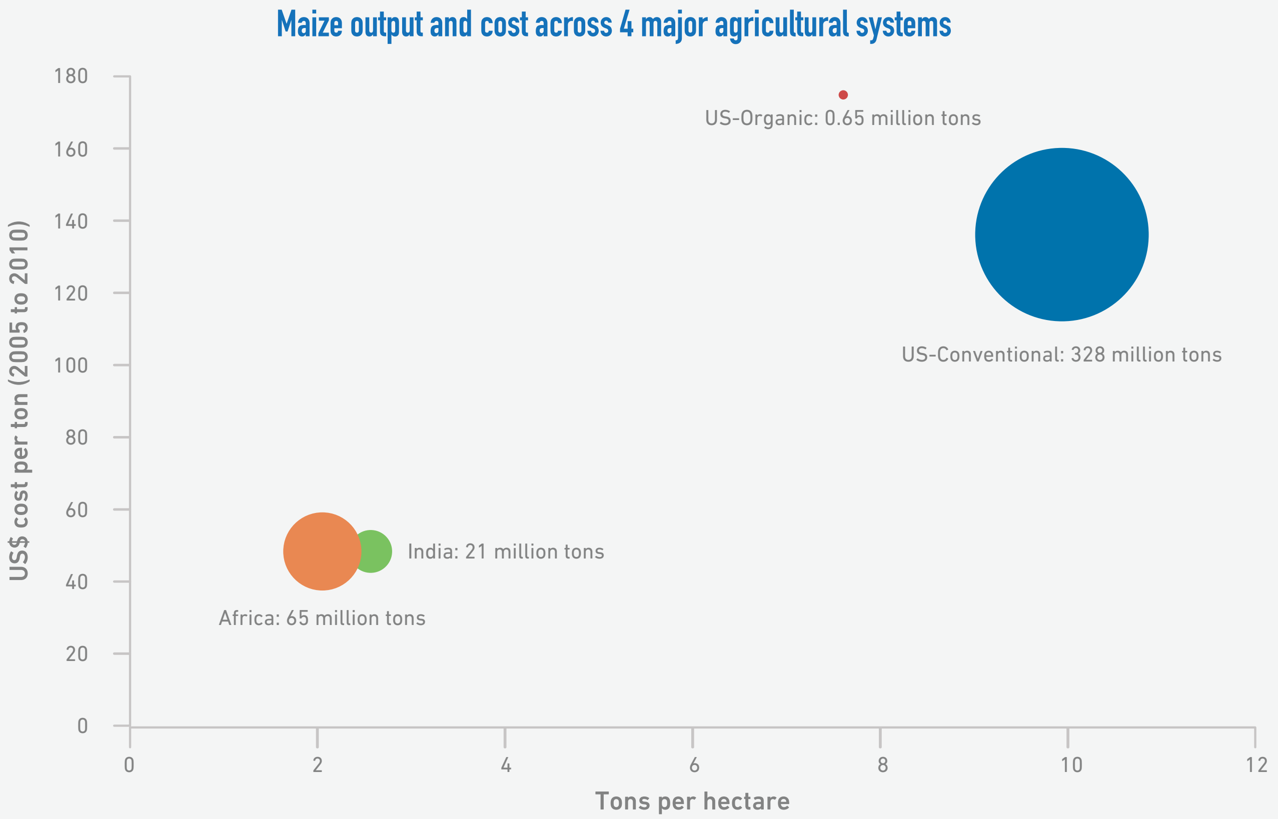


Exhibit 1: This exhibit illustrates the differences between four major agricultural production systems, using the example of maize. The US conventional system is the most prolific, producing 328 million tons annually. However, it also leaves a significant environmental footprint. Smallholder systems in Africa and India produce 65 million tons and 21 million tons, respectively, with much lower yields per hectare. US organic systems (based on some measures of environmental sustainability) are the most expensive. As discussed below, each of these systems poses stresses on the environment. (Source: ITT analysis)

Table 1 summarizes the sustainability challenges posed by each of these agricultural systems. As the table shows, none of the four systems is entirely sustainable. Large-scale industrial systems (like those used for conventional US farming) have been built on the strength of heavy use of water (increasingly non-renewable groundwater), fertilizers, pesticides and herbicides. Many of these factors also apply to the intensified practices of the Green Revolution.

Even the practices of resource-constrained smallholder African farmers cause problems with deforestation (due to extensification and increased land use), soil erosion (due to livestock rearing practices) and soil nutrient mining (because they cannot easily replenish the nutrients harvested with the crops). Even organic farming (at least as it is defined by the US Department of Agriculture) can cause environmental damage, for example from soil erosion and groundwater depletion.

Sustainability challenges posed by different agricultural production systems

Agricultural system	Typical sustainability challenges					
	Groundwater depletion	Water dead zones	Soil erosion	Deforestation	Chemical pollutants	Soil nutrient mining
Large-scale Industrial (US-Conventional)	High	High	Medium	Low	High	Low
Green Revolution Intensive (India)	High	High	High	Low	High	Low
Resource-constrained smallholder (sub-Saharan Africa)	Low	Low	High	High	Low	High
High-cost organic (US Organic)	Medium	Low	Medium	Low	Low	Low

Table 1: None of the agricultural production systems prevalent today is entirely sustainable. Each exists within specific socio-economic contexts and poses a different set of environmental challenges. Even organic farming does not necessarily guarantee preservation of groundwater and topsoil. (Source: ITT analysis)

2. Food demand will substantially increase as population and affluence grows

Global human population was relatively stable until recent generations; varying between 200 million and 700 million individuals between 1AD and 1700 (**Exhibit 2**) (US Census Bureau 2018). This represents an average population growth of 2 percent per 30-year human generation.

During this time, the concept of agricultural sustainability largely meant using farming techniques handed down from one generation to the next. Population has increased notably since then, requiring a much more proactive approach to ensuring food sufficiency. Between 1700 and 1950, population increased at an average rate of 35 percent per generation.

Since 1950, global population has been increasing by 88 percent—almost doubling—each 30-year generation (UN, 2017). Human population reached 1 billion people in around 1800, 2 billion in the 1920s, 4 billion in 1975 and 6 billion in 1999. Current (2018) human population is about 7.6 billion.

Agricultural sustainability has become more challenging during this period of rapid population growth, especially since 1950. This demands not just continuity of food production levels, but also continually increasing total production levels. Ironically, conventional agricultural development efforts have focused on the immediate need for increasing food production to nourish current populations, with less concern for longer-term consequences.

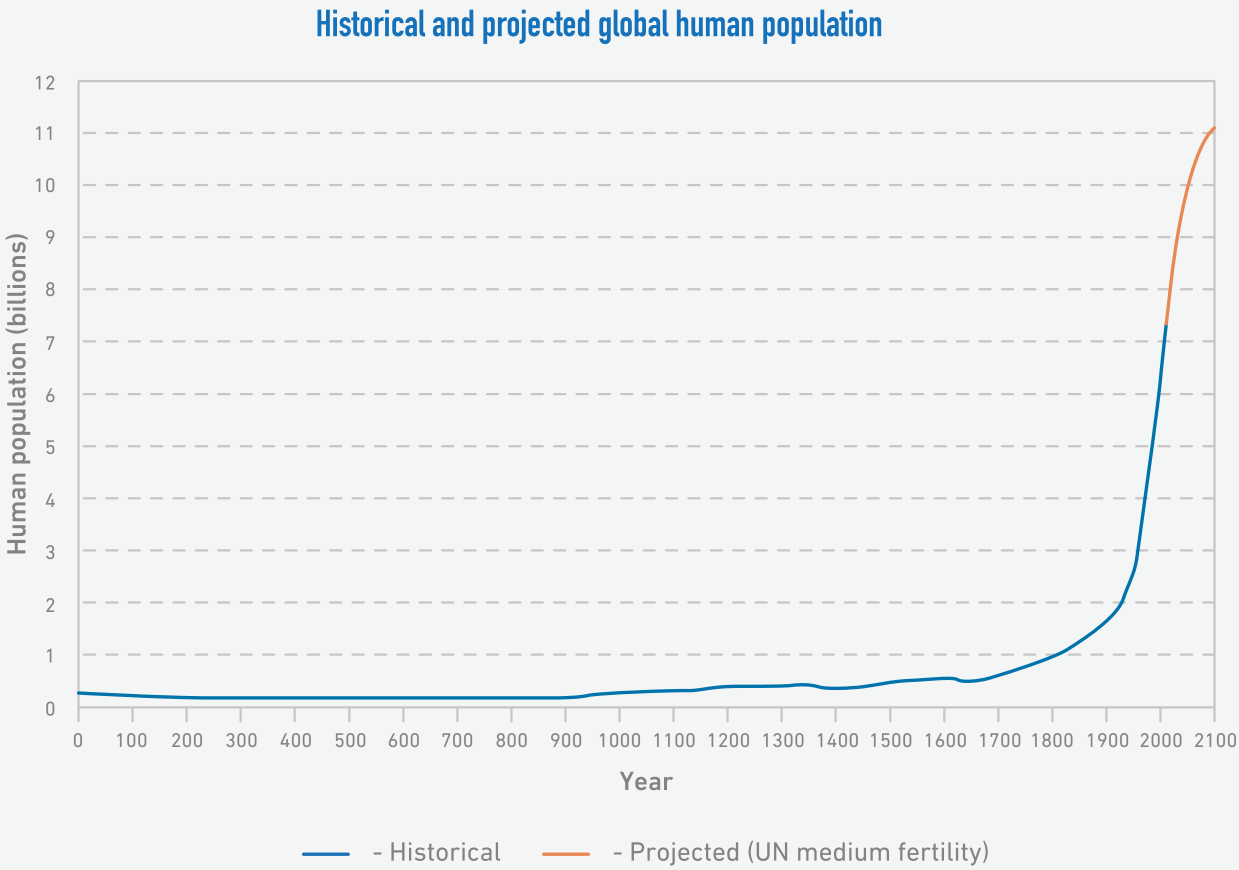


Exhibit 2: Global human population was relatively stable for much of the past 2 millennia, with fewer than 1 billion individuals until the year 1800. Population has increased markedly since then, and especially since 1950. Future population is projected to increase to 11.2 billion by 2100. (Source: historical data from US Census Bureau, 2018; projected data from medium fertility projection of UN, 2017)

Future success in agricultural sufficiency faces a moving target as global population continues to rise; though more slowly than during the period of maximum growth rate in the 1960s. Between 2018 and 2050, the human population is expected to increase about 28 percent, from the current number of 7.6 billion to about 9.8 billion (UN, 2017; Gerland, et al., 2014).

By the year 2100, the global population is projected to reach approximately 11.2 billion, a rise of 47 percent from 2018. Much of this population increase is expected to occur in Africa, from its current population of about 1.2 billion to a projected 4.2 billion in 2100.[16]

[16]These estimates are based on the medium fertility variant projected by the UN (2017). It should be noted that UN population projections are extrapolations of current demographic trends based on estimated future fertility rates and implicitly assume that adequate sustenance will be available for the resulting populations. These projections are not based on certainty of how many people may be adequately fed with the resources available; rather, this is left as a challenge for the international agricultural development community.

The total demand for food is a function not only of the number of people, but also of per capita food demand. Successful global development implies greater affluence and more room for personal choices. This, in practice, results in more food consumption and of food types that are more resource-intensive, such as meats.

Exhibit 3 shows the rising per capita consumption of various food products in India since the 1980s (NCAER, 2014). Globally, there is a consistent relationship between per capita GDP and per capita demand for crop calories and protein (Tilman, et al., 2011).

Although population is expected to rise by 28 percent between 2018 and 2050, food production must increase by 43 percent from 2018 levels to meet the demands of this larger, richer and more urban population (FAO, 2009; UN, 2017; FAO, 2018) (**Exhibit 4**).

During recent years, global stocks of major food commodities have remained fairly stable, as growth in global production of food commodities has kept up with growth in demand (**Exhibit 5**). These buffer stocks are equivalent to 50 to 130 days of consumption, and are available in case of temporary decreases in harvest levels (AMIS, 2018).

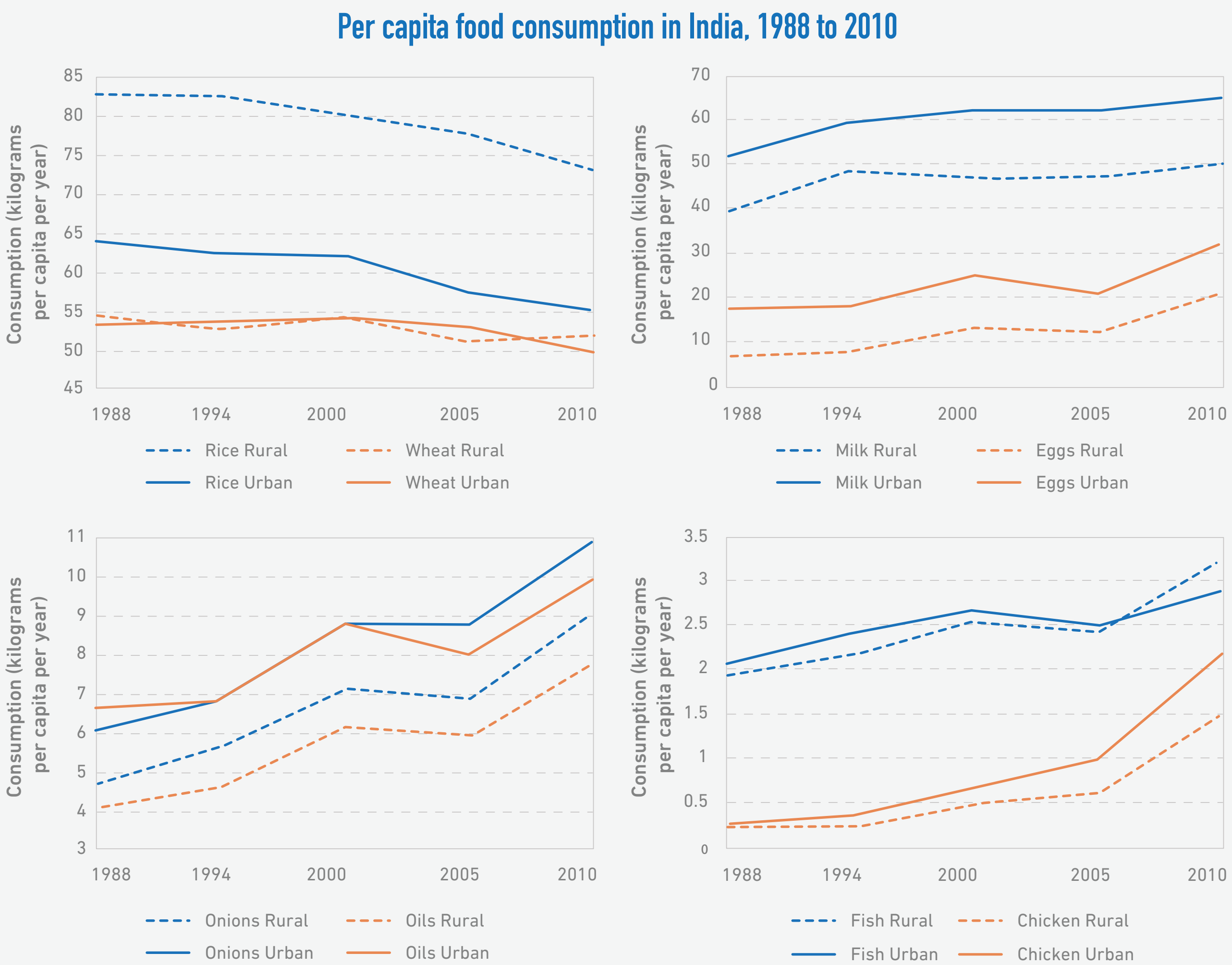


Exhibit 3: Per capita consumption in South Asia is increasing for many food products including milk, eggs, vegetables, oils, fish and chicken. Per capita consumption of rice and wheat is decreasing. Solid and dashed lines show trends in urban and rural areas of India, respectively. (Source: NCAER, 2014)

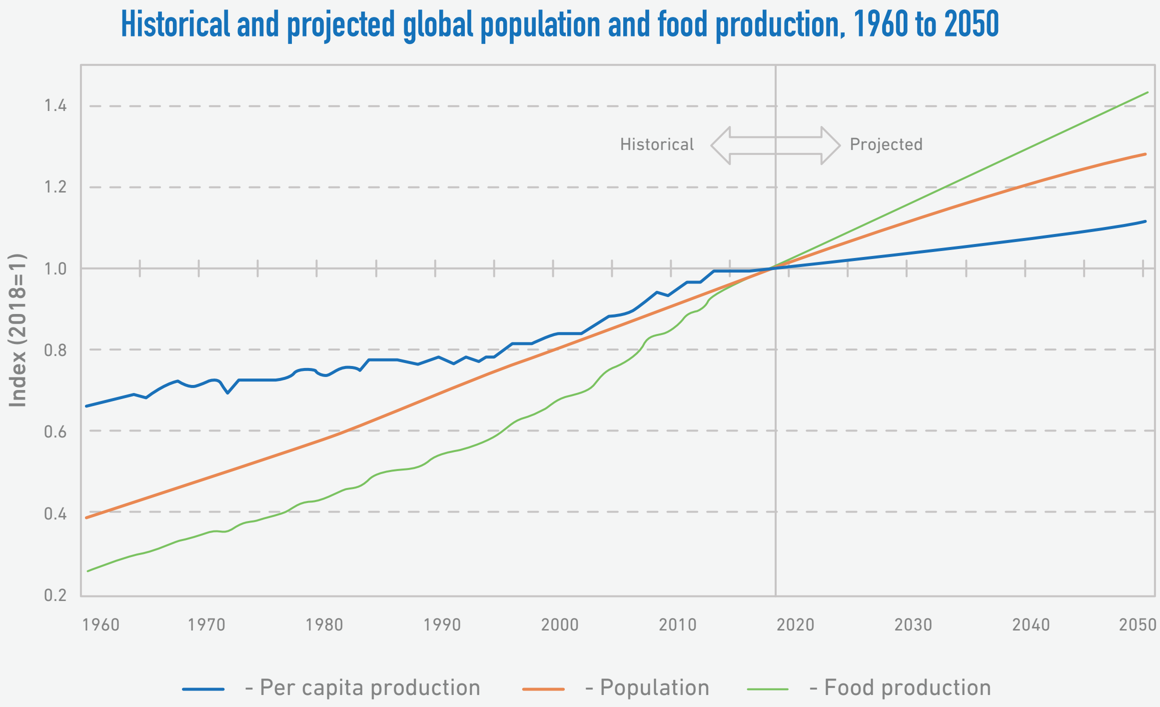


Exhibit 4: Total food production requirements are determined not just by total human population but also by per capita food demand. Both have risen substantially since 1960 and are projected to continue rising through and beyond 2050. (Source: FAO, 2009; UN, 2017; FAO, 2018)

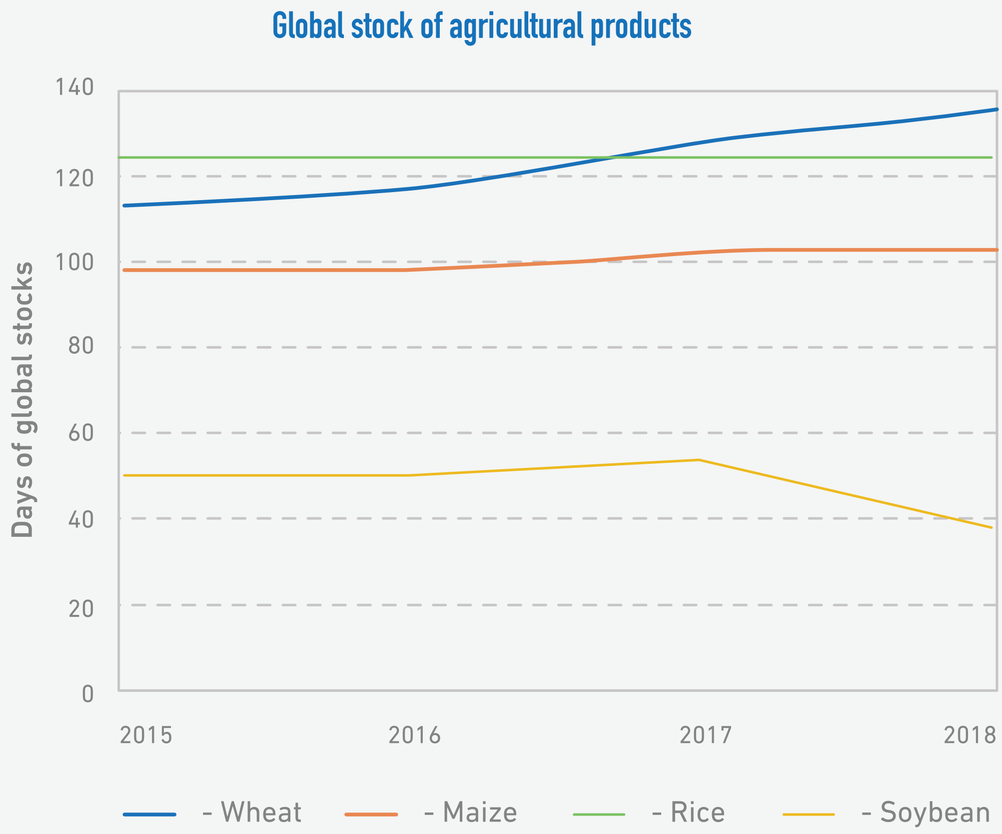


Exhibit 5: Growth in global production of food commodities has kept up with growth in demand and global stocks of cereals and soybean have remained fairly stable in recent years. These stocks are available for consumption in case of temporary decreases in harvest levels. (Source: AMIS, 2018)

3. Agricultural production has historically increased by both intensification and extensification

Broadly speaking, crop production can be increased in two ways. Agriculture can be made more intensive by obtaining larger or more frequent harvests from a hectare of farmland. Or, agriculture can become more extensive by expanding the area to include more hectares of farmland.

Exhibit 6 shows that since 1961, South Asia has increased cereal production primarily through intensification, while sub-Saharan Africa has increased cereal production mainly through extensification (VFRC, 2012).

Intensification can be achieved by removing constraints like lack of water (through irrigation) and nutrient deficiencies (through fertilization).

Another means of intensification is to increase the land utilization intensity (also known as cropping intensity), which determines the frequency with which a hectare of farmland is cultivated and harvested.

Land utilization intensity is the ratio of the land area that is cultivated and harvested per year compared to the total arable land area. This may be less than 1, where some land is left fallow and not used every year. It may also be greater than 1, when multiple harvests are made per year on the same land, particularly in well irrigated areas.

The lowest land utilization intensities related to total cropland extent (including fallow land) are in Southern Africa (0.45), Central America (0.49) and Middle Africa (0.54), while the highest intensities are in East Asia (1.04) and South Asia (1.00) (Siebert, et al 2010).

Cereal production, yield and land usage in South Asia and sub-Saharan Africa, 1961 to 2009

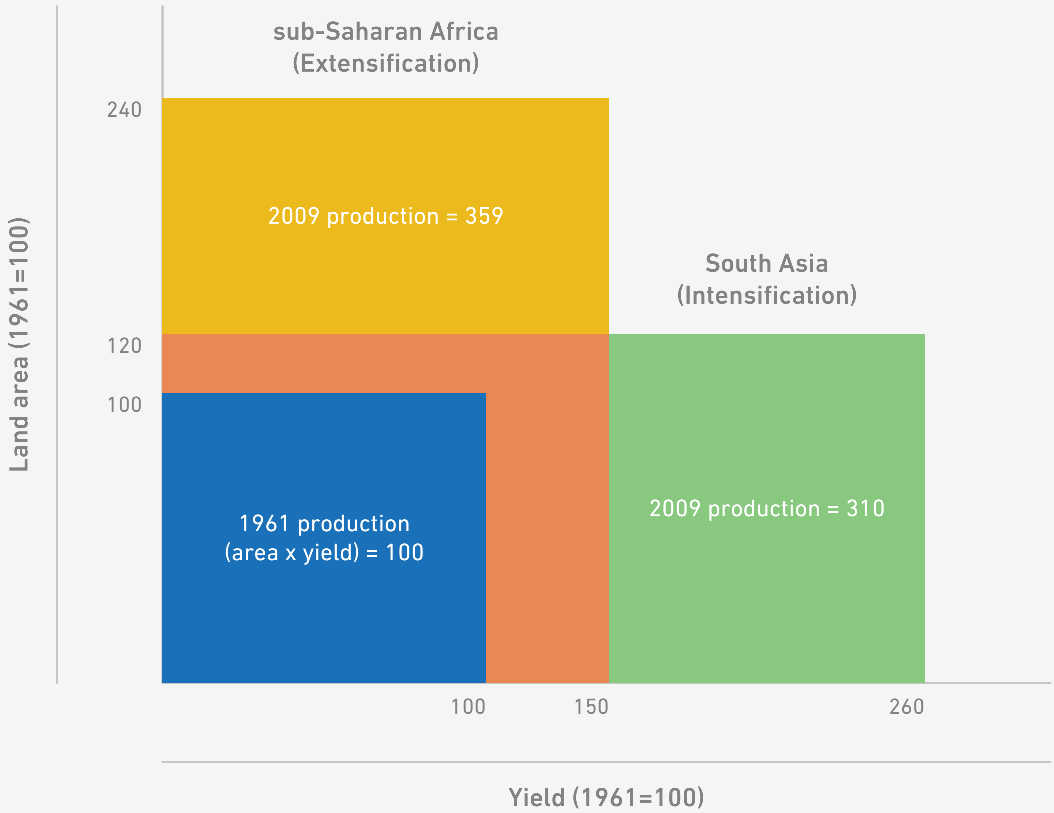


Exhibit 6: In South Asian countries agricultural yield increased dramatically over the past few decades due to intensified agricultural practices. Compared with 1961, per hectare cereal yield in South Asia has increased by 160 percent, leading to a total output increase of 210 percent, with only a 20 percent increase in cultivated land. During the same period in sub-Saharan Africa, there was a 140 percent increase in cultivated land and only a 50 percent increase in per hectare yield, for a total increase in output of 259 percent. (Source: VFRC, 2012)

With more demand for food, land utilization intensities will continue to rise due to shorter fallow periods and more multiple cropping. Many traditional farming systems rely on periodically leaving land fallow to allow natural ecological processes to restore soil fertility. Reducing or eliminating fallow may require other agricultural interventions such as fertilization.

Multiple cropping is the practice of growing two or more crops in the same space during a single growing season, and can take the form of double-cropping (in which another crop is planted after the first has been harvested) or relay cropping (in which the second crop is started amidst the first crop before the first has been harvested). Increasing the area of irrigated land also allows more multiple cropping. About one-third of the arable land in South and East Asia is already irrigated and this high share of irrigation of total arable land is one reason why the average land utilization intensities in these regions are higher than in others.

Future increases in crop production are likely to be achieved through somewhat different means than past increases. **Exhibit 7** details the sources of past (since 1961) and projected future (through 2050) increases in crop production in different regions. Agricultural extensification, or expanding the overall area of arable land, is likely to be relatively less significant in the future, especially in Asia. We expect intensification of agricultural practices, particularly by increasing the yield of crop harvests, to be more important.

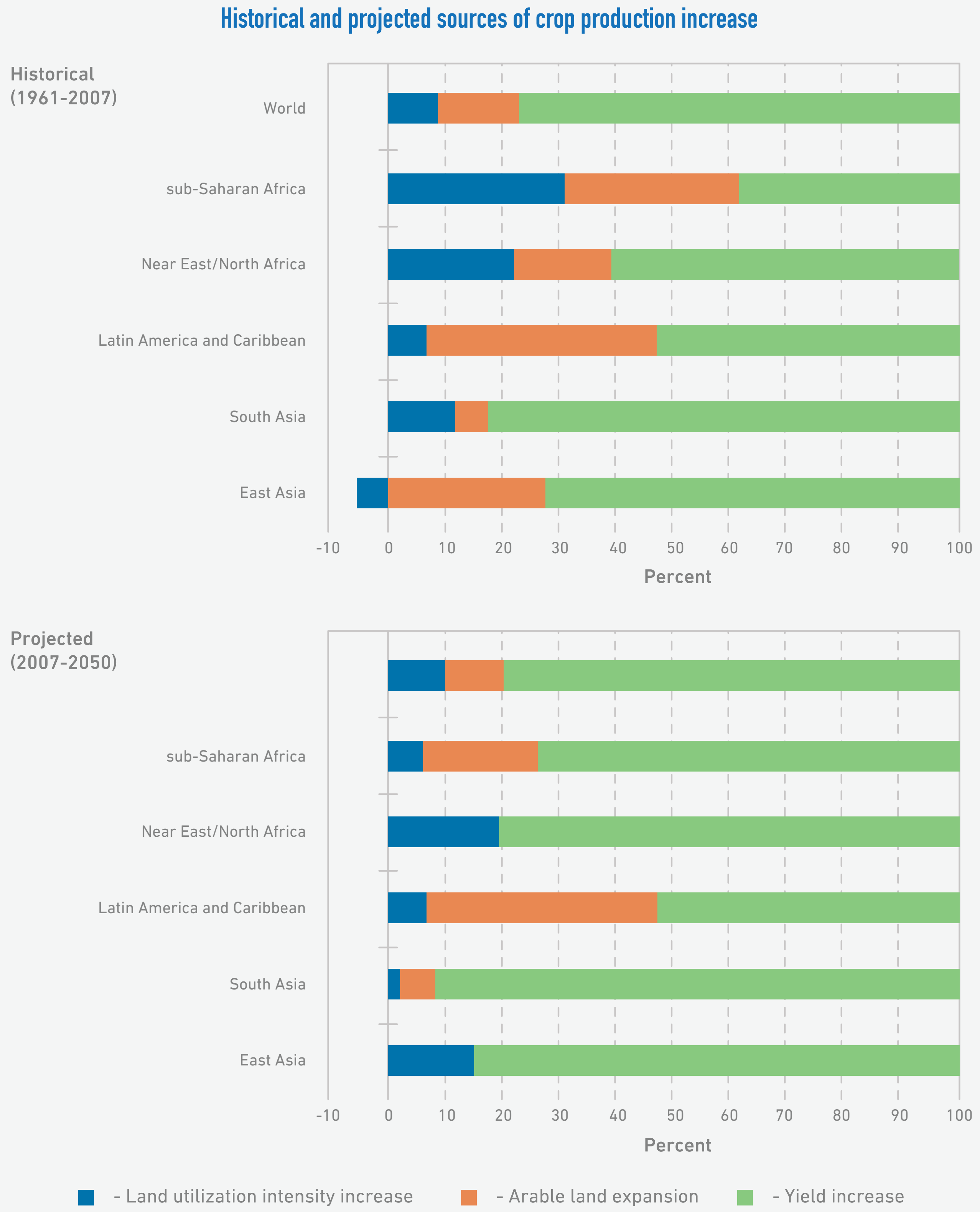


Exhibit 7: Crop production can be increased by extensification (expanding the area of farmland) or by intensification (getting bigger or more frequent harvests from existing farmland). Agricultural intensification can come from increasing yield, which provides more food per harvest, or by increasing land utilization intensity, which provides more frequent harvests. Compared to past sources of crop production increase, projected future increases are expected to rely more on increased yields. (Source: FAO, 2012)

4. Current methods of increasing agricultural production raise concerns for long-term sustainability

Most current models of agricultural production entail numerous, and often interlinked, sustainability stressors. These are expected to become more serious under business-as-usual development scenarios.

Wild land is converted to cropland
Expanding the area of arable land typically involves conversion of wild land to cropland. People have, over a span of centuries, converted substantial portions of land once covered by wild forests and grassland into managed cropland and pastures. **Exhibit 8** shows that approximately 10 million square kilometers of forestland has been converted and used for other purposes during the last three centuries (Ramankutty & Foley, 1999; Pongratz, et al., 2008; FAO, 2010; World Bank, 2013).

Cropland area (the extent of which may vary depending on the definition used) increased by about 15 million square kilometers during the same period. The area of natural grassland decreased and pasture land area increased, during the same period (not shown in the exhibit).

The rates of forestland decrease and cropland increase have remained fairly steady over the last 300 years, though have accelerated somewhat since about 1850. During the last three centuries overall, global forest area decreased at an average rate of 3.2 million hectares per year. The rate of deforestation from 2010 to 2015 is quite close to this centuries-old trend: forest area decreased by 3.3 million hectares per year (FAO, 2015).

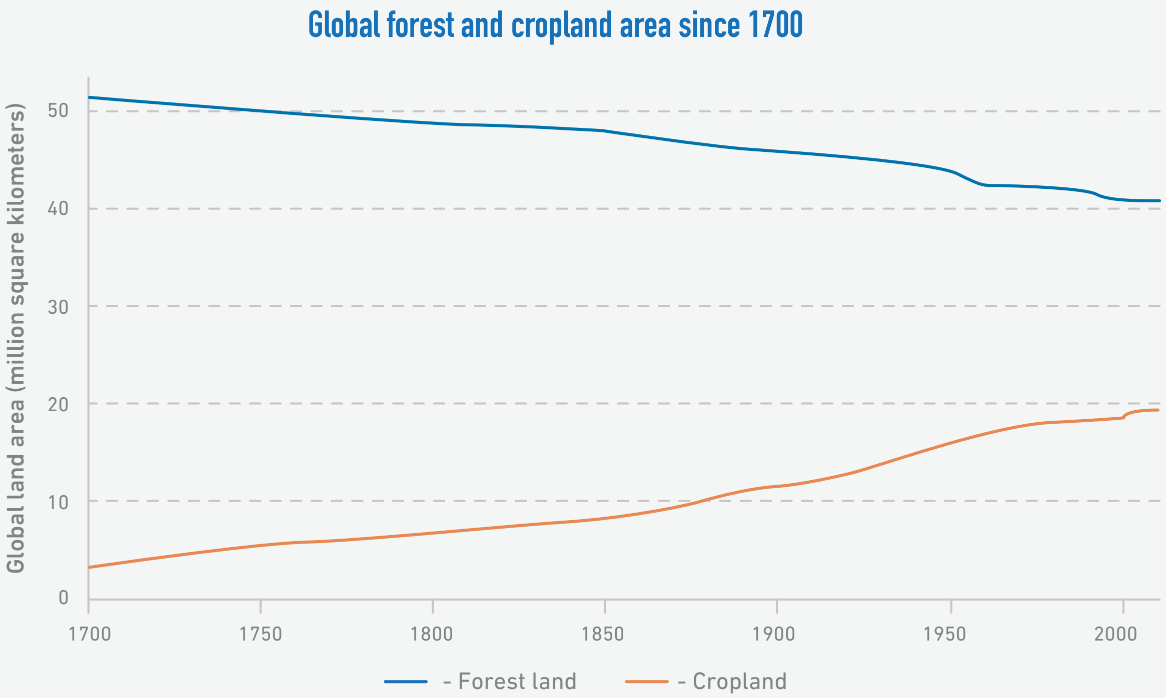


Exhibit 8: Over the last three centuries, humans have converted about 10 million square kilometers of forestland to other uses, and have turned about 15 million square kilometers of land into agricultural cropland. During the same period, natural grassland area has decreased and pastureland area has increased (not shown in figure). (Source: Ramankutty & Foley, 1999; Pongratz, et al., 2008; FAO, 2010; World Bank, 2013)

Exhibit 9 shows the past and projected area of arable cropland in use in different regions across the world. Since the 1960s, cropland area has increased substantially in sub-Saharan Africa and Latin America, with smaller increases in Asia (FAO, 2012). Arable cropland area is expected to continue to increase modestly through 2050 in sub-Saharan Africa and Latin America. Experts anticipate very little future increase of cropland area in Asia and North Africa.

These estimates for expansion of arable land are of net expansion of arable area and do not consider the need for additional land to compensate for erstwhile arable land taken out of production due to severe land degradation. It is estimated that about 3 million hectares of cropland worldwide are abandoned each year because of productivity declines due to land degradation (FAO, 2012).

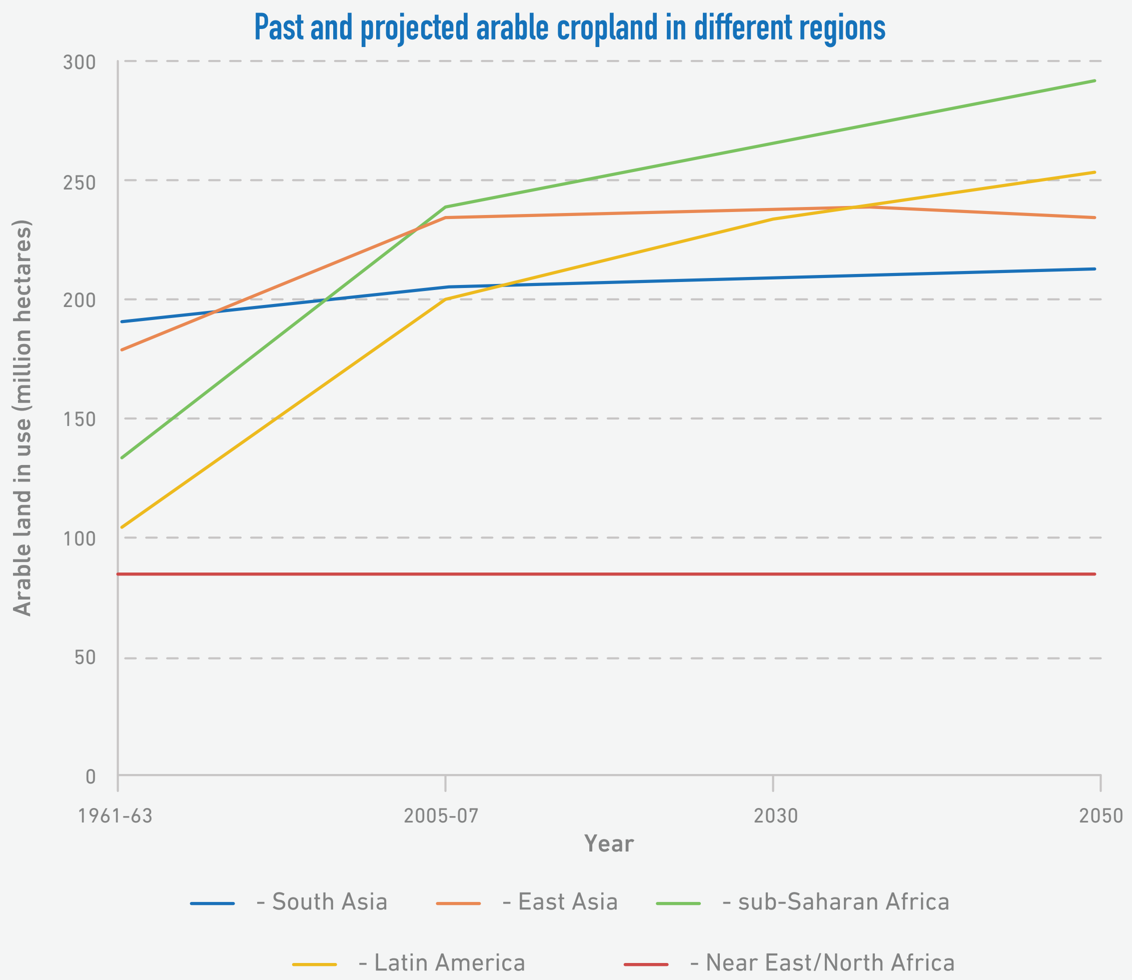


Exhibit 9: The area of arable cropland in use has increased substantially since the 1960s in sub-Saharan Africa and Latin America, with smaller increases in Asia. Arable cropland area is expected to continue to increase modestly through 2050 in sub-Saharan Africa and Latin America. Very little future increase in cropland area is anticipated for Asia and North Africa. (Source: FAO, 2012)

Cropland expansion is reducing biodiversity

The ongoing population shift from wild to domesticated animals and plants necessarily involves the simplification of the structure and functioning of ecosystems. Humans are causing ecosystems to lose complexity at several levels: species diversity (the number and variety of species), genetic diversity (the genetic possibilities a species contains) and ecosystem diversity (the variation between global ecosystem characteristics) (MEA, 2005).

The global simplification of biodiversity, which is caused in large part by agriculture, is likely to have serious eventual impacts on the success of agricultural efforts (FAO, 2019).

The distribution of species on Earth is becoming more homogenous, meaning that the differences are, on average, diminishing between the group of species at one location on the planet and groups at other locations.

Different types of species evolved in ecosystems in different regions through the combination of natural barriers to migration and local adaptations. These regional differences in the biota of the Earth are now diminishing. Genetic diversity, which serves as a way for populations to adapt to changing environments, is being lost.

Human actions (including destruction of habitat) are now leading to the extinction of other species at a rate 1,000 times greater than the natural background rate of extinction (Pimm, et al., 2014).

This ongoing simplification is illustrated in **Exhibit 10**, based on the Living Planet Index that is calculated periodically by WWF International (WWF, 2014). This index estimates changes in the state of the planet's biodiversity, using trends in population size for vertebrate species from different biomes and regions to estimate average changes in abundance over time (Collen, et al., 2008).

The latest index shows that across the globe, wild populations of vertebrate animals were on average 60 percent smaller in 2014 than they were in 1970 (WWF, 2018). The greatest reductions occurred in tropical regions, in particular South and Central America, where populations declined by 89 percent since 1970.

Tropical Asia also has strong declines. Temperate regions show smaller reductions, largely because those lands were cleared for agricultural use long before 1970, and now include abandoned farmlands that are reverting to natural growth. Freshwater species numbers have also declined dramatically, with the Freshwater Index showing an 83 percent decline since 1970.

Simple proxy indicators such as species populations are imprecise measures of overall impact to complex ecosystems. Nevertheless, the global trends toward simpler ecosystems with fewer species number and variety are robust and increasingly well documented.

For example, Hallmann, et al. (2017) report a 76 percent decline in flying insect biomass in German nature protection areas over the last 27 years, and Lister & Garcia (2018) report that populations of insects, lizards, frogs and birds have declined by more than half during the past four decades in rainforests of Puerto Rico.

A global review of insect biodiversity found that some taxa (such as butterflies, bees, and beetles) are decreasing strongly and face eventual extinction, while a small number of adaptable, generalist species (such as *Plusia putnami, Laemostenus terricola* and *Hippodamia variegatais*) are increasing and occupying the vacant niches left by the declining insects (Sánchez-Bayo, et al., 2019). Wild fish populations are also declining strongly, which is detailed in the Fisheries and Aquaculture section of this chapter.

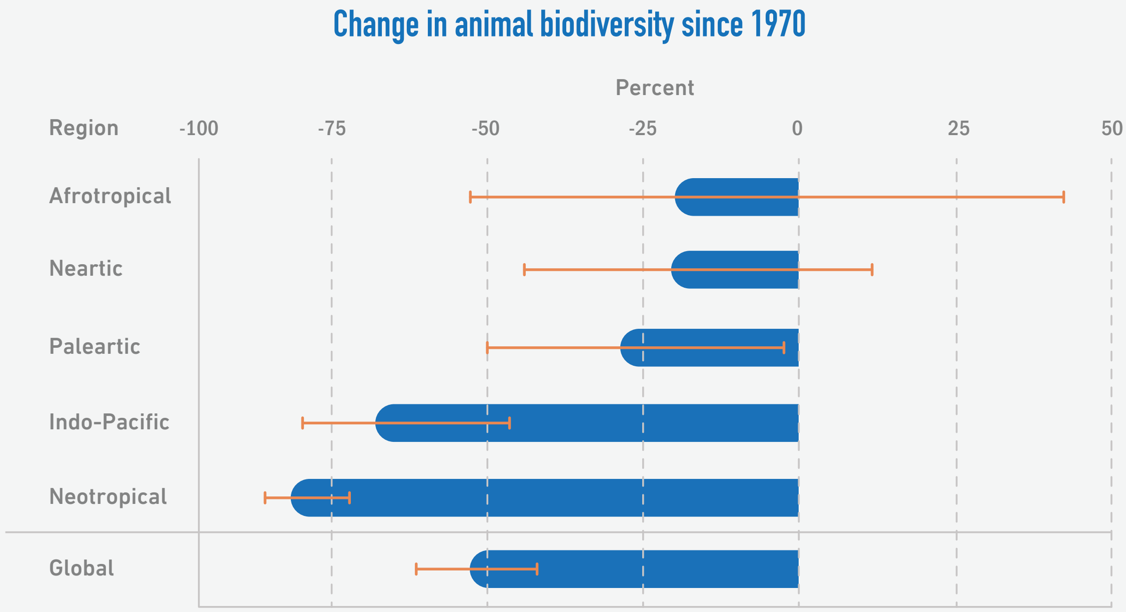


Exhibit 10: Regional and global biodiversity has generally decreased in recent decades, as estimated by WWF's Living Planet Index, based on wild populations of vertebrate animals between 1970 and 2010. Error bars represent 95 percent confidence limits. The five regions are biogeographic realms, where terrestrial species have evolved in relative isolation over long periods of time. Afrotropical includes sub-Saharan Africa. Nearctic includes North America. Palearctic includes Europe, North Africa, the Middle East and most of Asia. Indo-Pacific includes South Asia and Australasia. Neotropical includes South and Central America. (Source: WWF, 2014)

Agricultural fertilization leads to water pollution and other environmental consequences

Plants need a supply of nutrients to support their growth, as discussed in the chapter on fertilizers. This supply increasingly takes the form of chemical fertilizers, manufactured offsite and applied to the farmland. The plant roots only absorb a part of the fertilizer. The rest is typically washed away by rain into streams and rivers. This causes water pollution and increasingly leads to aquatic dead zones.

Essential to life on Earth, nitrogen is needed to make amino acids, nucleotides and other basic building blocks of plants, animals and other life forms. Nitrogen comprises about 78 percent of Earth's atmosphere, but in the very stable N_2 form, with two nitrogen atoms bound tightly together, unwilling to form partnerships.

A limited amount of nitrogen, known as reactive nitrogen, is fixed from the atmosphere and then made available to living organisms in a more reactive form. There are several natural routes of nitrogen fixation, including by particular bacteria living in symbiosis with specific types of plants. Humans have long managed croplands to incorporate these types of plants within crops rotation systems in order to fix a modest amount of nitrogen within agroecosystems.

During the last 50 years, the amount of nitrogen that is fixed through human actions has increased steadily and now occurs at a scale similar to that of all natural land ecosystems (MEA, 2005; Robertson & Vitousek, 2009) (**Exhibit 11**). Most of this increase is due to fertilizer production based on the Haber-Bosch process, using non-renewable natural gas as feedstock. The temporary reduction in nitrogen fertilizer production during the early 1990s was due to the collapse of the Union of Soviet Socialist Republics (USSR). Other human actions that fix atmospheric nitrogen include fuel combustion and managed biological fixation.

This alteration of the nitrogen cycle has allowed us to grow significantly more food for consumption than otherwise would have been possible. However, this has led to nitrogen runoff well beyond the farmlands on which the fertilizer is applied, into rivers, estuaries and seas. The increased overall availability of nitrogen fertilizer, coupled with the difficulty of precisely targeting application to ensure complete absorption by plants, have enabled this fugitive flow.

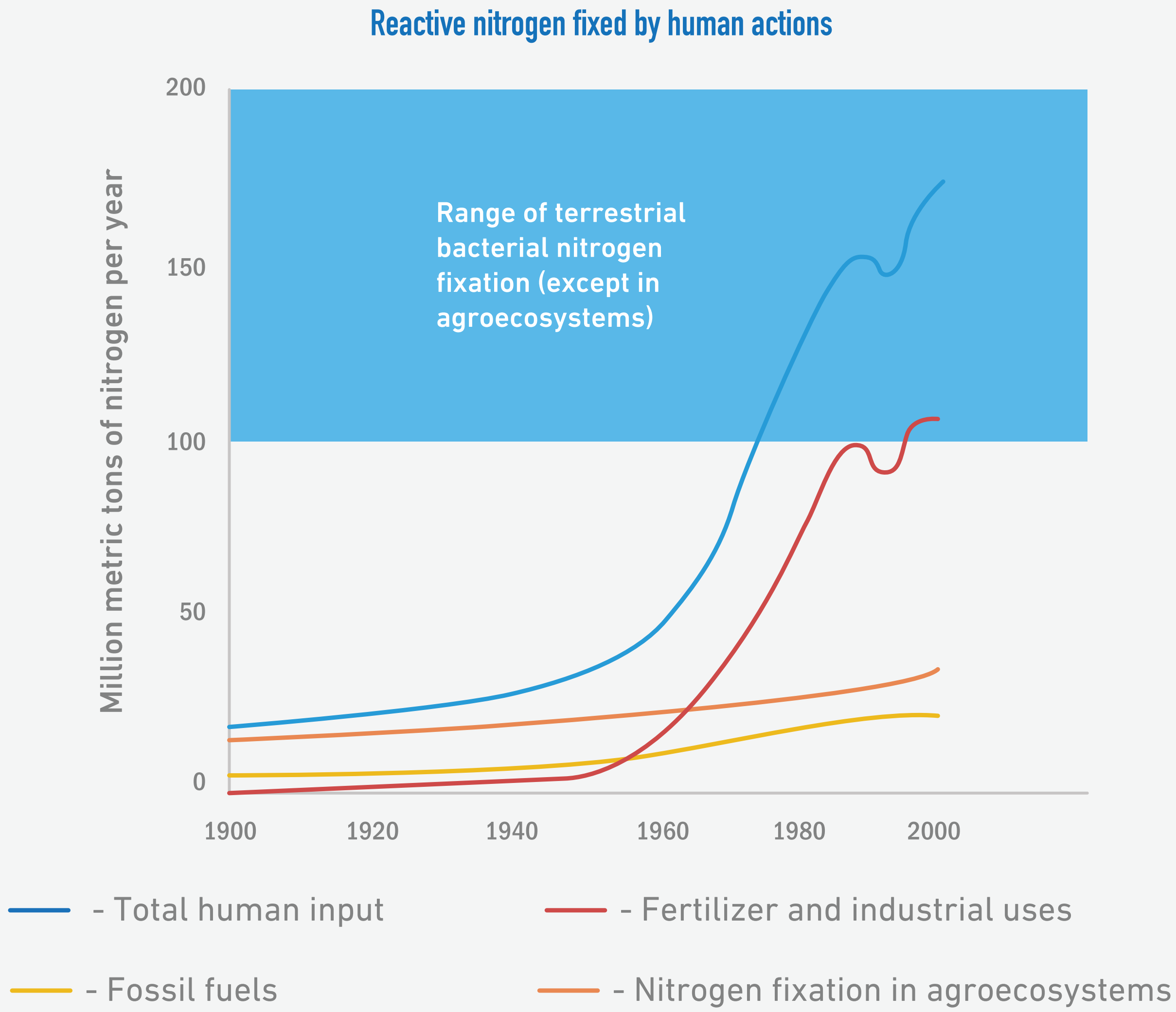


Exhibit 11: Human production of reactive nitrogen has increased substantially during the last 50 years and now occurs at the same rate as it does in all natural land ecosystems put together. Most of this increase is due to fertilizer production using the Haber-Bosch process. (Source: MEA, 2005)

Another important plant nutrient is the chemical element phosphorus, which is essential for plant growth and is an important input to intensive agriculture. Phosphorus fertilizers are necessary because of the slow natural cycling of phosphorus, the low solubility of natural phosphorus-containing compounds and the essential nature of phosphorus to living organisms.

Traditional sources of agricultural phosphorus are animal manure and guano (bird droppings). **Exhibit 12** shows that phosphate rock mining expanded considerably after 1950 and is now the dominant source of phosphorus fertilizer (Cordell &White, 2014).

Three countries currently mine 70 percent of global phosphate rock production: China, the United States and Morocco (USGS, 2014). Global reserves of high-quality phosphate rock are concentrated in the Western Sahara region of Africa, a disputed region controlled by Morocco. Sustained disruption of supply, whether due to geological or geopolitical forces, could affect food security (Dawson & Hilton, 2011).

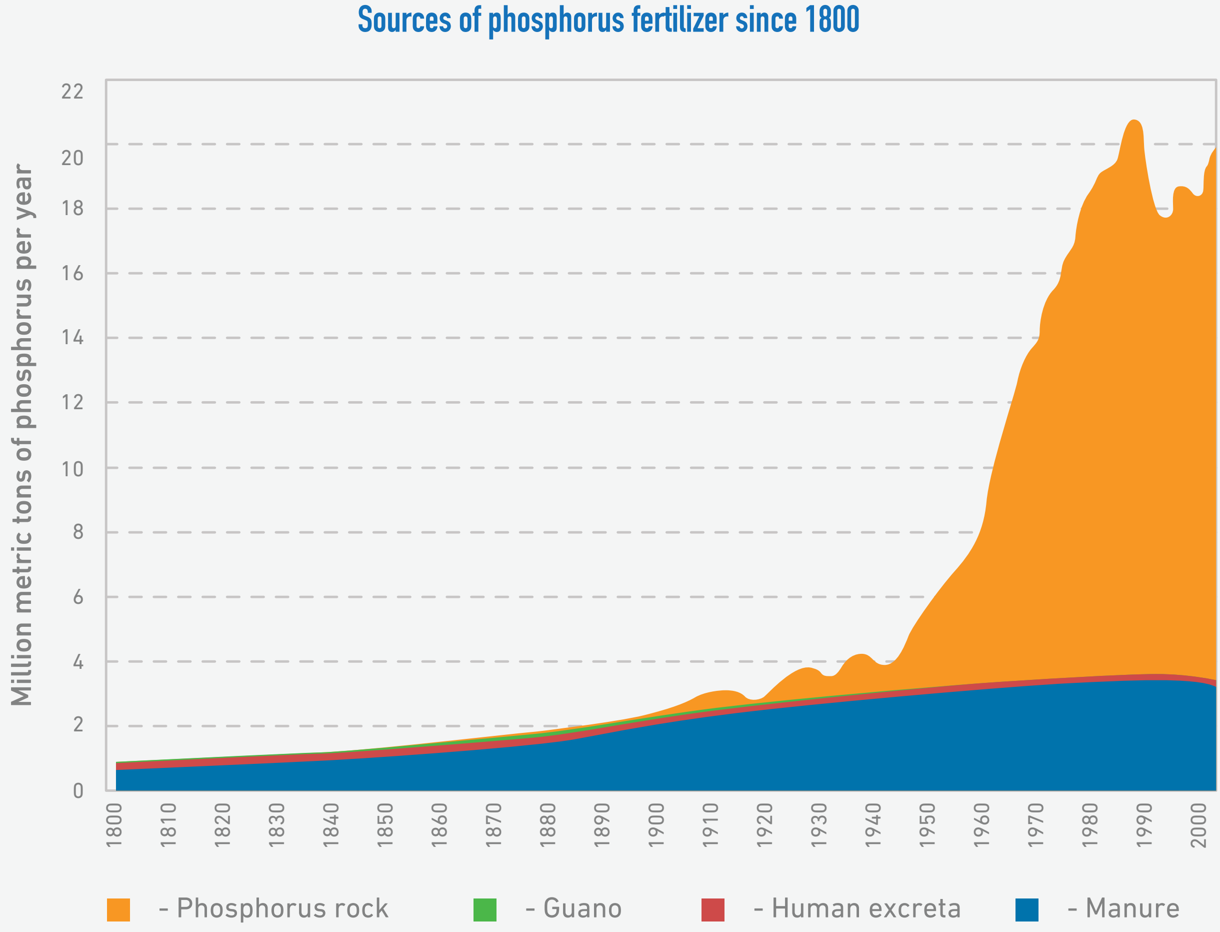


Exhibit 12: Mining of phosphate rock expanded considerably after 1950 and is now the dominant source of phosphorus fertilizer used in agriculture. (Source: Cordell & White, 2014)

Agricultural runoff of nitrogen and phosphorus fertilizers is a major source of water pollution. Just as fertilizing agricultural fields can stimulate crop growth, increasing nutrient levels in rivers, lakes and estuaries can cause eutrophication or excessive growth of algae and other aquatic plants. Huge blooms of cyanobacteria (also known as blue-green algae) and other organisms can come to dominate aquatic ecosystems, seriously degrading water quality (Smith, 2003).

Negative effects include hypoxia, or depletion of oxygen in the water, which causes the death of fish and other animals in the water. More than 400 marine dead zones resulting from nutrient runoff are reported worldwide, having approximately doubled each decade since the 1960s (Diaz & Rosenberg, 2008).

Many cyanobacteria also produce toxic compounds that are hazardous to humans and domesticated animals. Mass blooms of toxic cyanobacteria occur regularly in water subject to nutrient runoff, with the timing and duration of the bloom season varying by location.

In recent decades, the amount of reactive nitrogen in rivers has increased dramatically (Green, et al., 2004) (MEA, 2005), with river basins in North America, continental Europe and South and East Asia showing the greatest change (**Exhibit 13**). In the absence of mechanisms to protect sources of drinking water from pollution, it is likely that developing countries with fertilizer overuse face a continuing degradation of their water sources. Africa suffers little from nutrient pollution, mainly because fertilizer use is still very low in that continent.

Reactive nitrogen pollution in rivers

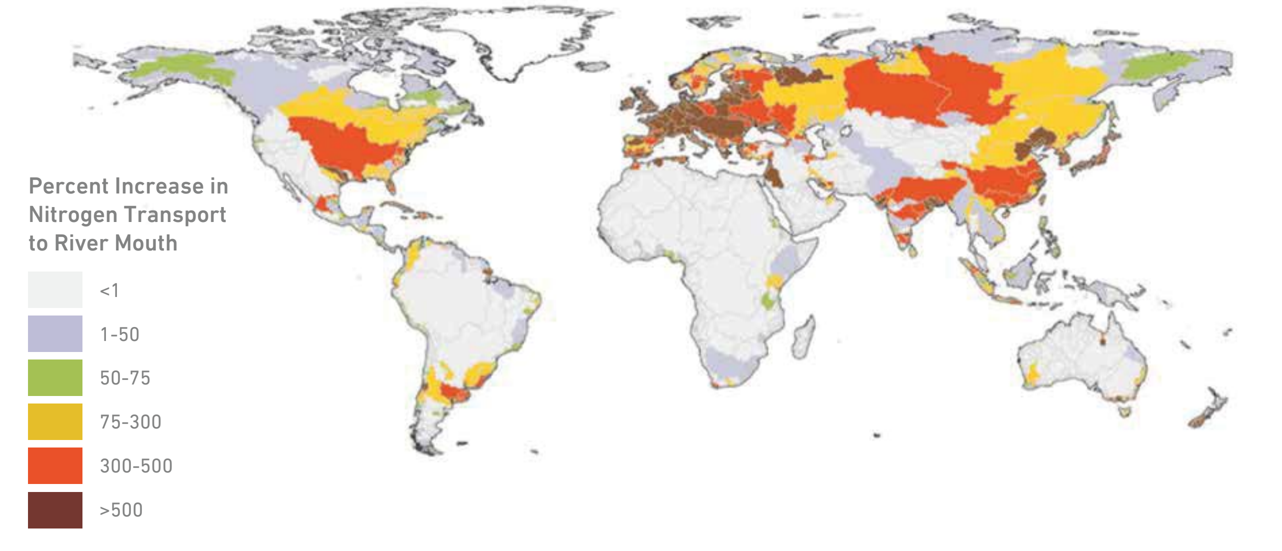


Exhibit 13: Reactive nitrogen flows in many river systems have increased dramatically in recent decades—primarily due to fertilizer runoff from agricultural lands—especially evident in Europe, Asia and North America. This has led to dead zones in waterways. (Source: Green, et al., 2004; MEA, 2005)

An increasing amount of non-renewable groundwater is used for Irrigation (especially in South Asia)

Irrigation has proven to be a fundamental requirement to adequate agricultural yields. Over time, irrigation has increasingly tapped into groundwater, which currently supplies at least half of all irrigation water globally (Famiglietti, 2014). Groundwater sources used for irrigation can be renewable or nonrenewable.

The former periodically replenishes when sufficient precipitation infiltrates the soils or when floodplains become inundated. The latter is fossil groundwater reserves locked in deep aquifers that have little or no long-term source of replenishment. When such non-renewable water is extracted, it is effectively mined and the aquifer is eventually depleted.

In recent decades, an increasing amount of irrigated farming has been supported by non-renewable groundwater extraction. This is especially problematic in South Asia, where Green Revolution successes in yield increases were achieved (in part) through exploitation of groundwater resources that are now being permanently depleted.

Globally, for the year 2000, non-renewable groundwater extraction was used for about 18 percent of gross irrigation water demand (Wada, et al., 2012). **Exhibit 14** shows the sources of water used globally for irrigation in 1960 and 2000, during which time the share of non-renewable groundwater increased from 12 percent to 18 percent. In absolute terms, however, the use of non-renewable groundwater more than tripled, from 75 to 230 cubic kilometers per year.

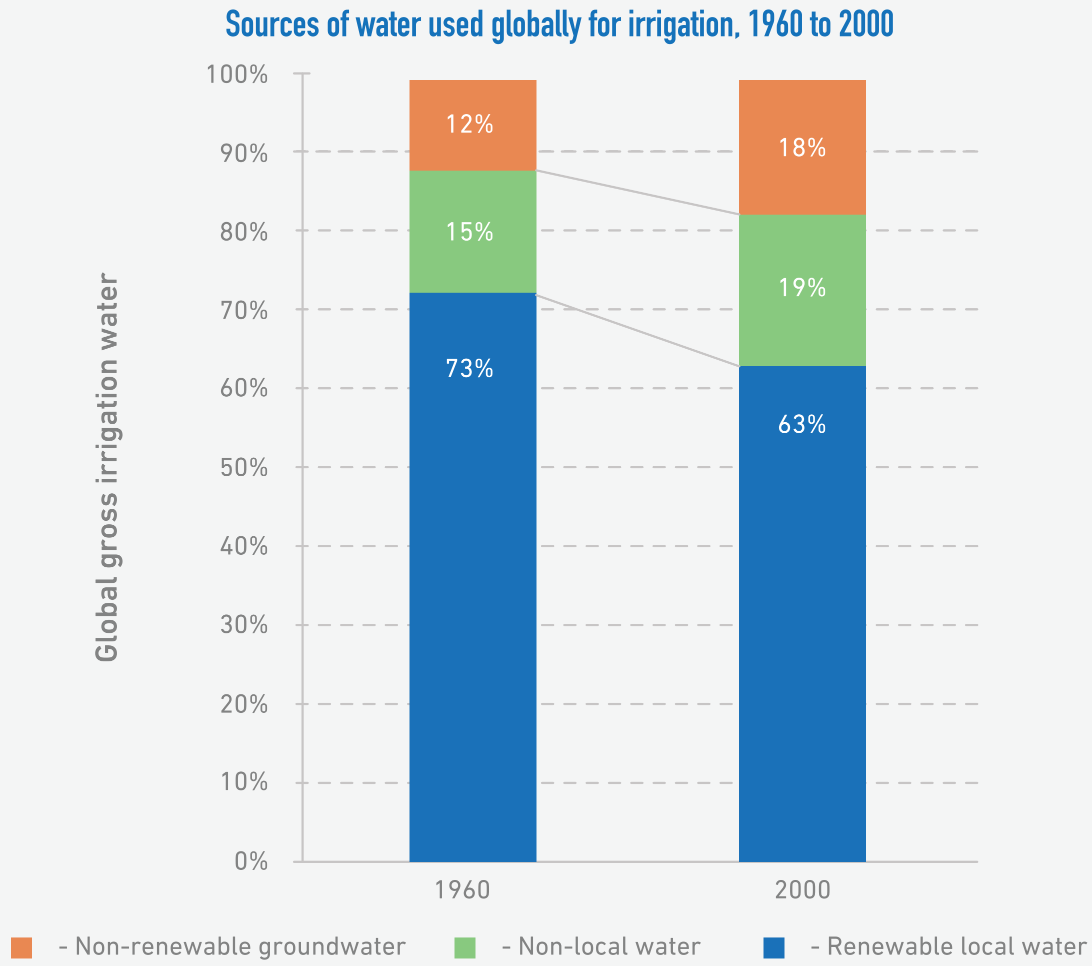


Exhibit 14: Between 1960 and 2000, the share of non-renewable groundwater increased from 12 to 18 percent of global gross irrigation water. The share of non-local water resources, transported to the regions via canals and pipelines for example, increased from 15 to 19 percent of global gross irrigation water. Renewable local water comprised a smaller share of global gross irrigation water in 2000 than in 1960. In absolute terms, gross irrigation water use increased two-fold (from 630 to 1,340 cubic kilometers per year) and non-renewable groundwater use increased three-fold (from 75 to 230 cubic kilometers per year, between 1960 and 2000. (Source: Wada, et al., 2012)

Relatively few countries, notably India, Pakistan and the United States, are responsible for most of the non-renewable groundwater use (Gleason, et al., 2012). **Exhibit 15** shows that in 2000, India used more non-renewable groundwater for irrigation than any other country.

About 19 percent of India's irrigation water came from non-renewable sources. Other countries used a smaller volume of non-renewable water, but it comprised a larger proportion of their total irrigation water use. In both Pakistan and the United States, the share of non-renewable groundwater was 24 percent and in Iran it was 40 percent. More than 70 percent of irrigation water in Libya and Saudi Arabia was sourced from non-renewable groundwater (Wada, et al., 2012).

Groundwater depletion affects food security by limiting the amount of water available for agriculture and other human uses and making the available water more difficult and costlier to obtain. As groundwater supply becomes more limited, wells could intermittently or constantly go dry.

Wells may need to be extended deeper to reach water and more energy is needed to pump water from greater depths. Water quality of depleting freshwater aquifers may deteriorate due to intrusion of brackish water from surrounding aquifers. South Asia is particularly affected by shrinking groundwater resources, and strategies for future food security must now account for constrained groundwater extraction.

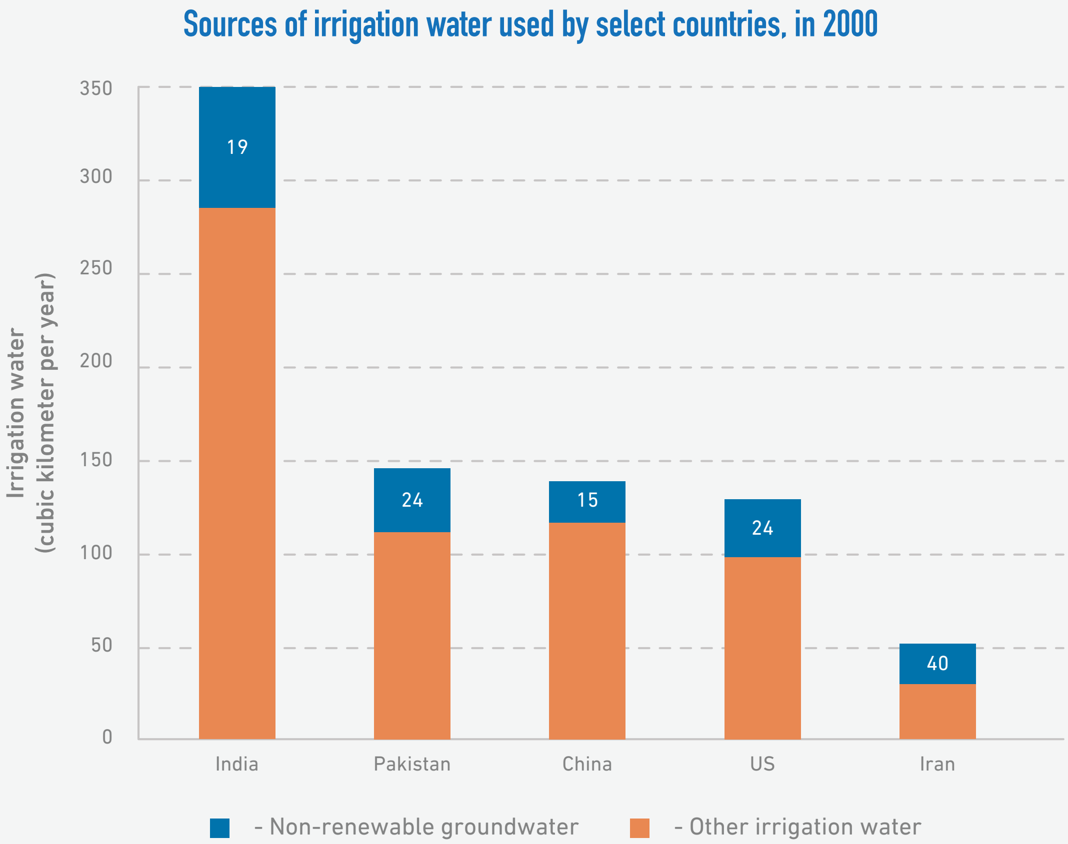


Exhibit 15: Non-renewable groundwater is a significant part of gross irrigation water used in several major countries. India uses more non-renewable groundwater for irrigation than any other country (68 cubic kilometer per year in 2000). Iran uses less in absolute terms (20 cubic kilometers per year) but more as a percent of total irrigation water: 40 percent of Iran's irrigation water is sourced from non-renewable groundwater. "Other irrigation water" includes non-local water and renewable local water. (Source: Wada, et al., 2012)

Sub-Saharan Africa appears to have relatively abundant renewable groundwater resources (MacDonald, et al., 2012) but faces economic water scarcity.[17] While tapping into the available groundwater resources will be critical for improving overall agricultural yields across Africa, it will be equally critical to remember the lessons from South Asia and ensure future sustainability of an important resource.

Unsustainability of groundwater use for irrigation is a concern not only for countries that are using groundwater intensively, but also the world at large since international trade directly links food production in one country to consumption in anothe

Current agricultural practices cause soil erosion and reduce the long-term fertility of farmland

Soil erosion is the removal of soil from the land surface, typically via rain or wind. Some level of soil erosion is natural and over geologic time spans has shaped the river valleys and deltas of our landscape. Soil erosion under native vegetation occurs at roughly the same rate at which new soil is produced through natural geomorphological processes.

However, agricultural practices, such as tillage and heavy grazing, remove vegetative cover and expose the soil surface to rain and wind. Soil erosion in agricultural fields occurs at rates 10 to 100 times greater than erosion from natural land surfaces (Pimentel, 2006; Montgomery, 2007).

[17]It should be noted that some parts of South Asia also have abundant groundwater yet face economic water scarcity, including northeast India and Bangladesh. This is discussed further in the Economic Water Scarcity section of the Water Security chapter.

Such soil displacement and degradation is widespread: About 80 percent of global agricultural land suffers moderate to severe erosion (Pimentel & Burgess, 2013). Erosion is much greater on sloping land, where soil particles are carried away downhill by flowing water.

Wind can also carry soil particles for long distances. Soil erosion by water is the most serious cause of soil degradation globally and heavy rainfall and extreme weather events aggravated by climate change increase soil erosion (Panagos, et al., 2017).

Exhibit 16 shows a global map of estimated soil erosion (Borrelli, et al., 2017). A global total of 36 billion tons of soil is estimated to erode each year. The continent with the highest average erosion rate is Africa, with 3.9 tons of soil eroded per hectare per year. South America has the next highest erosion rate at 3.8 tons per hectare per year, followed by Asia at 3.5 tons per hectare per year.

Global hot spots with soil erosion exceeding 20 tons per hectare per year include China (6.3 percent of the country), Brazil (4.6 percent of the country), equatorial region of Africa (3.2 percent of the region), India (7.5 percent of the country) and the United States (1.9 percent of the country).

Global soil erosion

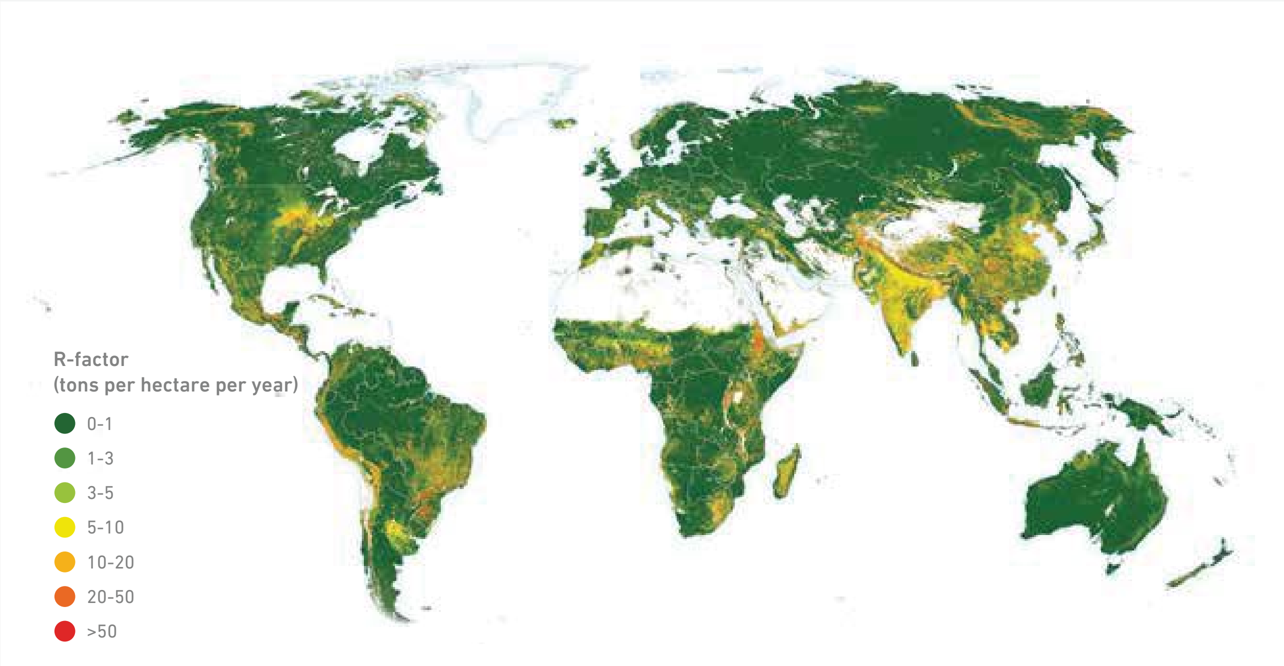


Exhibit 16: Soil erosion varies widely by region, depending on rainfall amount and timing, soil properties, land use, vegetation cover and other factors. Total global erosion is estimated at 36 billion tons of soil per year. (Source: Borrelli et al., 2017; JRC, 2017)

Soil erosion affects global development by reducing food security. Loss of fertile, nutrient-rich cropland soil reduces the productive capacity of the land and causes lower harvest yields. This is a major problem for poor rural populations living on marginal land with low soil quality and steep topography.

As productivity of agricultural fields is reduced, farmers are compelled to apply fertilizers to maintain yields (Lal, 2009). Eventually, when enough productive soil is lost, the land is not worth using and is abandoned. According to FAO (2012), about 3 million hectares of cropland worldwide are abandoned annually because of productivity declines due to severe land degradation.

Agricultural practices that reduce soil disturbance and ensure a continuous cover of vegetation on the land surface can reduce soil erosion. Depending on approach, these may require more human labor input or chemical herbicides for selective weeding.

A related issue is desertification, which is the gradual degradation of drylands to become infertile. Drylands occupy 41 percent of Earth's land area and are home to more than 2 billion people. Drylands include all terrestrial regions where water scarcity limits the production of crops, forage, wood and other ecosystem provisioning services (**Exhibit 17**). While less arid than deserts, drylands are characterized by low and erratic precipitation, high temperatures and high rates of evapotranspiration.

At least 90 percent of dryland populations are in developing countries and on average have lower human wellbeing and development indicators than the rest of the world. Outside of cities, many inhabitants of dryland regions are either pastoralists or agro-pastoralists.

Over millennia they have developed a range of coping strategies to overcome variable rainfall and frequent droughts. Traditional drylands livelihoods represent a complex form of natural resource management, involving a continuous ecological balance between people, livestock, crops and land.

Increasingly, this balance is disturbed by environmental, socio-economic and demographic factors, rendering many of these strategies insufficient (UNDP, 2009).

While desertification was traditionally ascribed to overgrazing, it is now known that it is caused by many interlinked factors, including soil erosion, climate change, soil nutrient depletion and loss of vegetation cover (D'Odorico, et al., 2013). Underlying driving forces include demographic, economic, technological, institutional, socio-cultural and meteorological factors.

Land degradation and desertification are caused by interactions between natural processes like weather variability including droughts and floods and human actions of unsustainable land use practices on fragile resources. External forces are also key drivers, including inadequate governance mechanisms, ineffective land tenure and global economic forces.

Locally, this leads to decreased land productivity, overexploitation and a worsening spiral of land degradation, poverty and food insecurity.

Desertification vulnerability across the world

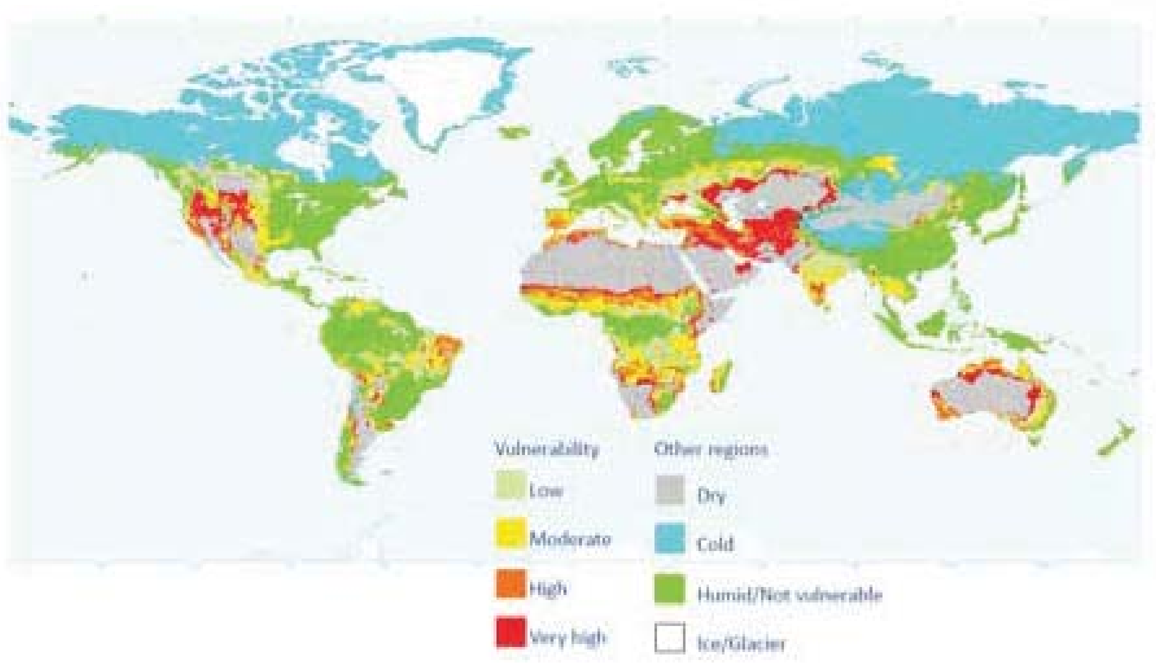


Exhibit 17: Dryland regions, which occupy 41 percent of Earth's land area and are home to more than 2 billion people, are at particular risk of land degradation and desertification. (Source: USDA, 1998)

Large-scale irrigation schemes risk waterlogging and salinization over time

Successful agriculture requires adequate soil drainage to allow excess water and salts to flow away from the plant root zone. When large-scale canal irrigation systems were initially designed and built in South Asia and other places, natural drainage was adequate because the water table was typically many tens of meters below ground, allowing salts to drain into deeper soil.

During the past century or longer, human hydraulic interventions in some areas have substantially increased inflow to groundwater from canal leakage and irrigation drainage, thus altering the groundwater balance and causing water tables to rise in some places. Soil in the lower reaches of some canal command areas is now often waterlogged. Within South Asia the worst affected region is the IBIS irrigation system in Pakistan, where about 24 percent of the total irrigated area is considered waterlogged, with a water table depth of less than 1.5 m (Zaman & Ahmed, 2009). In Sindh province, in particular, more than half of the irrigated area is waterlogged (see **Exhibit 18**).

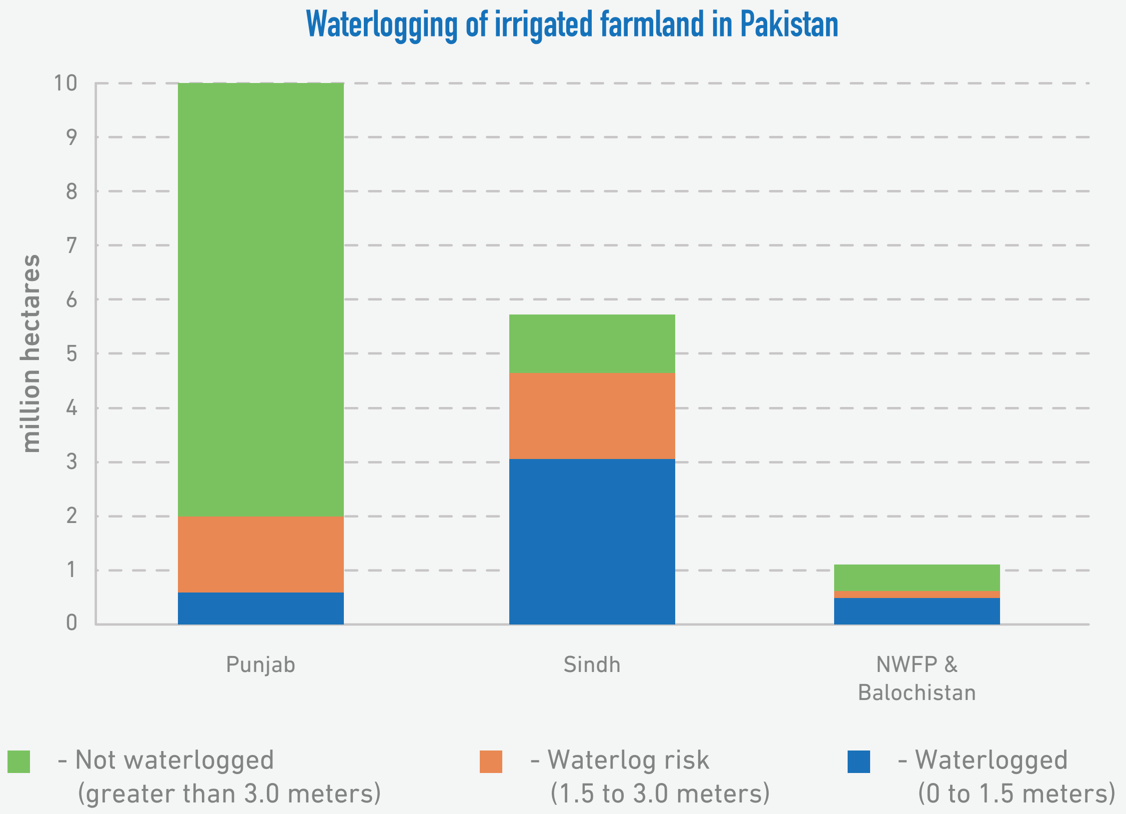


Exhibit 18: Waterlogging status by region of the IBIS irrigation scheme in Pakistan. More than half of the irrigated area of Sindh province is waterlogged. (Source: Zaman & Ahmed 2009)

Inadequate soil drainage typically leads to salt accumulation, or salinization. Large-scale irrigated agriculture generally faces the challenge of salinization, because freshwater supply used for irrigation inevitably has some minor salt content. Evapotranspiration during crop growth sends pure water to the atmosphere, leaving salt accumulated in the soil (see **Exhibit 19**).

Repeated year after year in the absence of adequate drainage, this leads to salt build-up and reduced crop yields. The accumulated salt may be sodium chloride (NaCl) producing saline soil or sodium carbonate (Na_2CO_3) producing alkaline soil. Soil can also naturally contain salt from the original mineral composition or weathering of the soil.

Salt balance of the Indus river basin

Exhibit 19: Estimated flows of salt in the Indus River basin, in units of million tons per year. Low salinity water from the Himalayan headwaters, which previously had flowed into the ocean, is now diverted in canals and applied to farmland. Pure water is removed by evapotranspiration, leaving salt accumulation in soil and groundwater. Each year, at least 8 million tons of salt accumulate within the Indus basin. (Source: adapted from World Bank, 2005)

Soil salinization causes reduced crop yields, and in some cases, forces the abandonment of farmland. Salt-induced land degradation is more common in arid and semiarid regions where rainfall is too low to maintain a regular leaching of salts in the soil through rainfall infiltration. Region-wide assessment of salinization is challenging due to scarcity of information on the subject and lack of commonly agreed methods to assess the degree of irrigation-induced salinization.

It is thought that in Pakistan about 2 million hectares of irrigated land, or 10 percent of all irrigated land, has been lost from production due to salinization (Aslam & Prathapar, 2006). An estimated 28,000 to 40,000 hectares per year are lost per year in Pakistan, or 0.14 percent to 0.20 percent of Pakistan's irrigated land per year. If this trend continues at the same rate, an additional 5 to 7 percent of Pakistan's irrigated land will be lost by 2050.

India is also affected by salinization and it is estimated that about 9.4 million hectares of cropland in India, or about 6 percent of all arable land, is degraded by saline or alkaline soils (Dagar, 2005).

Climate change will alter temperature and precipitation patterns and increase the challenges faced by smallholder farmers

Climate change is a long-term alteration of global weather patterns, due to increased heat energy accumulated in the Earth system largely as a result of greenhouse gases emitted into the atmosphere. Some level of future climate change is unavoidable due to previous emissions, which remain in the atmosphere for long time spans.

The extent of future climate change impacts depends on levels of current mitigation and future adaptation efforts. Current greenhouse gas emissions trajectories correspond closely to high emission scenarios (RCP8.5) modeled by climate scientists. If such trends continue, a global mean temperature increase of about 4 degrees Celsius is expected by 2100 (IPCC, 2014) (**Exhibit 20**).

Beyond extrapolation of current trends, there are various self-reinforcing feedback effects that could be triggered by a changing climate, eventually leading to uninhabitable "hothouse Earth" conditions regardless of mitigation efforts (Steffan, et al., 2018).

These feedback effects include the thawing of permafrost, dieback of tropical and boreal forests, decomposition of ocean methane hydrates, loss of polar ice sheets and alteration of ocean circulation patterns. Scientific and political voices in the climate change arena have tended to understate such existential risks, resulting in limited impetus for effective mitigation action (Spratt & Dunlop, 2018).

Nevertheless, global cooperation towards greatly reduced greenhouse gas emissions could curb temperature rise and any corresponding feedback effects. Such cooperation has not been forthcoming to date (UNEP, 2018). Indeed, the atmospheric concentration of carbon dioxide continues to go up at an increasing rate and therefore accelerating in the wrong direction.

Historical and projected global average surface temperature, 1900 to 2100

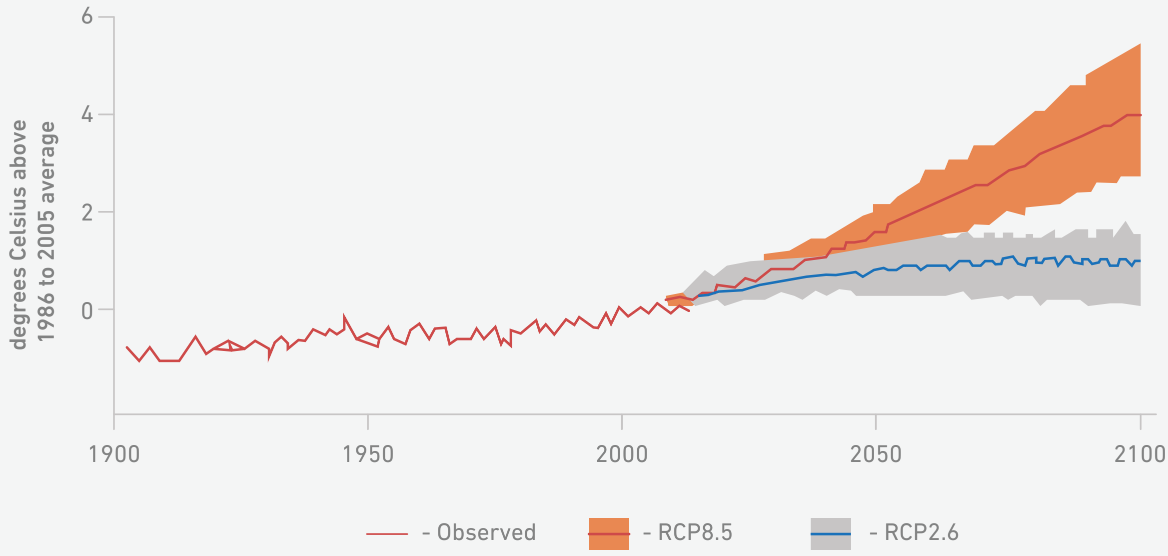


Exhibit 20: Global average surface temperature is projected to increase during this century. The temperature increase will be greater if levels of greenhouse gas emissions continue as predicted in the RCP8.5 emission scenario. A much smaller temperature increase is projected to occur if emissions are limited to the lower RCP2.6 scenario. Temperature changes are shown relative to the average temperature from 1986 to 2005. (Source: IPCC, 2014)

Rising temperatures are expected to affect global development due to potentially significant effects on food security, water supply and health. **Exhibit 21** summarizes numerous published estimates of the impact of rising temperatures on crop yields, based on a range of analysis methods including global grid-based and local point-based models, statistical regressions and field-warming experiments.

For each degree Celsius increase in global mean temperature, global average yield reductions of 6 percent for wheat, 3.2 percent for rice, 7.4 percent for maize and 3.1 percent for soybean are expected (Zhao, et al., 2018). These estimates do not include the potential effects of carbon dioxide fertilization, effective adaptation and genetic improvement.

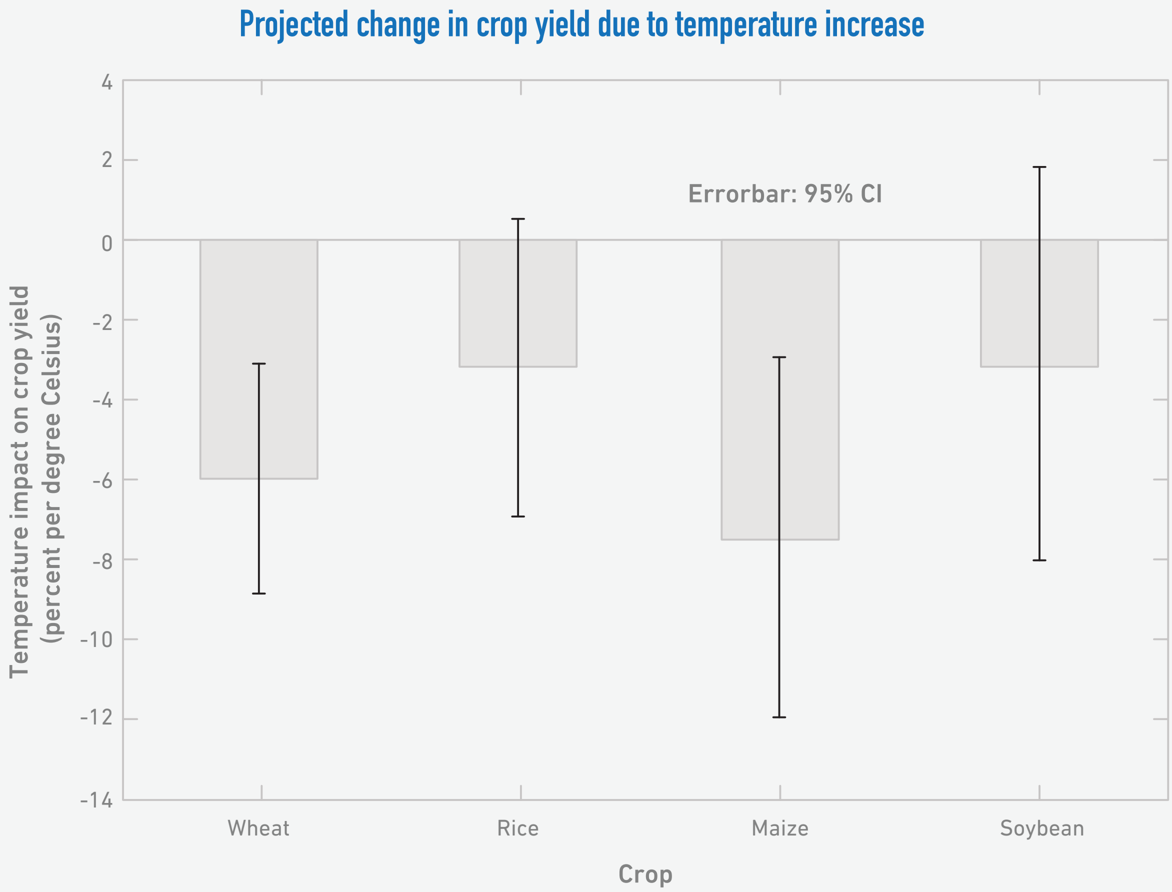


Exhibit 21: Yields of wheat, rice, maize and soybean, which together provide two-thirds of human caloric intake, are expected to decline due to rising temperatures. This exhibit summarizes published estimates based on four analytical methods: global grid-based models, local point-based models, statistical regressions and field-warming experiments. The error bars represent 95 percent confidence intervals. (Source: Zhao, et al., 2018)

Exhibit 22 details the expected reduction in maize yield in different regions resulting from global temperatures increases of 2 degrees Celsius and 4 degrees Celsius (Tigchelaar, et al., 2018). The United States, Brazil, Argentina and Ukraine, which together account for 87 percent of global maize exports, are the top four maize-exporting countries.

The probability that these nations will have simultaneous maize production losses greater than 10 percent in any given year is currently virtually zero. However, the probability increases to 7 percent with a 2 degrees Celsius increase in temperature and 86 percent with a 4 degrees Celsius increase in temperature.

As such, greater levels of global warming are expected to result in rising instability in global grain trade and international grain prices, which will particularly affect populations living in extreme poverty, who are also the most vulnerable to food price spikes.

Projected maize yield changes due to climate change

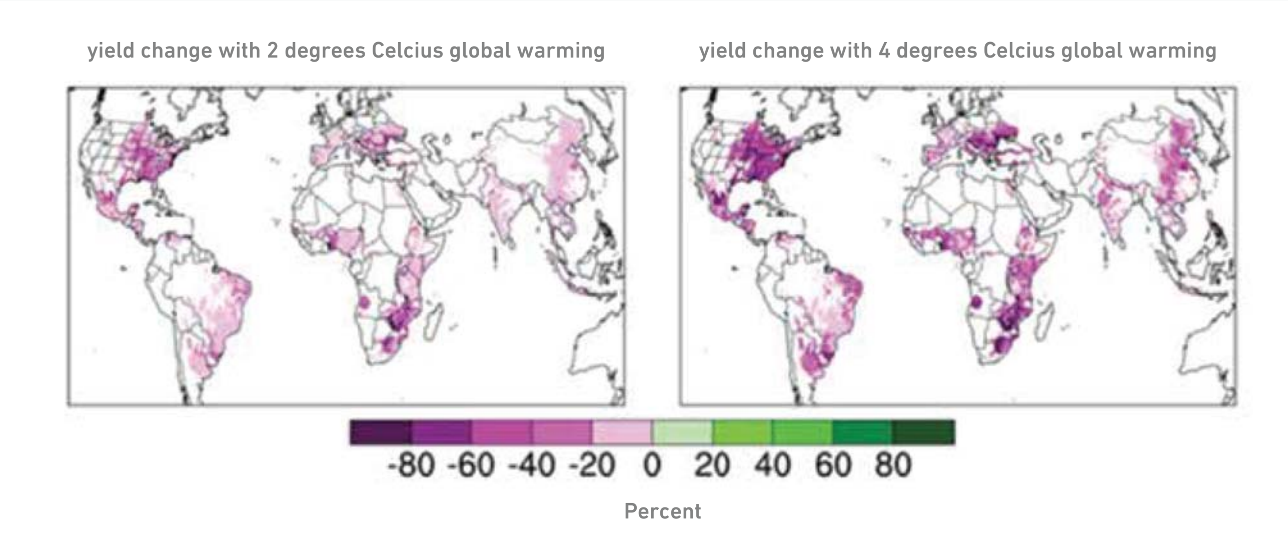


Exhibit 22: Maize yield is projected to decrease globally with mean global temperature increases. (Source: Tigchelaar, et al., 2018)

Average long-term precipitation patterns will shift

As the climate warms, the global water cycle is expected to change (IPCC, 2013). Average global precipitation is projected to gradually increase in the 21st century. The global hydrological cycle will intensify due to global warming and mean water vapor, evaporation and precipitation are projected to increase on average.

Changes of average precipitation in a much warmer world will not be uniform, with some regions experiencing increases and others decreases or little change. Precipitation is expected to increase in many wet tropical areas and in high latitudes. Many mid-latitude and subtropical arid and semi-arid regions will likely experience less precipitation. The Asian monsoon is expected to increase in average total precipitation but with greater variation from year to year.

Global climate change will affect our water supplies in various ways. The melting of snowpack and glaciers will affect the amount and timing of water flows in downstream areas. This is critical for Pakistan, where glacial melt contributes more than 40 percent of the total flow of the upper Indus River (Lutz, et al., 2016). Melting of Himalayan glaciers is projected to alter the Indus River flow in the coming decades, contributing to both floods and droughts (ITT, 2018).

Water pollution issues are also expected to increase due to higher water temperature and altered flow patterns. Armed conflicts fueled by social and political tensions are likely to be exacerbated by the impacts of climate change on water supply and in particular climate-related natural disasters, such as droughts (Schleussner, et al., 2016).

Despite variability and uncertainty in climate change projections, there is now agreement from a number of different climate models that Africa is at the highest risk from climate change, given the magnitude of existing stresses in the continent (UNDP, 2009). It is highly likely that significant areas of Africa will experience changing rainfall patterns in the coming decades.

Exhibit 23 shows model projections of future changes in average rainfall during rainy seasons in Africa, under global temperature rises of 2 degrees Celsius and 3 degrees Celsius (Weber, et al., 2018). Average precipitation is expected to decrease in northern and southern Africa and increase in central and eastern Africa. Nikulin, et al. (2018) and Maúre, et al. (2018) reached similar conclusions.

Projected change in precipitation due to climate change

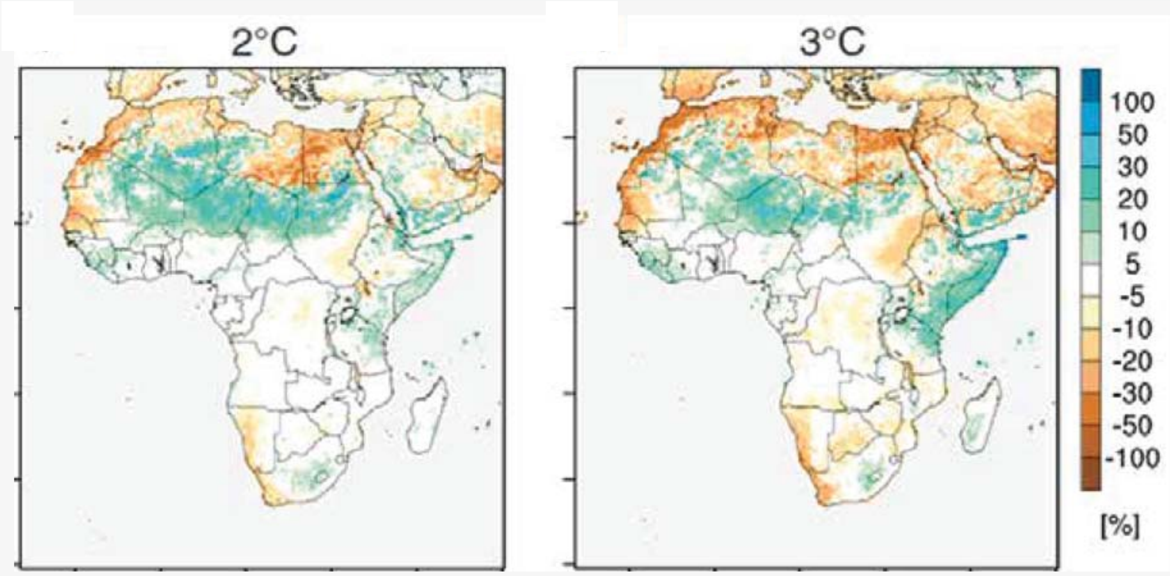


Exhibit 23: Results from climate models suggest that precipitation patterns in Africa will change as global temperature rises. Average rainfall during rainy seasons is expected to decrease in northern and southern Africa and increase in central and eastern Africa. The effect is more pronounced with a 3-degree Celsius temperature rise (right) than a 2-degree Celsius rise (left). (Source: Weber, et al., 2018)

Extreme weather events, such as drought, storms and floods will likely become more frequent and more intense

Global climate change is expected to result in more frequent and intense extreme weather events. Warm spells and heat waves will very likely occur more frequently (IPCC, 2014). Storms, such as tropical cyclones, are expected to become more severe, including storm surges in coastal areas.

Precipitation is more likely to occur as heavy rainfall (even in regions that receive less total precipitation), leading to increased erosion, landslides and flooding. Precipitation extremes are projected to negatively affect water quality, due to increased sediment, nutrient and pollutant loadings caused by heavy rainfall, reduced dilution of pollutants during droughts and disruption of treatment facilities during floods.

Frequent and prolonged droughts in some regions are expected to have the most significant impact of extreme weather events on human development. Many climate models project an increased likelihood of agricultural droughts in regions that are presently dry, with extended decreases in soil moisture (IPCC, 2014).

Farmers and pastoralists in drylands with insufficient access to drinking and irrigation water risk the loss of agricultural productivity. This will affect the livelihoods of rural people, particularly those who depend on water-intensive agriculture. There is a corresponding risk of food insecurity and conflict over available water and food resources (UNDP, 2009).

Droughts also affect urban populations, due to insufficient water supply for domestic and industrial use, leading to health and economic impacts. Droughts can also significantly affect energy security as their impact reduces the energy supply from hydropower stations and can force water-cooled thermal power stations to shut down.

Between 2013 and 2016, 14 of India's largest thermal power utility companies experienced disruptions at least once due to cooling water shortages (WRI, 2018). A major drought in 2001 in Brazil, where 80 percent of electricity is from hydropower, caused a 20 percent reduction in electricity supplies in the country and led the government to introduce rationing (Lee, at al., 2012). Ethiopia is particularly vulnerable to droughts because of its high dependence on agriculture as well as hydropower for electricity.

KEY CHALLENGES

1. Human population is growing, which demands greater absolute levels of food production

Satisfying food demand for rising populations requires not just sustaining current agricultural production, but also achieving continually increasing production levels. Global population is projected to rise by 28 percent between 2018 and 2050 to about 9.8 billion people (UN, 2017).

Many agricultural sustainability stressors are directly related to the amount of food produced. Conventional agricultural development strategies have necessarily focused on increasing immediate farm productivity (measured, say, as the number of tons of grain that may be harvested this year from a hectare of cropland) often at the expense of longer-term sustainability.

2. An increasing share of crop production is used for non-food purposes

Sustainability of agriculture and the broader food system is strongly affected by how we choose to use the primary farm output. The greater affluence and personal choice that result from global human development leads to higher per capita consumption of resource-intensive foods including meats.

About 37 percent of annual US maize production is used as feed for livestock rearing rather than for direct human consumption (USDA, 2018) (**Exhibit 24**). For each unit of animal biomass (meat) produced, the animals themselves consume many units of feed. Livestock rearing methods that use feed that is potentially eaten by people are less sustainable than food systems that use inedible plant byproducts as feed to produce animal biomass.

An additional 39 percent of US maize production is used to make ethanol, of which 97 percent is used as biofuel. More maize is used in the United States to make ethanol fuel than is produced in all of Africa.

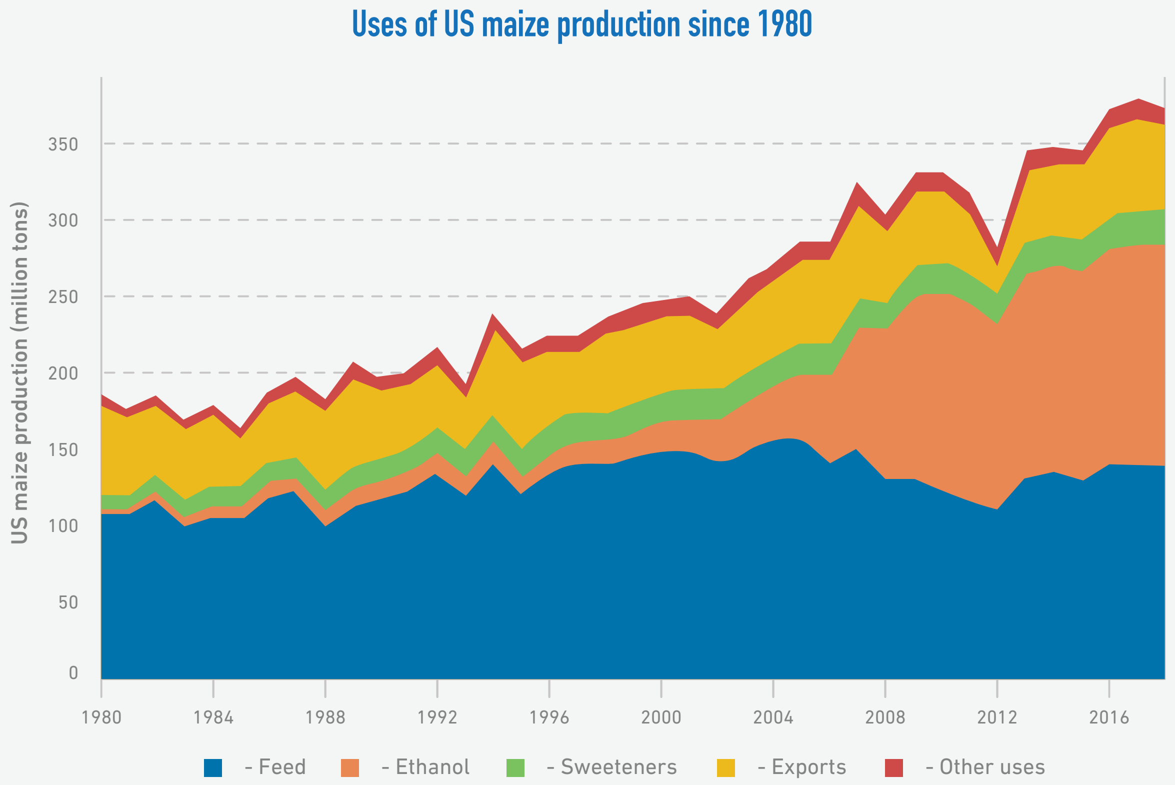


Exhibit 24: About 39 percent of current US maize production is used to produce ethanol, most of which is used as fuel for automobiles. Another 37 percent is used to feed domesticated animals. Sweeteners include high-fructose corn syrup, glucose and dextrose. Other uses include cereals, starch and seeds. (Source: USDA, 2018)

3. Global climate change is altering the accustomed patterns of temperature and precipitation

Global climate change entails different—and more challenging—future temperature and precipitation regimes, relative to the past climate conditions in which agriculture developed. Some level of future climate change is unavoidable due to previous greenhouse gas emissions, which remain in the atmosphere for long time spans. The extent of future climate change impacts will depend on levels of current mitigation efforts and future adaptation efforts.

Current greenhouse gas emission trajectories correspond closely to high emission scenarios (RCP8.5) modeled by climate scientists. Continuation of such trends can be expected to result in a global mean temperature increase of about 4 degrees Celsius by 2100 (**Exhibit 20**). Global cooperation towards greatly reducing emissions (corresponding to the RCP2.6 scenario) could result in a smaller temperature rise. Such cooperation has not been forthcoming, to date.

4. Sustainable forms of agriculture are more expensive than conventional agriculture

Currently, there is no economically viable mechanism—at the production scales required globally—to sustainably intensify agricultural production. Of the various forms of agriculture practiced around the world, very few are fully sustainable—even at a small scale.

As discussed at the beginning of this section (**Exhibit 1** and **Table 1**), even forms of agriculture that are ostensibly sustainable (such as US Organic), do not fully address all environmental stresses. Nonetheless, accepting US Organic farming as a benchmark for sustainability, the costs of replicating such agronomic practices—at more the three times current costs in sub-Saharan Africa and South Asia—will be far too prohibitive for smallholder farmers to adopt.

SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

It is becoming increasingly clear that current models of food production—especially combined with population pressures—will exact an increasingly irreversible toll on our planet's finite resources and fragile ecosystems. New forms for production, facilitated by a new generation of technologies, will be required.

In that context, we believe there are eight technological breakthroughs that can make a significant improvement in the sustainability of food production.

Breakthroughs:

1	2	3	4	5	6	7	8	9	10
11	12	13	14	15	16	17	18	19	20
21	22	23	24	25	26	27	28	29	30
31	32	33	34	35	36	37	38	39	40
41	42	43	44	45	46	47	48	49	50

1 A low-cost system for precision application of agricultural inputs, ideally combining water and fertilizer

In some regions like South Asia, the Green Revolution has brought unfortunate consequences including over-exploitation of groundwater resources and over-application of synthetic fertilizers. In other regions like sub-Saharan Africa, the Green Revolution has not arrived and there is under-utilization of groundwater resources and ongoing nutrient mining of soils. There is need for a low-cost, robust, scalable technology to precisely meter and distribute irrigation water and fertilizer to field crops. This would allow farmers to apply the right amounts of water and nutrients (not too much or too little) at the right time to maximize economic returns and reduce nutrient loss. If made affordable, precision application systems for irrigation and fertilizers, calibrated to local crop type and soil conditions, could be a very effective way to increase agricultural yields, while also reducing negative impacts on the environment.

Enabling better management of the timing and formulation of irrigation and fertilization in cropping systems would ensure that water and nutrients are available where and when needed by the plant roots. Crop yields respond very well with initial inputs of fertilizer, but as additional nutrients are supplied the marginal yield increase becomes smaller. Optimal results occur somewhere along that gradient, depending on the cost of fertilizer and seeds, land and selling price of harvested crops. For maximum returns, it is necessary to not just apply the right quantity of fertilizer, but to also apply it at the right time and place for optimal nutrient uptake by the plant. This would also protect watersheds and populations downstream from farm fields, by greatly reducing runoff.

The efficiency of using agricultural inputs, such as fertilizer is low in conventional farming. It is estimated that overall efficiency of applied fertilizers is about 50 percent for nitrogen, less than 10 percent for phosphorus and about 40 percent for potassium. The rest is wasted as runoff. The mismatched timing between availability of nitrogen and crop need for nitrogen is likely the single greatest contributor to excess nitrogen loss in annual cropping systems. Ideally, nutrients should be applied in multiple small doses and when plant demand for them is greatest.

Current State

Development Stage: Engineering

Time to market (years)

<3 4-6 7-10 10+

Deployment: Challenging

Associated 50BT Chapters

Food Security

Global Change

SDG Alignment

Impact

Increased Access to Food (# of People)

<1M 10M+ 100M+ 1B+

New Income Generated (# of People)

<1M 10M+ 100M+ 1B+

Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

In principle, variations of existing programmable irrigation and fertigation systems used in industrialized countries can be adapted to the needs of smallholder farmers. Already, small-scale drip and sprinkler systems—along with other methods for increasing water usage efficiency—are beginning to emerge in markets like India.

Cultivated area under drip irrigation in India has grown from 71 km^2 in 1992, to 2,460 km^2 in 1998, to 18,970 km^2 in 2010, up to 33,700 km^2 in 2015. The cost of such systems will continue to drop as scale of production increases.

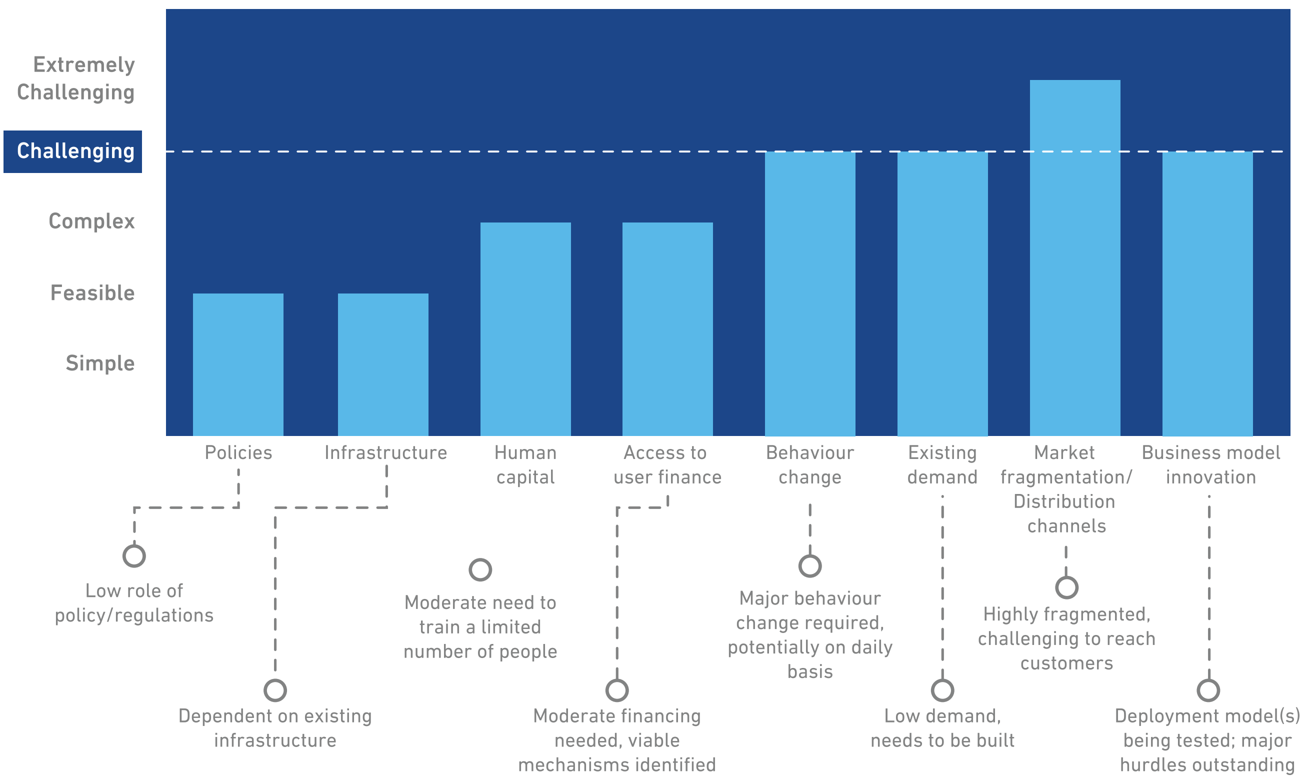
This breakthrough would be strongly leveraged by three other breakthroughs, 5 Low-cost shallow groundwater drilling technologies, 6 Affordable solar-powered irrigation pumps, and 9 Low-cost soil nutrient analysis device.

Overall, such devices would help farmers better predict crop nutrient requirements, better schedule irrigation and fertilizer applications, and avoid over-fertilization and nutrient runoff. If complemented with adjusted crop rotation patterns and additional biotic complexity, it could improve the plant community's ability to take up more of the available nutrients.

However, there is limited evidence to suggest that users—farmers or otherwise—will be interested in spending money on technologies to conserve water when the resource itself is available free of cost. The potential for saving fertilizer can prove to be a positive incentive, although the current demand for fertilizers is very low in sub-Saharan Africa.

It will face some deployment challenges that are common to the African smallholder farmer market, including structural barriers such as a fragmented market of farmers, limited access to finance for potential users, and lack of training to install, use and maintain the technology. The difficulty of deployment in this case would be CHALLENGING.

Breakthrough 1: Difficulty of deployment



2. A very low-cost scalable technique for desalinating brackish water

This breakthrough focuses on developing and enabling systems for very low-cost, high-efficiency desalination of brackish water resources. Households, industries and farms can utilize such systems to provide additional freshwater supplies for water-constrained regions. The introduction of very low-cost desalinated water could enable sustainable irrigation in vast regions of the world that contain brackish groundwater.

Desalination is increasingly used to provide household and industrial water in regions with scarce freshwater but abundant salt water. Most current desalination facilities are located in the Middle East, use seawater as feedwater and are powered by fossil fuels. The city of Chennai in southern Indian gets about a quarter of its municipal water from reverse osmosis seawater desalination plants.

Conventional desalination methods typically use seawater as feed. Seawater desalination technologies based on membranes, such as reverse osmosis, are approaching the thermodynamic limits of efficiency and have limited opportunity for further improvement. It is unlikely that major technology breakthroughs will fundamentally alter the seawater desalination landscape. Additionally, desalinated seawater is too expensive to use as irrigation water for crop production.

In contrast, there are large potential efficiency gains by using brackish water as feed. There are major opportunities for significant reductions in brackish water desalination cost and energy use through innovative electrochemical or other emerging techniques. The minimum theoretical energy requirement for desalination varies with the salinity of the feedwater—less energy is fundamentally needed to desalinate brackish water compared to seawater.

Electromagnetic desalination processes such as electrodialysis (ED) and capacitive deionization (CDI) are limited to low-salinity feedwater, but potentially have much lower cost and energy than pressure or thermal techniques. They offer many advantages when used with brackish feedwater, such as high water recovery and high brine concentrations. They also require little or no feedwater pre-treatment and membrane fouling can be prevented by reversing the electrode polarities.

However, electromagnetic processes only remove ions from the water, leaving organics and colloids in suspension—this is a concern for household water, but less so for irrigation water. Furthermore, the selection and configuration of membranes is currently highly dependent on feedwater characteristics, thus must be adapted to local conditions of feedwater composition and concentration.

Current State

Development Stage: Engineering

Time to market (years): <3 | 4-6 | **7-10** | 10+

Deployment: Complex

Associated 50BT Chapters

Water Security

Food Security

SDG Alignment

2 ZERO HUNGER

6 CLEAN WATER AND SANITATION

Impact

Increased Access to Food (# of People): <1M | 10M+ | **100M+** | 1B+

New Income Generated (# of People): <1M | **10M+** | 100M+ | 1B+

Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

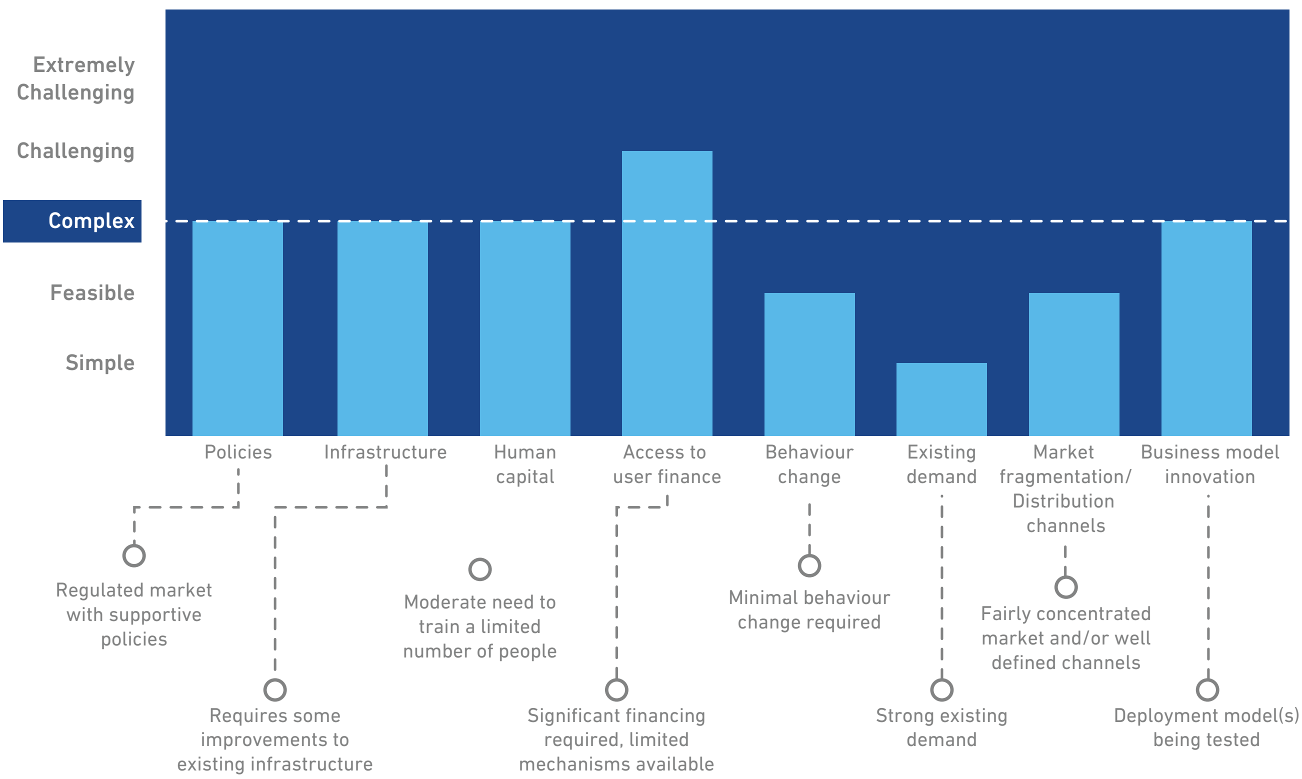
Concerted R&D efforts can overcome current obstacles to enable a major source of low-cost freshwater in regions with brackish resources. The appropriate unit scale of desalination facilities may vary depending on the application (such as household, irrigated farm, urban water utility). The salinity of the product water may also vary depending on the purity requirements of the end uses.

Costs can be further reduced by matching the salinity of the product water to the salinity thresholds for different uses; in other words, removing only enough salt to make the water viable for its intended use. Ideally, facilities will be powered by onsite renewable energy sources, such as photovoltaic solar arrays, to provide reliable and sustainable operation. Developing appropriate business models will be essential to ensure economic sustainability and continuing impact.

End-uses for the desalinated water will include drinking, cooking, washing and other domestic uses and industrial water uses. Efficient techniques for large-scale desalination of brackish water resources will also enable the use of desalinated water for production of agricultural crops using efficient irrigation techniques.

Substantial research and development work is required and we expect that it will take seven to ten years for this breakthrough to be ready. Deployment challenges include access to finance and policies regarding location and discharge streams. We rate the difficulty of deployment, COMPLEX.

Breakthrough 2: Difficulty of deployment



8 New processes of nitrogen fixation that are less capital intensive than current (Haber-Bosch) processes

Perhaps the single most significant hurdle to the availability of affordable nitrogen fertilizer for smallholder farmers in sub-Saharan Africa is that the known processes for producing usable forms of nitrogen are extremely capital intensive, and must be located near the sources of particular natural resources.

For example, a facility for the Haber-Bosch process, the only known scalable process for synthetic nitrogen fixation, costs hundreds of millions of dollars to build, and needs to be located near a source of natural gas. As a result, there is virtually no fertilizer produced in sub-Saharan Africa (outside of South Africa), and what little is used has to be shipped in.

This means that the same fertilizer costs the African smallholder farmer considerably more than it costs a farmer in countries where the fertilizer is produced.

An ideal alternative will be significantly less capital-intensive, less energy-intensive, and will not require close proximity to sources of natural gas or other extractive resources. This will enable nitrogen fixation closer to farms, or even on farms, thus reducing or eliminating transport costs.

However, there are significant technical challenges involved, especially in splitting nitrogen bonds. The fact that the only scientists to solve this problem in the past (Fritz Haber and Carl Bosch) won the Nobel Prize, underscores the magnitude of the challenge. The solution can be biological or electrochemical or some yet-undiscovered method.

While some emerging technologies offer promise (such as intra-cellular transplantation of nitrogen-fixing bacteria from natural host crops to other crops), a scaled solution still appears to be far away. There is limited incentive for private sector investment to address this problem, given that synthetic fertilizer is very well accepted in most of the world, and natural gas supplies are currently abundant.

Therefore, we believe it will take more than 10 years for such a technology to come to market.

Current State

Development Stage: R&D

Time to market (years): <3 | 4-6 | 7-10 | 10+

Deployment: Extremely Challenging

Associated 50BT Chapters

Food Security

SDG Alignment

Impact

Increased Access to Food (# of People): <1M | 10M+ | 100M+ | 1B+

New Income Generated (# of People): <1M | 10M+ | 100M+ | 1B+

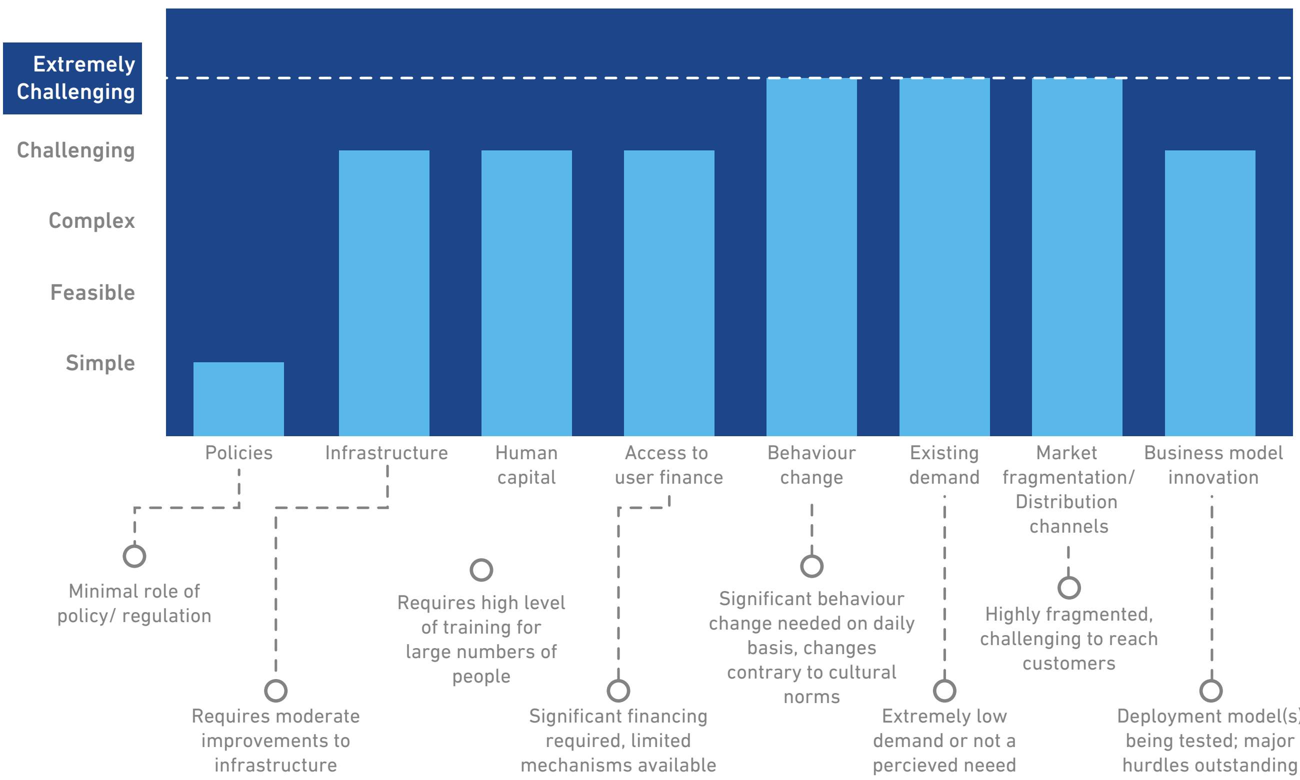
Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

Even when developed, such a technology will still face some deployment challenges, the most important being low demand from African smallholder farmers. Even if demand is created, low income farmers will need some form of financial support, possibly through micro-credit programs, so that they have the working capital to invest in fertilizer.

Extension services will likely be necessary for training farmers on how to use fertilizer appropriately. Overall, deployment will be EXTREMELY CHALLENGING.

Breakthrough 8: Difficulty of deployment



9 A low-cost, point-of-use device to evaluate soil nutrient content and recommend tailored use of fertilizers for specific crops

Understanding exactly which type of fertilizer is needed, how much should be applied and at what stage of the plant's lifecycle, is very critical for optimizing crop yields and maximizing returns on the farmers' investment. Smallholder farmers in Africa rely on advice from knowledgeable peers (like farmer cooperative leaders) or from extension workers.

A low-cost device, with a simple user interface, for rapid chemical analysis of the soil—tailored to the crop, underlying soil type, season and plant lifecycle—can prove extremely helpful in improving nutrient uptake, yield, and eventually demand for fertilizer. For greatest utility, the device would measure macronutrients like nitrogen, phosphorus and potassium, as well as essential micronutrients (like boron and manganese) that can limit crop growth. Using mobile technology for underlying computation, access to additional information and easy communication with appropriate extension workers can make such a tool more attractive for smallholder farmers.

Importantly, more precise knowledge of soil nutrient status would help avoid the problem of over-application of fertilizers. This would improve the economics of farming, and would also greatly reduce nutrient runoff which would protect watersheds and populations downstream from farm fields. In conventional farming practice, the efficiency of using fertilizer is very low. It is estimated that overall efficiency of applied fertilizers is about 50 percent for nitrogen, less than 10 percent for phosphorus and about 40 percent for potassium, while the rest is wasted as runoff.

Basic versions of such devices are in use in more developed markets. A recent wave of technological innovation has made them even more precise, and enhanced the benefits for farmers using such kits. However, these devices are still cost prohibitive for smallholder farmers in Africa and South Asia, and not necessarily intuitive to use by a person with limited formal education. While considerable reengineering is required to make such devices useful for smallholder farmers in low-income countries, there are no major scientific challenges involved.

Current State

Development Stage: Engineering

Time to market (years): <3 | **4-6** | 7-10 | 10+

Deployment: Challenging

Associated 50BT Chapters

Food Security

SDG Alignment

Impact

Increased Access to Food (# of People): <1M | 10M+ | 100M+ | **1B+**

New Income Generated (# of People): <1M | **10M+** | 100M+ | 1B+

Commercial Attractiveness

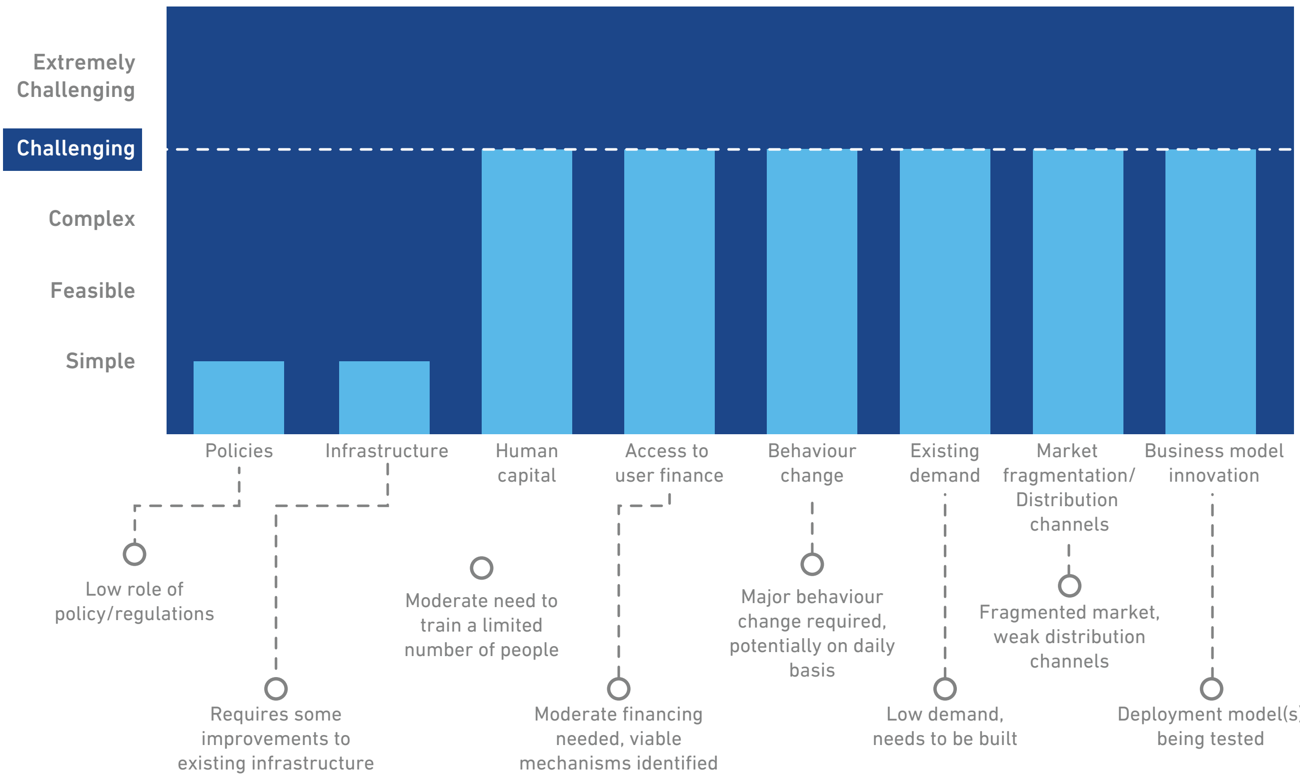
- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

However, demand for such a product is currently limited, and few resources are committed to making a low-cost device for analyzing soil nutrients. Based on the above assessment, the projected time to market readiness is about four to six years.

We anticipate that when such a technology is developed, there will be limited initial demand and it will have to overcome marketing and distribution challenges. Presumably, need for such a tool will depend on the demand for fertilizer and the value proposition of reducing the amount of money that farmers spend on fertilizer.t

The rapid proliferation of smartphones and ICT tools for smallholder farmers is a positive trend that may help in the acceptance of such a technology. Still, until fertilizer demand and use increases, such a technology will not be widely used. Considering the above, deployment will be CHALLENGING.

Breakthrough 9: Difficulty of deployment



10 New generation of affordable herbicides that are specific to most destructive weeds and are safe for humans

Herbicides are the most widely used method of dealing with weeds in industrialized markets. However, these are too expensive for the typical smallholder farmer in developing countries, and usually make economic sense only for high-value cash crops or in very heavily infested sites. Furthermore, most herbicides are non-specific, in that they can damage the crops in addition to the weeds.

As such, for optimum results they need to be accompanied by enhanced seeds. In addition, the ability of the weeds to develop resistance to herbicides means that the enhanced seeds will need to be periodically modified to keep up with adjustments in the herbicide to maintain crop yield. Given the limited R&D capacity in Africa and South Asia to continuously generate improved seeds, and the capital-intensive nature of herbicide production, it is not surprising that few customized solutions have been developed or scaled-up.

Novel herbicides are needed that specifically attack the most destructive weeds, but are harmless to the crops. Such herbicides must be more environmentally friendly than herbicides currently available in most markets, and be safe for human health.

To facilitate adoption and support local economies, an ideal herbicide would be based on agro-industrial raw materials and produced in smaller regional factories, thereby easing a major barrier to supply and distribution. Synthesizing such an herbicide will require significant R&D and will likely take 10 years (or more) to be market ready.

Current State

Development Stage: R&D

Time to market (years)

<3 4-6 7-10 10+

Deployment: Extremely Challenging

Associated 50BT Chapters

Food Security

SDG Alignment

Impact

Increased Access to Food (# of People)

<1M 10M+ 100M+ 1B+

New Income Generated (# of People)

<1M 10M+ 100M+ 1B+

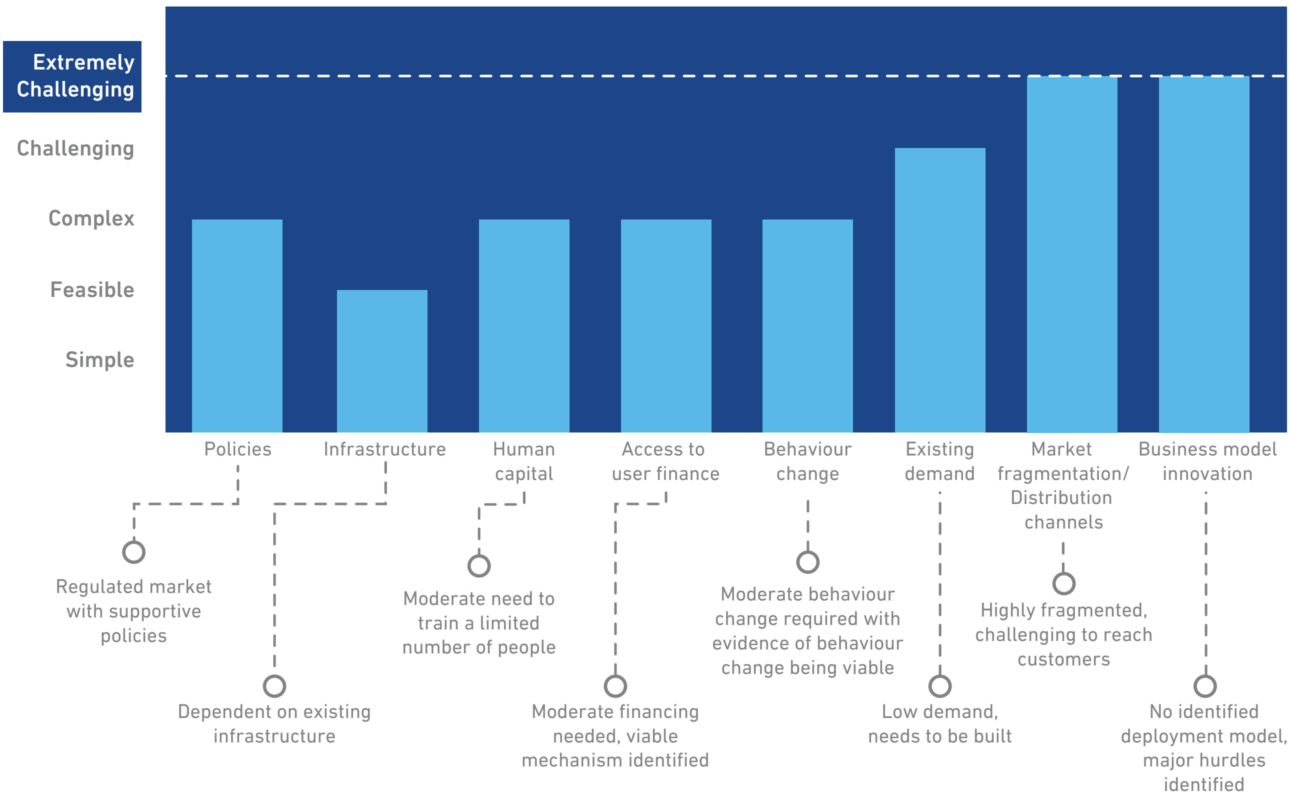
Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

Once such an herbicide becomes available, it will have to overcome limited demand, need for farmer financing, a highly fragmented market and a very sparse distribution network.

The difficulty of deployment will be EXTREMELY CHALLENGING.

Breakthrough 10: Difficulty of deployment



11 Novel, low-cost, environmentally friendly pest control mechanisms (chemical or spatial), specifically targeting the most destructive insects

Insects and other pests reduce potential yield by up to 15 percent for smallholder farmers in Africa. While crop damage is caused by numerous pests, a small number—borers, mealybugs, mites—cause a disproportionate share of these losses. Due to weak agricultural extension services, especially across Africa, it has proven extremely difficult to train smallholder farmers in optimal agronomic practices for integrated pest control.

A few farmers have access to general pesticides, but these tend to be harmful to the health of the farmers, as well as for the environment. Transgenic modifications to make crops repel pests (such as through the Bt bacterium) have many complicated externalities. Introducing them into any environment without the necessary infrastructure to study and manage these externalities can be a very risky proposition.

Spatial repellents emit particular sound frequencies and patterns, and may also be important for repelling on-farm as well as household pests. An important challenge is the limited scientific understanding of the sensory sensitivities of the many species of pests.

Considerable research is required to understand these sensitivities over the lifecycle of the pests, including variations between different sub-species.

Current State

Development Stage: R&D

Time to market (years): <3 | 4-6 | 7-10 | 10+

Deployment: Extremely Challenging

Associated 50BT Chapters

Food Security

SDG Alignment

2 ZERO HUNGER

12 RESPONSIBLE CONSUMPTION AND PRODUCTION

Impact

Increased Access to Food (# of People): <1M | 10M+ | 100M+ | 1B+

New Income Generated (# of People): <1M | 10M+ | 100M+ | 1B+

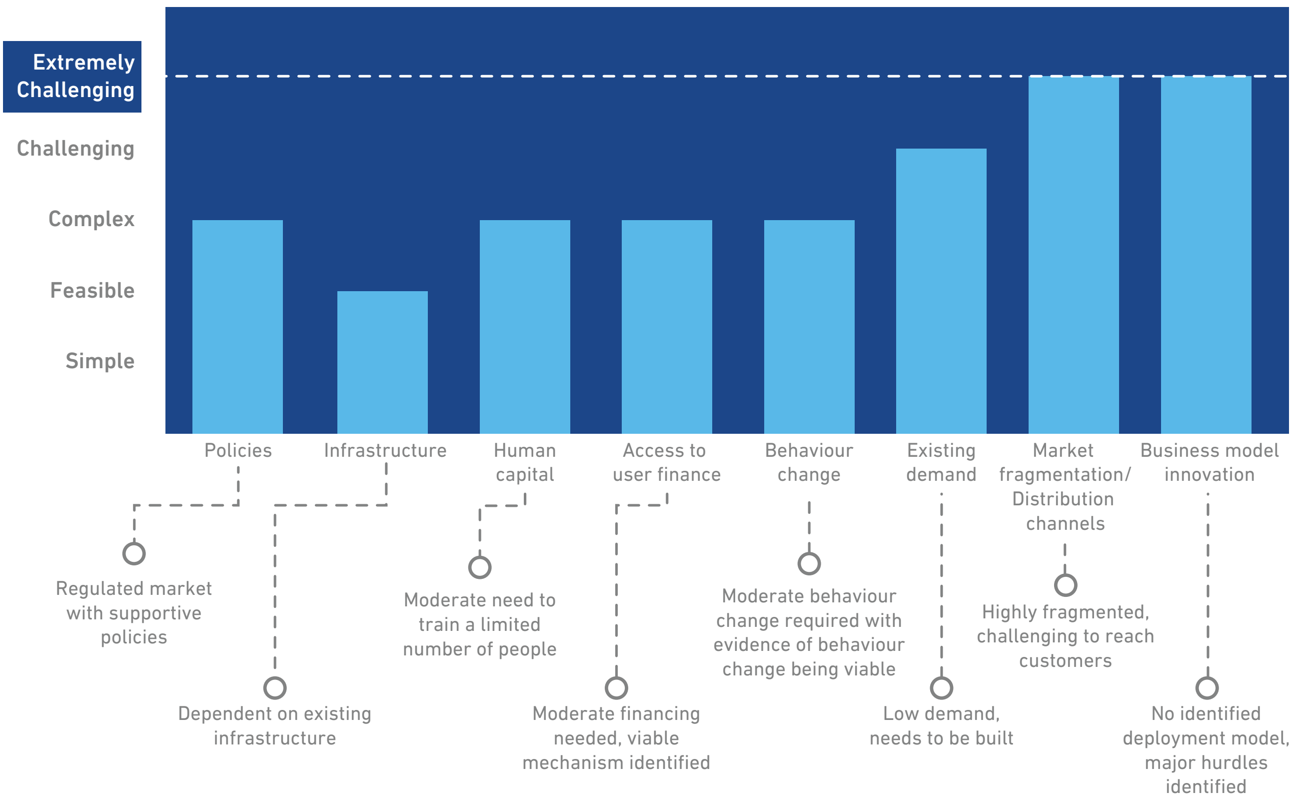
Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

A new type of pest control method is needed, specific to the most destructive pests and without negative effects on humans and the broader environment. If chemical-based, ideally it would be made from locally (or regionally) available agro-ingredients, to help catalyze the development of a large number of less capital-intensive production facilities closer to the market. Such a pesticide will require significant R&D; a major undertaking that may take more than 10 years before it becomes a reality.

It will also face many of the same challenges as a novel herbicide: low demand, need for financing, market fragmentation and the absence of reliable distribution networks. We expect that the difficulty of deployment will similarly be EXTREMELY CHALLENGING.

Breakthrough 11: Difficulty of deployment



16 Alternative meat production system that is affordable, desirable and environmentally sustainable

The environmental consequences of large-scale conventional meat production systems are increasingly evident, such as deforestation and polluted waterways.

Alternative meat production techniques are being developed, that if successful could satisfy our growing meat demand with reduced environmental impacts. Such products are potentially healthier and more efficient alternatives to conventional meat, with lower use of land, water and agricultural inputs.

If the conditions for alternative meat production could be sufficiently controlled and manipulated at industrial scale, it would offer safe and affordable food with a healthy nutritional profile, to improve food security and quality of life.

There are two primary avenues for alternative meat production. The first avenue, often called substitute meat or meat analog, involves the conversion of non-animal biomass to have the characteristics of actual meat. This begins with the conventional agricultural production of feedstocks such as soybean, wheat or peas, followed by industrial conversion into a material with texture and taste similar to meat.

A notable example is Impossible Foods, which is primarily made of soybean protein concentrate and vegetable oils, with additional plant-based additives to mimic the flavor of meat. Impossible Foods products were initially introduced in 2016, and in 2019 the firm partnered with Burger King to serve alternative meat burgers in fast-food restaurants throughout the US.

The second avenue, often described as cultured meat, cellular meat or in-vitro meat, involves the managed growth of actual animal cells. This tissue engineering process begins with collection of stem cells from living animals, which are then allowed to grow and reproduce in a bioreactor, a device for carrying out biochemical processes.

The living cells are provided with nutrients in a suitable culture medium, typically composed of water, glucose, amino acids, lipids, vitamins and salts.

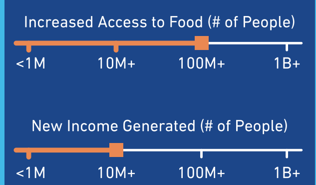
If the cultured meat is to match or exceed the nutritional value of conventional meat, any nutrients found in meat that are not synthesized by the growing cells must be supplied in the culture medium.

Current State

Associated 50BT Chapters

SDG Alignment

Impact



Commercial Attractiveness

- **Attractive for industrialized markets (high profits)**
- Attractive for emerging markets (lower profits)
- Emerging markets potential; requires derisking (sustainable)
- Non-commercial (unprofitable)

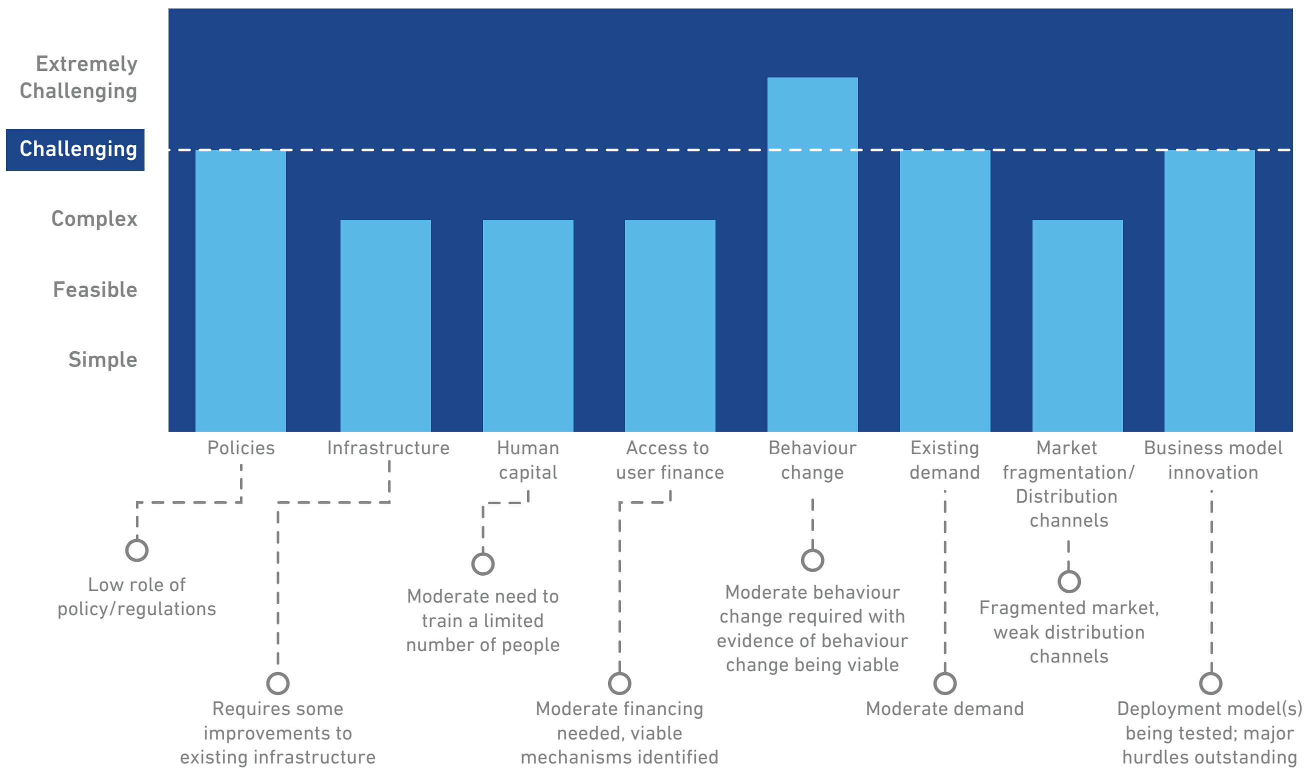
There are many technical challenges to sustainable in vitro meat culturing system on a large scale. The technology now exists to produce in-vitro meat on very small scales, as its major use to date has been regenerative medicine of a variety of tissues and organs.

Current cultured meat processes require large energy input for industrial processes, as biological functions such as digestion and nutrient circulation are replaced by industrial equivalents. The climate implications of cultured meat are complex, and depend on emissions of carbon dioxide, methane and other greenhouse gases from the cultured and reference animal-based systems.

Scaling alternative meat technologies as a global food security solution will depend on many economic, cultural and technical factors. Widespread deployment will face a number of hurdles, primarily along acceptance by consumers and regulators, and limited current demand for alternative meat products.

Initial substitute meat products are already on the market, and cultured meat products are likely to be market-ready in three to five years. Large-scale deployment is projected to be CHALLENGING.

Breakthrough 16: Difficulty of deployment



17 New seed varieties that are tolerant to drought, heat, salinity and/or other emerging environmental stresses (ideally using cis-genetic modification)

Agriculture will face numerous stressors during the coming decades, such as droughts due to climate change, salinization of farmland and groundwater, and basin-level limits to water supply. Conventional plant breeding techniques are hard-pressed to develop crop varieties that accommodate such rapid changes.

A new generation of crop varieties is needed with tolerance to worsening conditions of drought, heat and salinity. Genome editing techniques such as CRISPR/Cas9 have successfully been used to create variants of maize that have higher grain yield under water stress conditions and have no yield loss under well-watered conditions, compared to conventional maize types.

Varieties with tolerance to heat and salinity are also expected, allowing continued expansion of agricultural production despite growing environmental challenges.

Genome editing techniques are capable of precisely and site-specifically (rather than randomly) add, modify or delete genes from plant and animal genomes. Genome editing methods include clustered regularly interspersed short palindromic repeats (CRISPR), zinc-finger nucleases (ZFNs), and transcription activator-like effector nucleases (TALENs) systems.

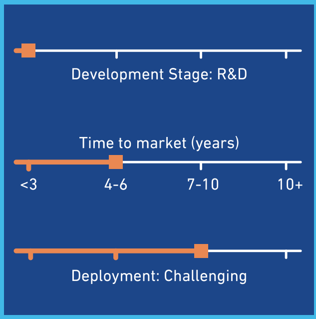
The CRISPR/Cas9 system, in particular, is proving to have many beneficial uses such as increasing crop yield, improving drought tolerance, increasing growth in nutrient-limited conditions, and breeding crops with improved nutritional properties. In this system, the Cas9 nuclease is complexed with a synthetic guide RNA and is delivered into a cell. It then cuts the cell's genome at a desired location, allowing existing genes to be removed and/or new genes to be added.

In water-stressed regions where all available annually-renewable water is fully allocated, CRISPR technology may enable crops that use water more efficiently, producing more biomass per unit of water transpired, to increase total agricultural production.

Many farmers do not use irrigation and instead depend on rainfall for crop water needs. While expanding the use of irrigation is possible in some areas, irrigation is constrained in many regions by lack of water sources or excessive economic costs. Using genetic editing tools to create varieties that make better use of the rainwater that falls on dryland farms, total agricultural production can increase without the need to harness additional water sources.

Importantly, gene editing with CRISPR is cisgenic rather than transgenic modification, meaning that genes are artificially transferred between organisms that could otherwise be conventionally bred. Many consider cisgenic editing to be less controversial than transgenic modification, because the edited organisms could, in principle, have been created through conventional breeding.

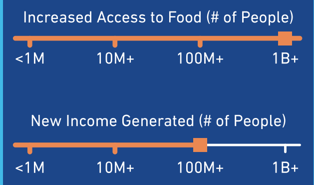
Current State



Associated 50BT Chapters

SDG Alignment

Impact



Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

For this reason, both regulatory procedures and consumer acceptance are proving to be less challenging for cisgenic editing than for transgenic modification.

Of more immediate concern may be the asymmetric economic relationship between the producers and planters of edited seeds, as genetically modified organisms have typically been produced and marketed by large multi-national corporations with narrow interests.

The global seed industry is undergoing consolidation, and four firms are now estimated to control over 60 percent of global proprietary seed sales. Structures should ensure that improved seeds are accessible to all farmers in need, to avoid further widening social inequalities.

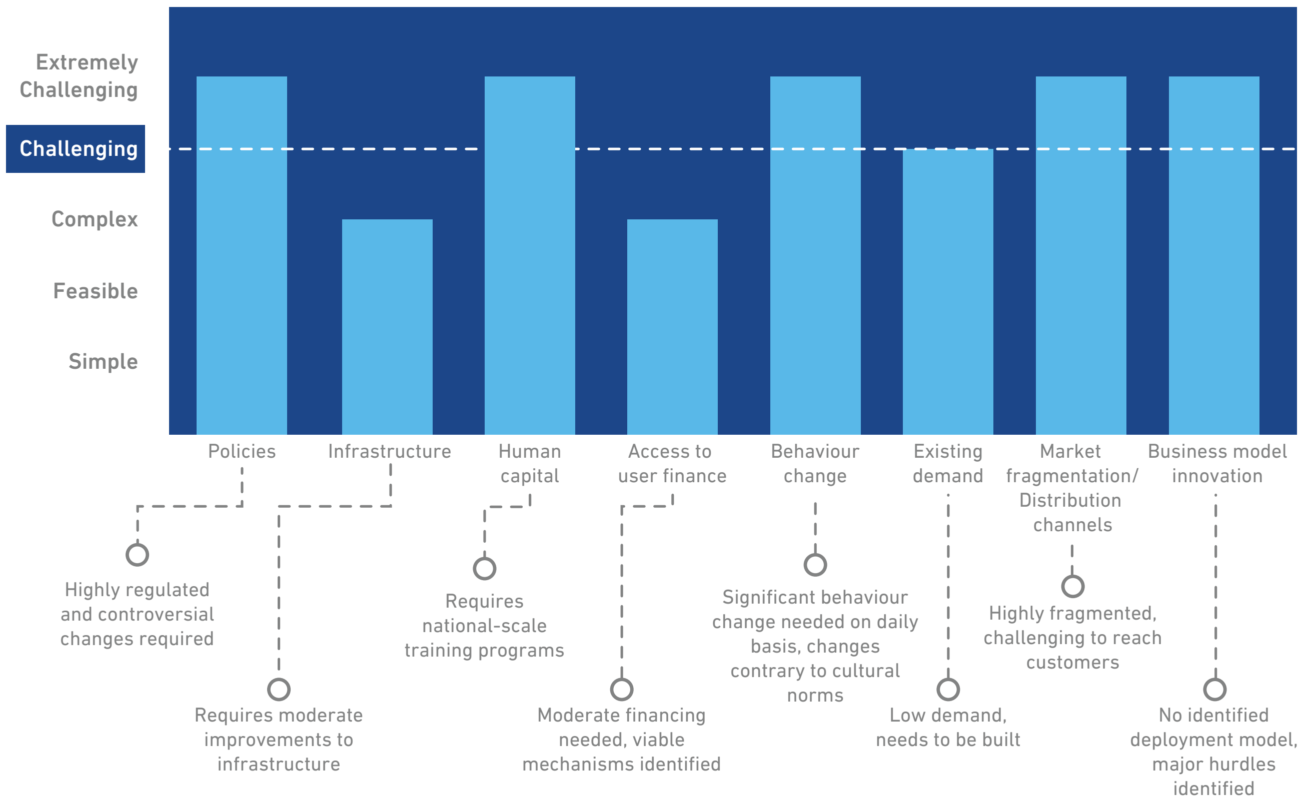
The production of seeds within low-income countries, by existing and emerging biotechnology centers, would provide opportunity for local control. It will also be important to take steps to avoid unwanted second-order environmental effects of edited seeds.

Initial genetically edited varieties with some drought tolerance already exist for crops like maize, and it is reasonable to believe that more can be developed for other staple crops within four to six years assuming there is interest and funding.

One important constraint to the pace of genetic editing breakthroughs is the polygenetic nature of many of the traits we would like to breed into plants and animal, which are determined by many different genes in ways that are not yet well understood.

Furthermore, there are significant barriers with respect to adoption by farmers and governments alike, which makes deployment CHALLENGING.

Breakthrough 17: Difficulty of deployment



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EDUCATION

INTRODUCTION

Across primary, secondary and tertiary levels of education, there are a number of recurring themes that reduce access to, or diminish the quality of, education.

These include, but are not limited to, low government budgets that lead to a dearth of adequately equipped schools and qualified teachers, lack of accountability to meaningful outcomes and readiness for the job market, potential discrimination against segments of the population based on either gender or religion, and the high opportunity cost of older students to enroll and stay in school instead of earning a living.

Fundamental solutions to this problem require systemic improvements in infrastructure, better teacher training and certification and ensuring accountability to stakeholders. However, one particular technology can play a powerful role in making education more accessible.

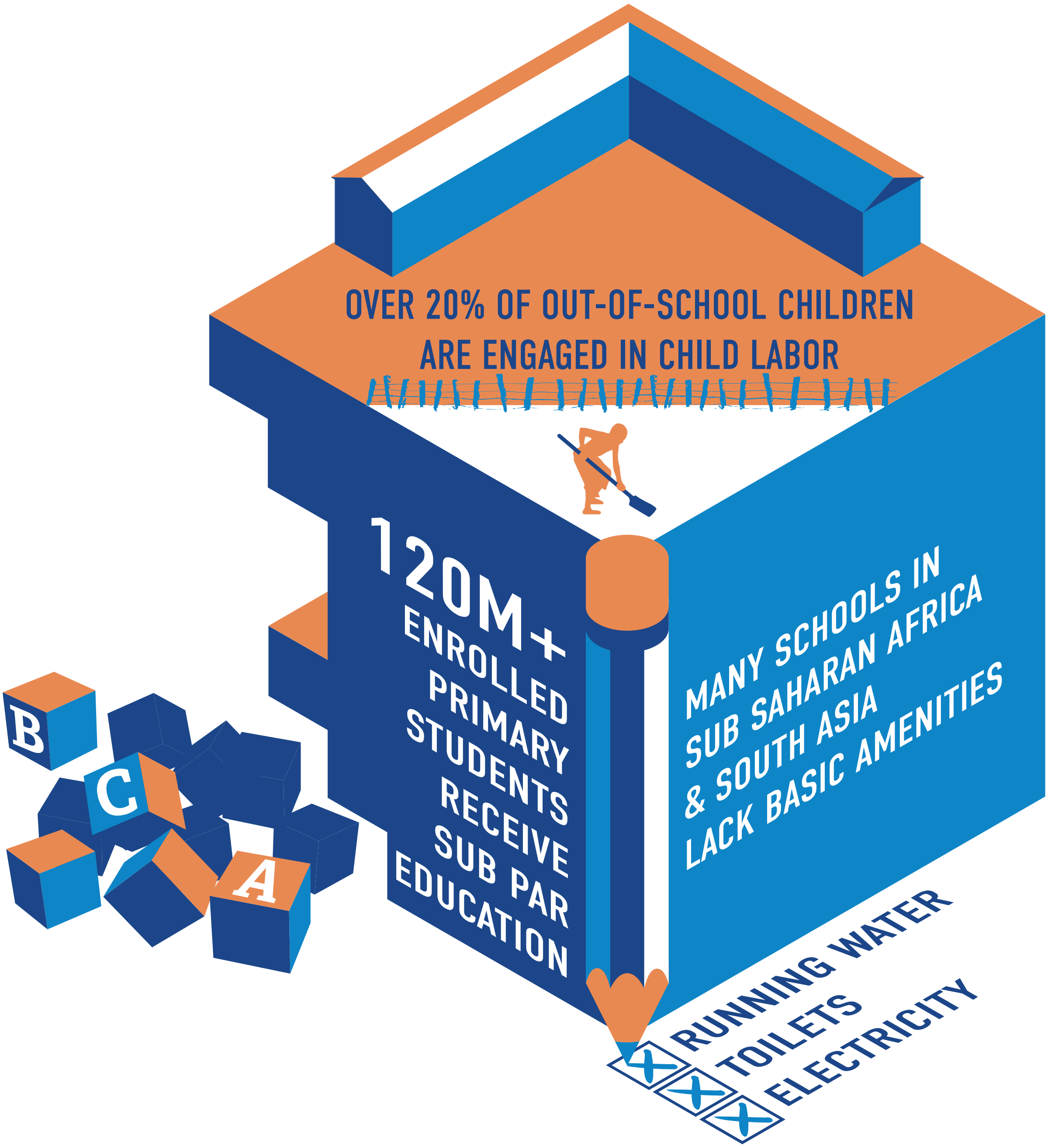
- Breakthrough 18. Smart electronic textbooks that dynamically adapt content for different skill levels, languages and other user specific needs

Education is the foundation of long-term development. A well-educated population, trained in technical topics, such as the sciences, medicine, engineering and jurisprudence, is essential for advancing a country's industries, institutions and laws, without prolonged external assistance. A workforce skilled in running businesses can serve as the engine of a strong private sector economy. A populace educated in the arts and humanities contributes to the society's cultural wellbeing. Unfortunately, educating a country's population quite literally takes a generation. Building the necessary infrastructure and systems can take even longer. As a result, it can be very difficult to design effective and sustainable education programs, and even harder to measure their long-term impact. This chapter examines the design of education programs across the age continuum: primary (age 6 to about 13 years), secondary or youth (about 14 to 19 years) and post-secondary (focused on readiness for the job market)

CORE FACTS AND ANALYSIS

The Sustainable Development Goals aim to "By 2030, ensure that all girls and boys complete free, equitable and quality primary and secondary education" (UN, 2015).

Since this declaration, countries and institutions around the world have galvanized to accomplish these collective goals.



PRIMARY EDUCATION

Primary Education

1. There is a strong link between a country's level of development and its protection of citizen rights

As shown in **Exhibit 1**, primary school enrollment in sub-Saharan Africa has increased from 58 percent in 1999 to 78 percent in 2018 (UNESCO, 2018). In South Asia it increased from 75 percent to 90 percent during the same period. Notwithstanding this seeming progress, several major challenges remain.

Enrollment percentages increased until about 2008, after which they have stagnated. As of 2018, out of the approximately 810 million children of primary school age around the world, 64 million remained out of school (**Exhibit 2**).

These out-of-school children are concentrated in Sub-Saharan Africa (34.3 million) and South and West Asia (11.6 million). Specifically, a number of countries have a very high prevalence of out-of-school children; these include Somalia (76 percent), South Sudan (74 percent), Liberia (57 percent), Chad (50 percent), Niger (50 percent), Burkina Faso (48 percent) and Mali (47 percent) in sub-Saharan Africa, and Afghanistan (36 percent) and Pakistan (36 percent) in South Asia (UNESCO, 2018).

After very strong gains in the early part of the millennium, the overall number of out-of-school children appears to have stalled at 62 to 64 million. This is likely because these children either live in extremely remote areas that are difficult to reach or are from very vulnerable populations and face extremely challenging hurdles in attending school.

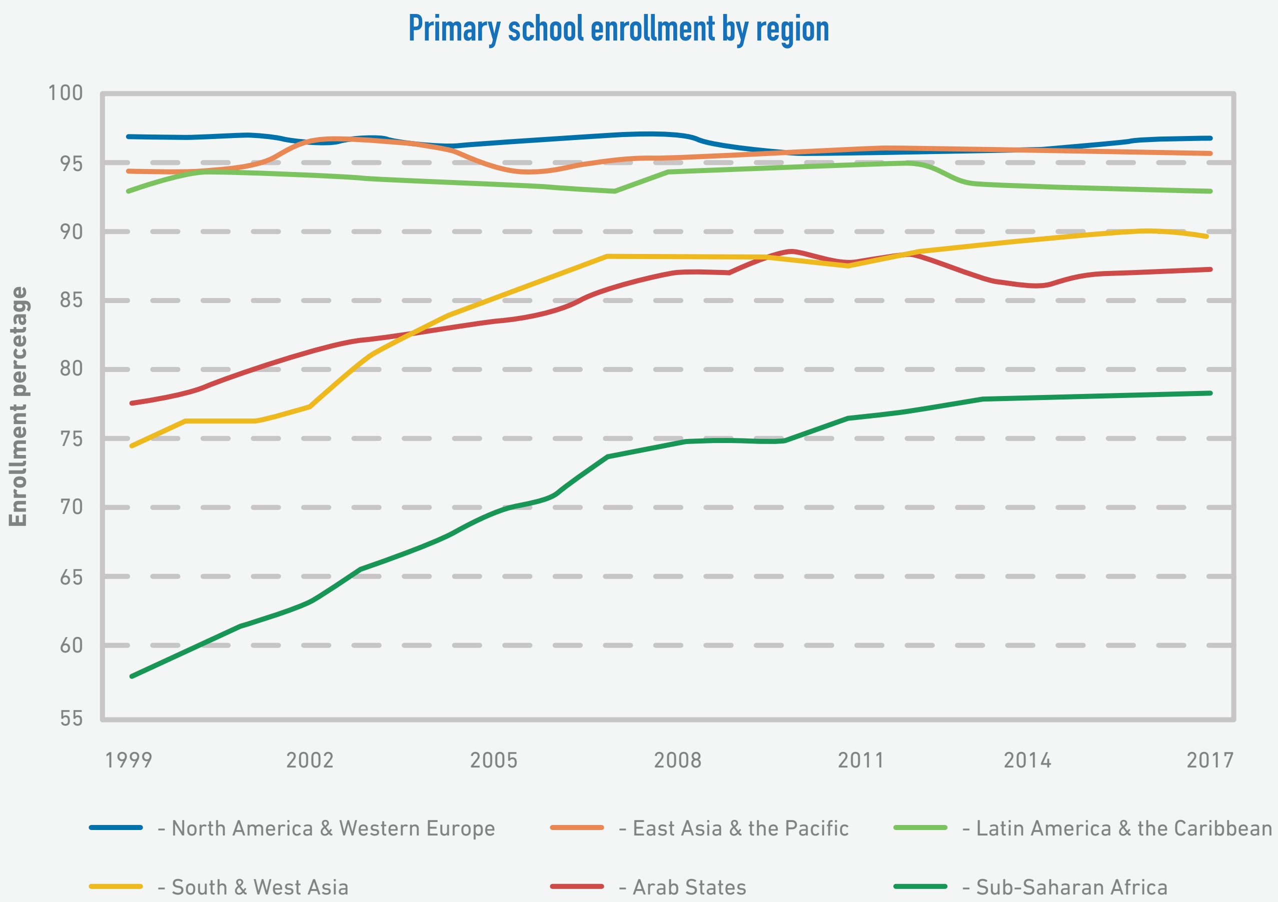


Exhibit 1: Primary school net enrollment has increased dramatically in sub-Saharan Africa, South Asia and West Asia since 1999. (Source: UNESCO, 2018)

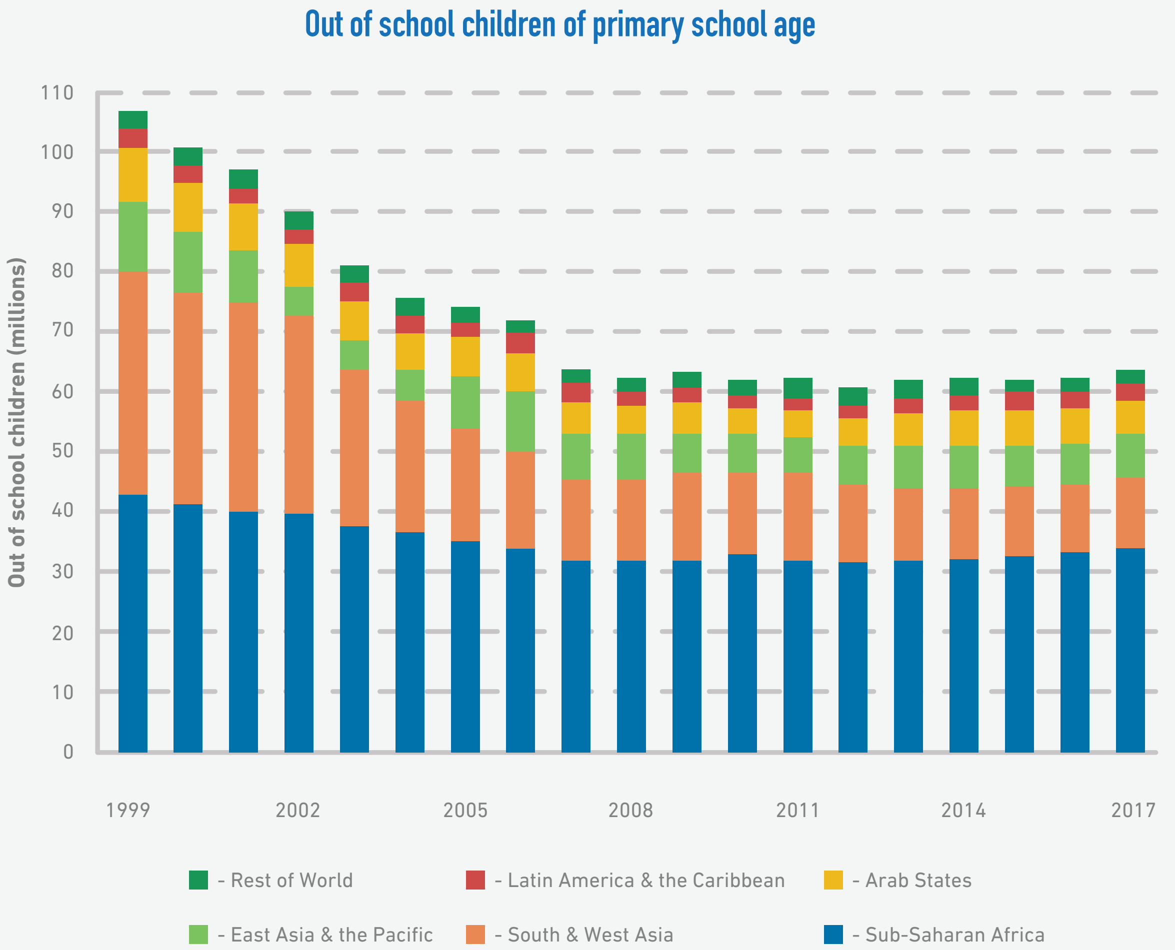


Exhibit 2: Despite the increase in primary school enrollment rates, 64 million primary school age children remain out of school worldwide. Most of these children are in sub-Saharan Africa and South and West Asia. (Source: UNESCO,2018))

2. At least 120 million enrolled primary school children receive subpar education

Quality of education is difficult to measure. Not only is there limited agreement on appropriate metrics for determining quality, but also most developing countries do not collect standardized data on student performance. Based on the little data that is available, both sub-Saharan Africa and South Asia have major gaps along the key drivers of education quality.

- **Attendance**

  In addition to the children who are out of school, a very large number of students in developing countries, despite being nominally enrolled, do not regularly attend school.

  Exhibit 3 shows that 30 percent of enrolled primary school students in sub-Saharan Africa and 23 percent in South Asia do not regularly attend school (UNICEF, 2012). Around the world, about 138 million children enrolled in primary schools do not attend regularly, mostly in developing countries.

Primary school absentee rates

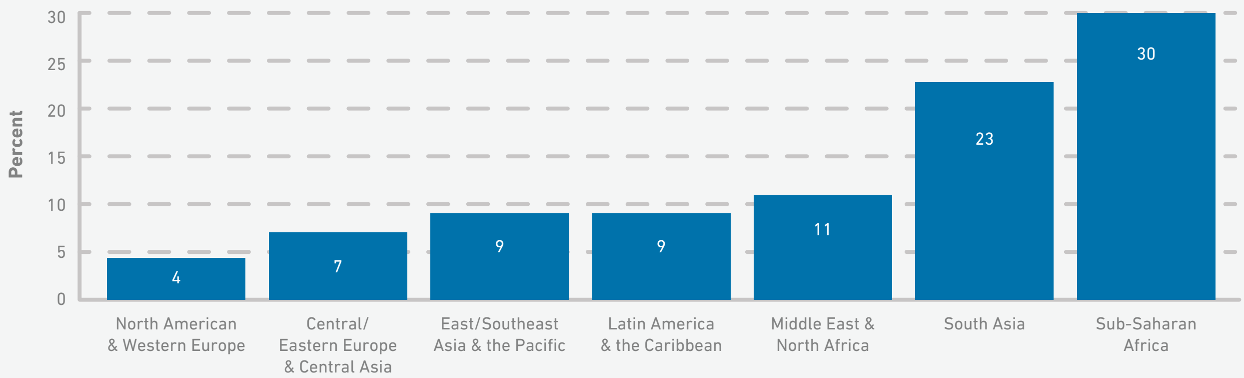


Exhibit 3: 30 percent of enrolled primary school students in sub-Saharan Africa and 23 percent in South Asia do not attend school regularly. (Source: UNICEF, 2012)

- **Student-to-teacher ratios**
  The more students there are in a class, the less attention a teacher can give to each student. As **Exhibit 4** shows, the average student-to-teacher ratio is 40 to1 in sub-Saharan Africa and 34 to 1 in South Asia.

In comparison, the average ratio in North America and Western Europe is 14 to 1 (UNESCO, 2018)).

Primary school student-to-teacher ratio

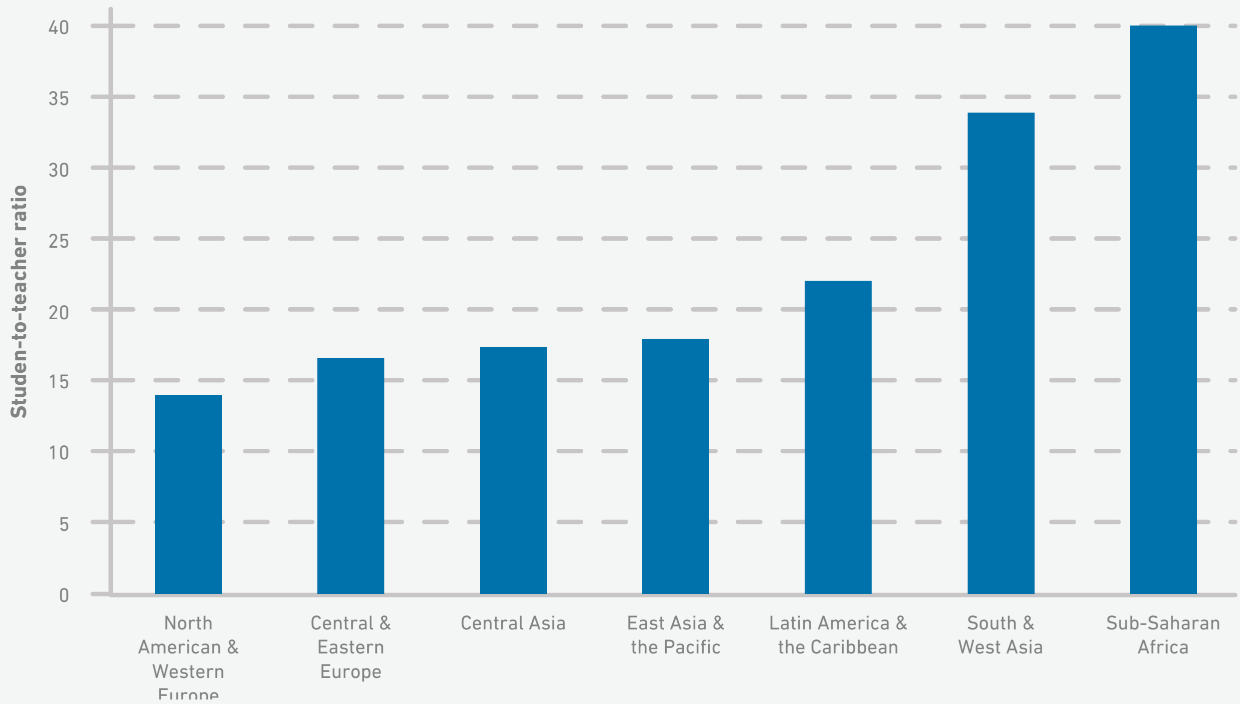


Exhibit 4: Student-to-teacher ratios, a key determinant of education quality, are far higher in South Asia and sub-Saharan Africa than in other regions. (Source: UNESCO, 2018)

- **Teacher qualifications and training**
  Teachers' qualifications and training determine their teaching ability and are an integral contributor to overall education quality that students receive. **Exhibit 5** shows findings from a UNESCO study of 100 countries (UNESCO, 2006), categorizing teacher qualifications according to the minimum education level required for instruction in primary schools.

  These qualifications are characterized in terms of the International Standard Classification of Education (ISCED) levels; ISCED 2 refers to 9 years of schooling, ISCED 3 refers to 12 to 13 years, ISCED 4 to 13 to 15 years, and ISCED 5 refers to advanced degrees.

According to the survey, almost half the countries in sub-Saharan Africa require only ISCED levels 2 or 3 (that is, a secondary-level education or less), and only 8 percent require an advanced degree.

In some South Asian countries, the requirements are even less stringent. Despite the less stringent requirements in these regions, only 70.8 percent of primary school teachers in South Asia, and 63.7 percent in sub-Saharan Africa, meet the basic required qualifications (**Exhibit 6**).

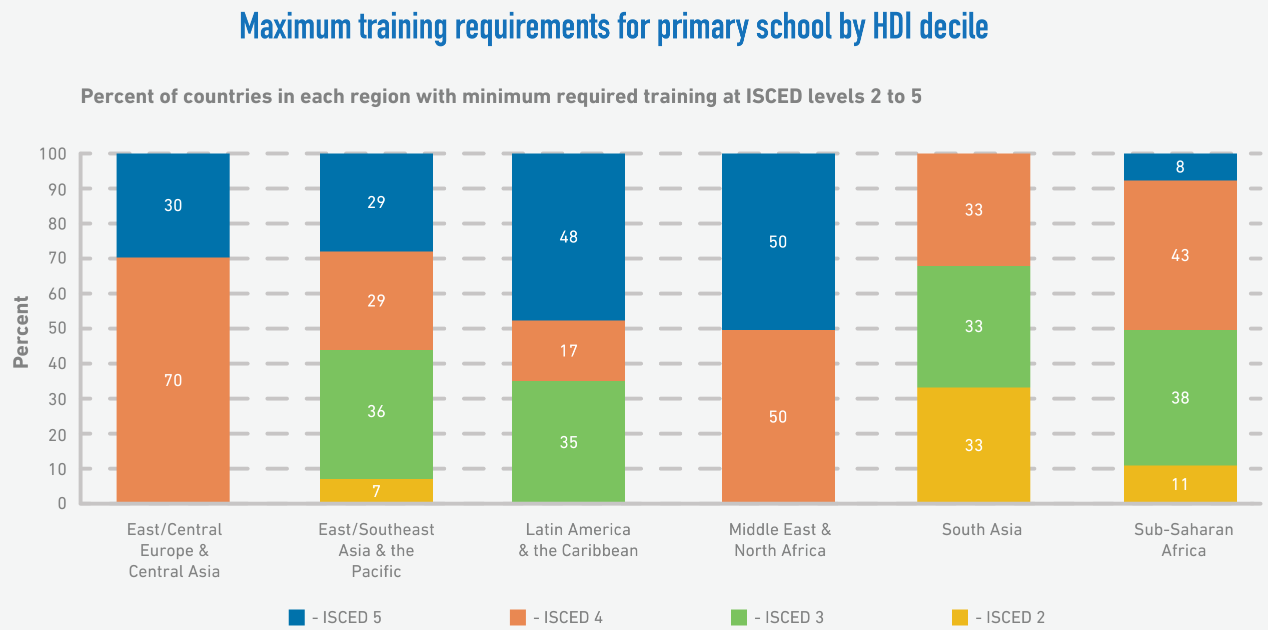


Exhibit 5: The minimum qualifications for primary school teachers varies across countries and regions. In sub-Saharan Africa, only 8 percent of countries require ISCED 5. The requirements in most South Asian countries are, likewise, low. Note that this UNESCO study does not include India and Pakistan, South Asia's two largest countries. (Source: UNESCO, 2006)

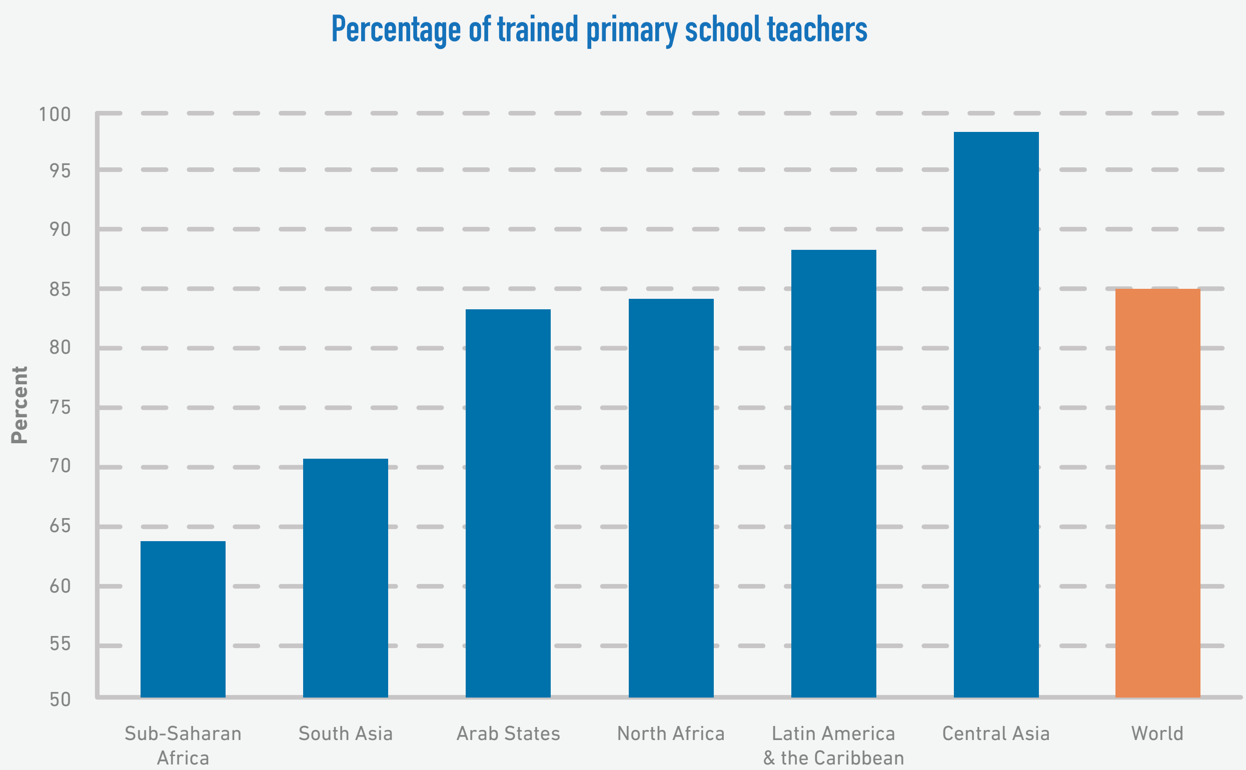


Exhibit 6: Compared to the global average, fewer primary school teachers in sub-Saharan Africa and South Asia are properly trained. (Source: UNESCO, 2018)

Judging only by the number of teachers who do not meet the minimum national standards in their respective countries, we estimate that approximately 120 million[1] students enrolled in primary schools—18 percent of students enrolled globally and almost 25 percent of those enrolled in South Asia and sub-Saharan Africa—do not receive an education of adequate quality.

This is, most likely, a highly conservative estimate given that many of these minimum standards would be considered inadequate by experts. Moreover, teacher training is only one of the several drivers of education quality.

[1]ITT Analysis based on UNESCO data

3. Many low-income parents send their children to private schools, especially in urban areas

One of the more contentious debates in international development is the role of government versus the private sector in providing education to the poor, especially at the primary level (Colclough, 1996).

Proponents of public (that is, government-run) education believe that it is the only meaningful way to provide free (or affordable), universal and equitable education for the poor. Detractors argue that public systems lack accountability for quality or financial management and that private schools are much more accountable (Tooley & Dixon, 2005; Tooley, 2009; Lutyens, 2011).

Our study does not take a stance on that debate, nor do we believe that the two approaches are mutually exclusive. Across all income groups in sub-Saharan Africa and South Asia, 13.5 percent and 32 percent of primary school students, respectively, are enrolled in private schools (UNESCO, 2018) (**Exhibit 7**).

More interestingly, a targeted study of the urban poor in India, Nigeria and Ghana found that 72 percent of low-income students go to private schools, of which 68 percent do not receive any financial aid (Tooley & Dixon, 2005) (**Exhibit 8**).

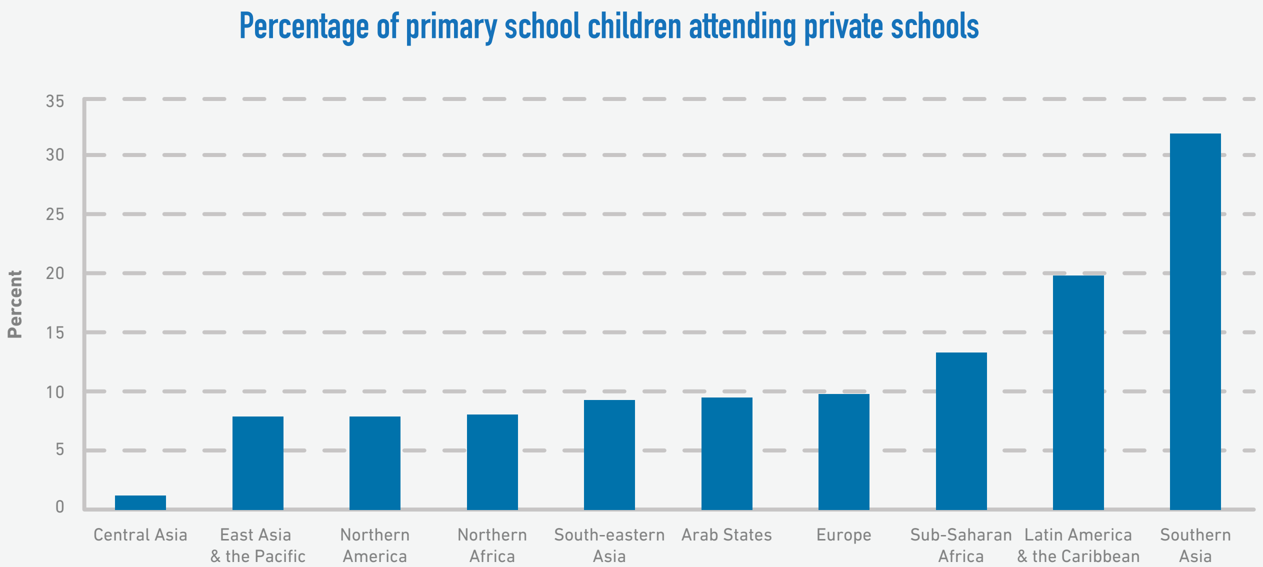


Exhibit 7: In general, there appears to be no correlation between the poverty level in a country and overall enrollment in private schools; 13.5 percent of primary school students in sub-Saharan Africa and 32 percent in South Asia attend private schools. (Source: UNESCO, 2018)

Public versus private school enrollment of low income students in urban areas of India, Ghana and Nigeria

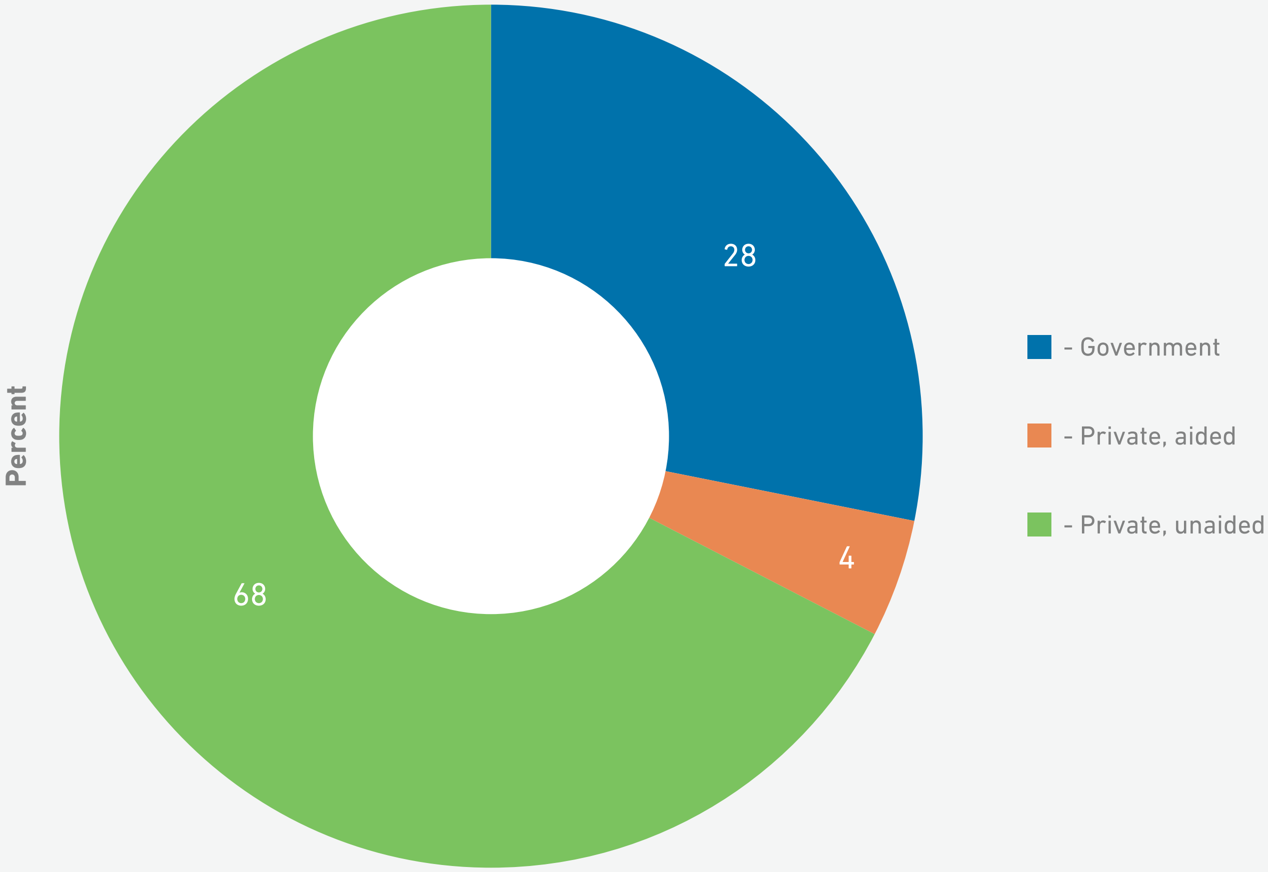


Exhibit 8: Targeted studies in India, Ghana and Nigeria show that 72 percent of surveyed households among the urban poor rely on private schools for their education. (Source: Tooley & Dixon, 2005)

SECONDARY EDUCATION

Secondary Education

4. Enrollment in secondary schools is significantly lower than that in primary schools

Secondary schooling—or other formal education—for youth, has not received the same level of global priority as primary education. Also, there is no formal definition of standard age group that defines youth.

Some institutions define youth starting as early as 12 years and others at 15 years; some define the end of youth at 19 years, while others extend the definition to include individuals as old as 24 years.

This section uses the age range typically associated with secondary school years: ages between 15 and 19. The global population of individuals in that age range is about 594 million (**Exhibit 9**). Of these, 103 million live in sub-Saharan Africa and another 173 million live in South Asia (UN, 2017)).

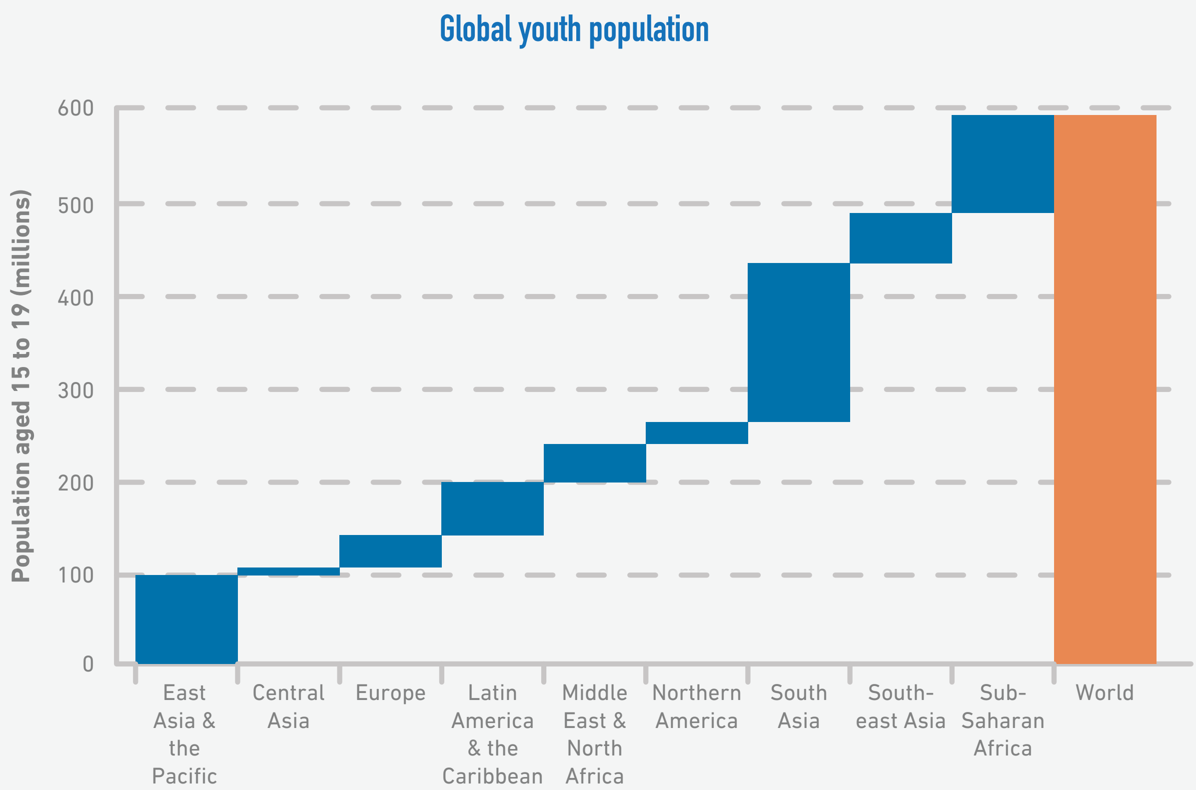


Exhibit 9: Globally, there are about 600 million youths in the 15 to 19 year age group. About 280 million of them live in South Asia and sub-Saharan Africa. (Source: UN, 2017)

During youth, the opportunity cost of going to school increases. At this stage, low income students enrolled in secondary school can start working to support their families. Going to school means students have to forego immediate income-earning opportunities for an education that may not position them for improving their livelihoods or income, especially in the near term.

Consequently, the relevance of secondary education—and how it can help these students increase their immediate and long-term income potential—is extremely important.

Public expenditure on secondary education, relative to primary education, differs vastly between countries and between regions.

Data shows there is significant variability in the ratio of primary to secondary expenditure between countries within a low-income region and between different low-income regions.

For instance, in South Asia, average government expenditure on secondary education is 79 percent of that on primary education; in sub-Saharan Africa, it is 188 percent. It is therefore difficult to draw a general conclusion about the overall quality of secondary education based simply on expenditure levels. However, metrics like student-to-teacher ratios suggest significant quality gaps (**Exhibit 10**).

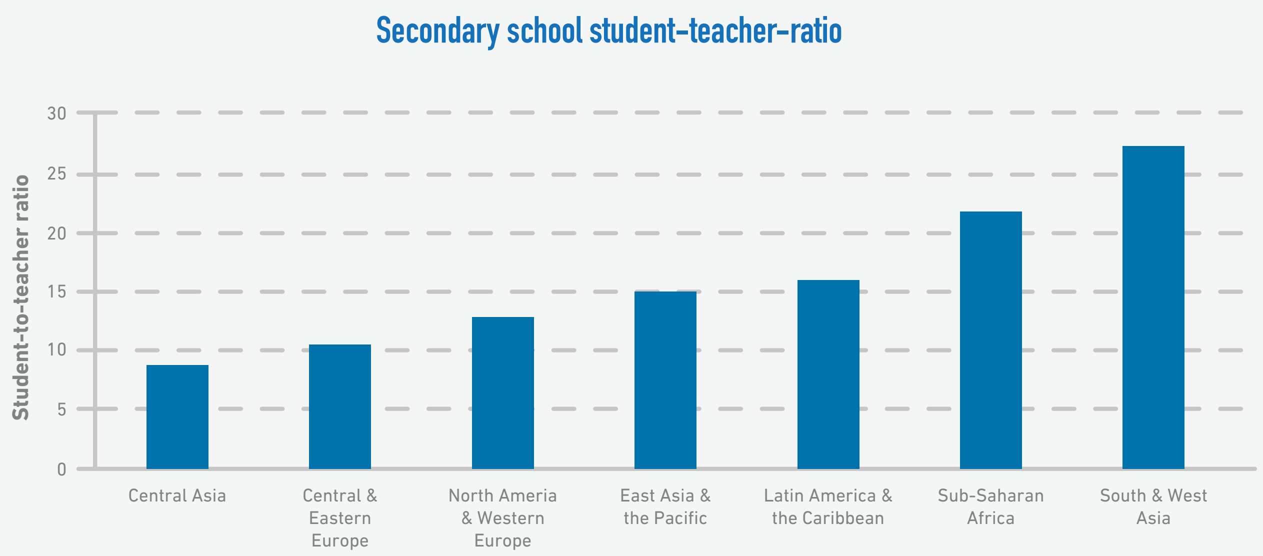


Exhibit 10: Secondary school student-to-teacher ratios in South Asia and sub-Saharan Africa are much higher than in other parts of the world—this likely reduces the overall quality of education. (Source: UNESCO, 2018)

Perhaps the most significant and telling statistic about youth education in developing countries is the drop in enrollment rates between primary and secondary education, as shown in **Exhibit 11**.

In sub-Saharan Africa, secondary enrollment is 32 percent, a drop of 46 percentage points compared to primary enrollment; in South and West Asia, secondary enrollment is 58 percent, a 32 percentage point drop from primary enrollment (UNESCO, 2018).

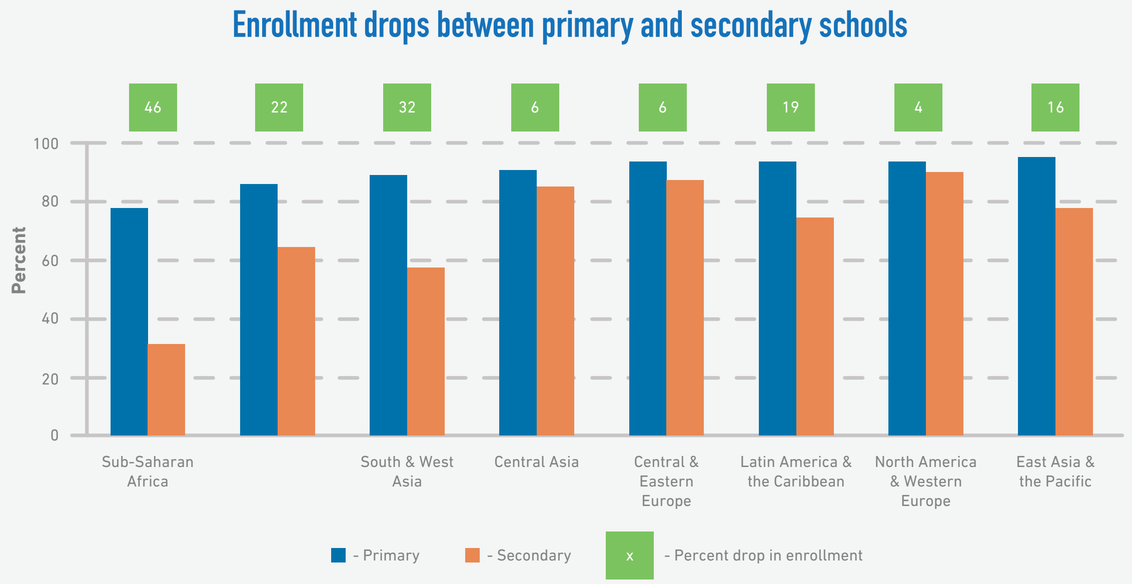


Exhibit 11: A significant number of students in sub-Saharan Africa and South Asia, who receive primary education, do not pursue secondary education. (Source: UNESCO, 2018)

5. The gender gap is more pronounced at secondary school level

As girls enter youth, many societal challenges begin manifesting themselves. These challenges have been discussed in detail in the Gender Equity chapter.

As **Exhibit 12** shows, the percentage of enrolled secondary students who are female drops from 48 to 46 in sub-Saharan Africa and from 49 to 47 in South and West Asia (UNESCO, 2018).

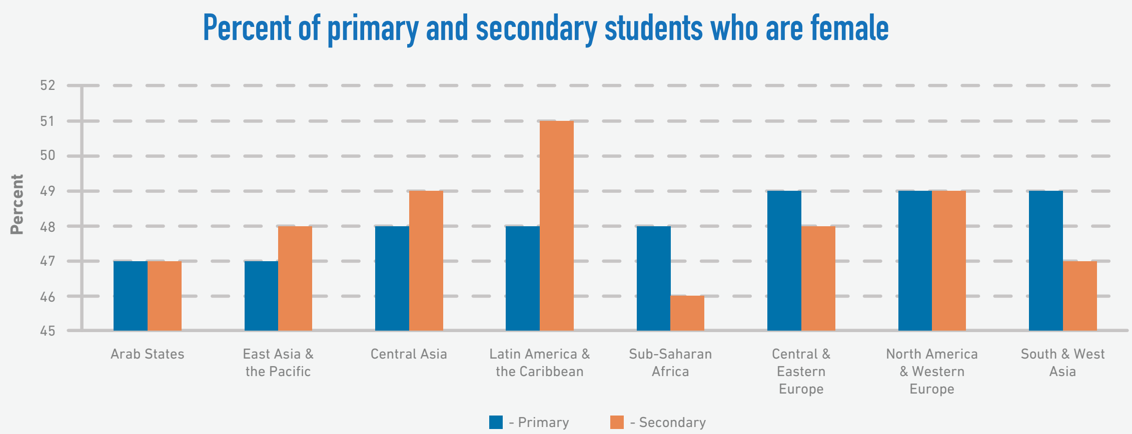


Exhibit 12: While the gender gap in primary education is minimal, it begins to grow in secondary school, in both sub-Saharan Africa and South Asia. (Source: UNESCO, 2018)

6. The role of private schools is more prominent in secondary education

The families of middle- and upper-income students in developing countries often choose to pay higher fees and have their children attend private secondary schools.

What is interesting, however, is that a large number of students even at the lower end of the income spectrum, appear to prefer private schools (Tooley & Dixon, 2005; Tooley, 2009). As **Exhibit 13** shows, a drastically higher number of students in sub-Saharan Africa and South Asia attend private institutions at the secondary school level than the numbers who attended private primary schools (UNESCO, 2012).

Percentage of students attending private schools

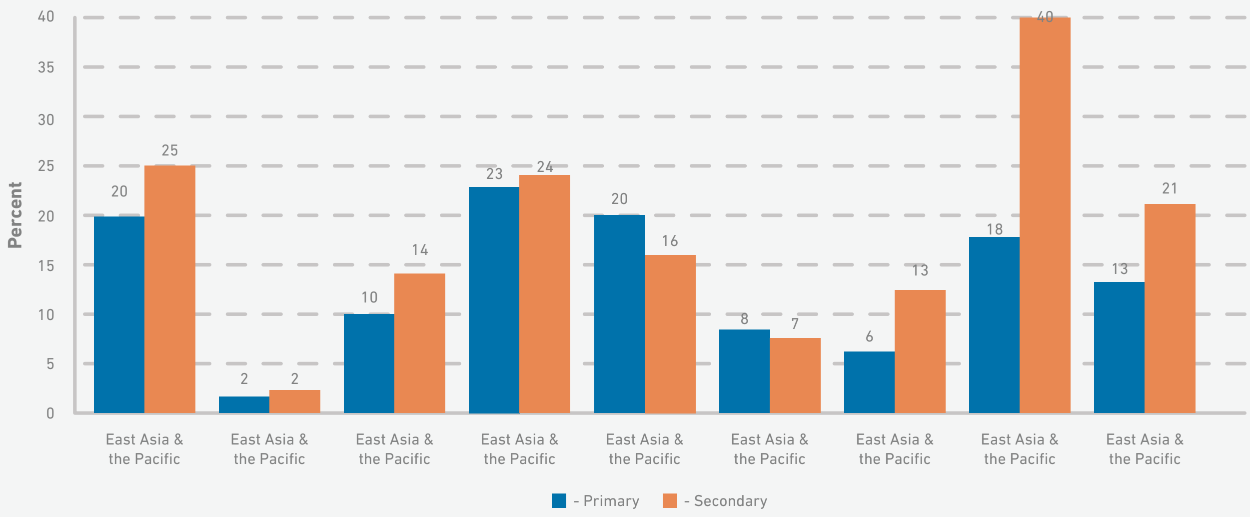


Exhibit 13: In sub-Saharan Africa and South Asia, there is a significant increase in the percentage of students who go to a private school at the secondary level when compared with the primary level. (Source: UNESCO, 2012)

7. Technical Vocational Education and Training (TVET) programs are gaining momentum as alternatives, or complements, to traditional secondary school education

Traditionally, secondary schooling curricula have emphasized preparation for higher education, focusing on topics like science, mathematics and literature. Recently, there has been a trend towards improving the employment prospects of secondary school graduates, leading to noticeable growth in TVET programs.

TVET programs typically have three components (UN, 2011; Leke, et al., 2010; Alemu, 2012):

1. General life and workplace skills, such as financial literacy and workplace etiquette
2. Training for jobs in specific industries, such as plumbing, furniture making, and various other trades
3. Entrepreneurship training, so that individuals can build their own businesses.

Examples of programs that offer different combinations of these components include: Junior Achievement Worldwide (which, through affiliates like INJAZ Al-Arab, relies on community volunteers from various professions to train and mentor youth using a standardized curriculum), Fundacion Paraguaya (which focuses on entrepreneurship, supported by microfinance), Go For Gold (a program in South Africa, which prepares graduates for employment in the construction sector), Aflatoun (which helps teenagers learn financial literacy and entrepreneurship through a learning-by-doing model) and the African Leadership Academy (which incorporates aspects of African History, leadership development and entrepreneurship in a standard secondary school curriculum).

TVET is a recent trend, however, and very few secondary schools in developing countries incorporate TVET into their formal secondary education curricula. In addition, only a small number of youths in developing countries enroll in formal TVET programs outside of secondary schools (Betcherman, et al., 2007). Note that TVET programs are not just for students of secondary school age, they can extend to students in older age groups, as well as to adults.

Out of the 256 million youth (ages 15 to 19 years) in sub-Saharan Africa and South Asia, about 62 million—based on an estimate of the percentage of students with access to trained teachers (UNESCO, 2012)—are enrolled in secondary schools of seemingly adequate (or superior) quality; 33 million are enrolled in schools of inadequate quality; about 5 million are enrolled in some formal TVET program outside of the secondary school system (although data on TVET enrolment is sparse); 95 million are literate but get little to no formal TVET or secondary education and the remaining 62 million are not literate enough to participate in any formal secondary level education even if it were accessible[2] (**Exhibit 14**). Of these 256 million youth, approximately 55 percent (141 million) are engaged in paid work (Betcherman, et al., 2007).

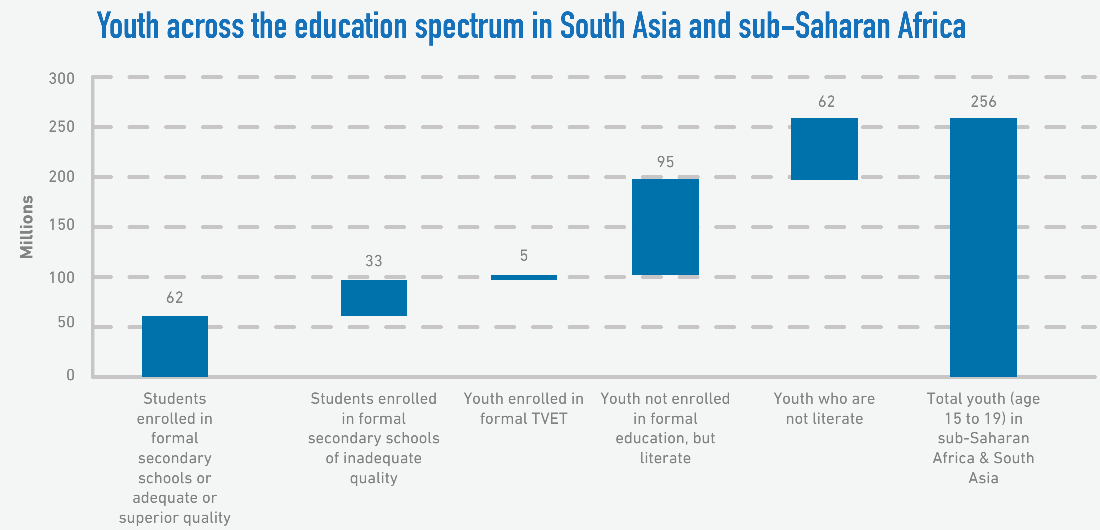


Exhibit 14: 95 million youth do not receive any formal post-primary education and only a small number (5 million) are enrolled in Technical Vocational Education and Training (TVET) programs. (Source: ITT analysis based on various sets of data)

[2]Note that statistics for education and literacy for youth 15 to 19 do not exist in any single source. These estimates are based on data available from multiple sources for different age ranges (chiefly from UNESCO) but normalized for the 15 to 19 age group.

TERTIARY EDUCATION

Tertiary Education

8. Tertiary enrollment in most developing countries is extremely low

In order to become competitive in the global economic ecosystem, it is essential for countries to have a large workforce with advanced education in a broad range of areas, such as engineering, the sciences, medicine and business management.

The most salient fact about post-secondary or tertiary education in developing countries is that a very small portion of the population participates in it. Tertiary enrollment in both South Asia and sub-Saharan Africa is extremely low (UNESCO, 2018). The enrollment rate among women and men in sub-Saharan Africa is 8 percent and 10 percent respectively and in South Asia enrollment is 24 percent for women and 25 percent for men (**Exhibit 15**).

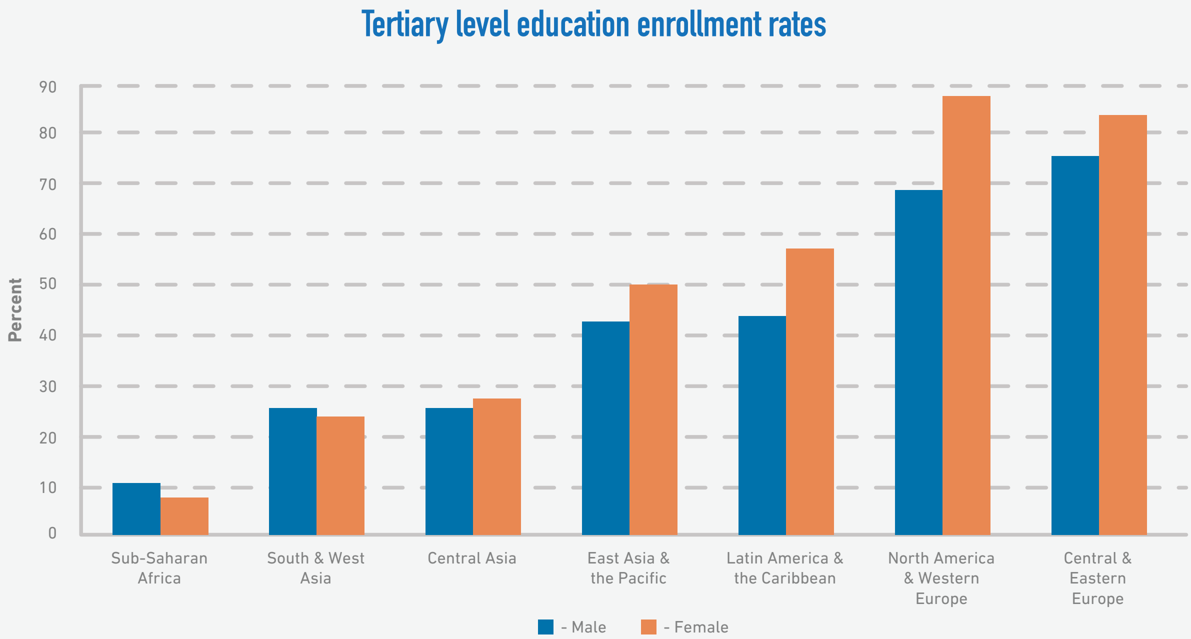


Exhibit 15: Across both genders, tertiary enrollment in sub-Saharan Africa and South Asia is a fraction of that in industrialized countries (Source: UNESCO, 2018).

9. The majority of college students in developing countries are enrolled in public institutions

In most developing countries, youth with secondary schooling generally have two educational tracks to follow: a three- or four- year undergraduate program provided at colleges and universities, or a post-secondary TVET program.

The latter are typically small and fragmented, can vary in duration from a few months to two years and provide education at a level somewhere between secondary-level TVET and undergraduate degrees.

Currently, the majority of students receiving undergraduate education in developing countries are enrolled in public universities (World Bank, 2000).

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The latter are typically small and fragmented, can vary in duration from a few months to two years and provide education at a level somewhere between secondary-level TVET and undergraduate degrees. Currently, the majority of students receiving undergraduate education in developing countries are enrolled in public universities (World Bank, 2000).

10. The focus of tertiary education in Africa is on humanities and social sciences, more than on technical areas like engineering and medicine; this is at odds with employment prospects

Over the past two decades, South Asia's largest country and economy, India, has witnessed considerable economic growth. By many accounts, this has been powered by the large technically trained workforce and a dramatic increase in the number of institutions providing relevant tertiary education (Dinakar, 2007; CLSA, 2008).

This phenomenon, however, is not uniform across income groups in South Asia; it is even less promising in sub-Saharan Africa (Chynoweth, 2012).

Exhibit 16 shows the academic disciplines in which college students in sub-Saharan Africa typically enroll. The social sciences (including business and law) and humanities (including the arts) account for 48 percent of all enrollment, education for 14 percent and the pure sciences for another 10 percent.

Only 6 percent study engineering, manufacturing and construction, another 7 percent are in health and medicine and only 3 percent are in agriculture (UNESCO, 2012). In order to be relevant to students and help them gain meaningful employment, the academic coursework offered will need to closely match the industrial sectors and functional areas with the greatest opportunity.

Exhibit 17 shows an illustrative analysis of these industries in Africa based on the intersection of the share of national economic growth and the multiplier factor. According to this analysis, the most attractive sectors are: agriculture and agribusiness, wholesale and retail, transport and telecom and financial services.

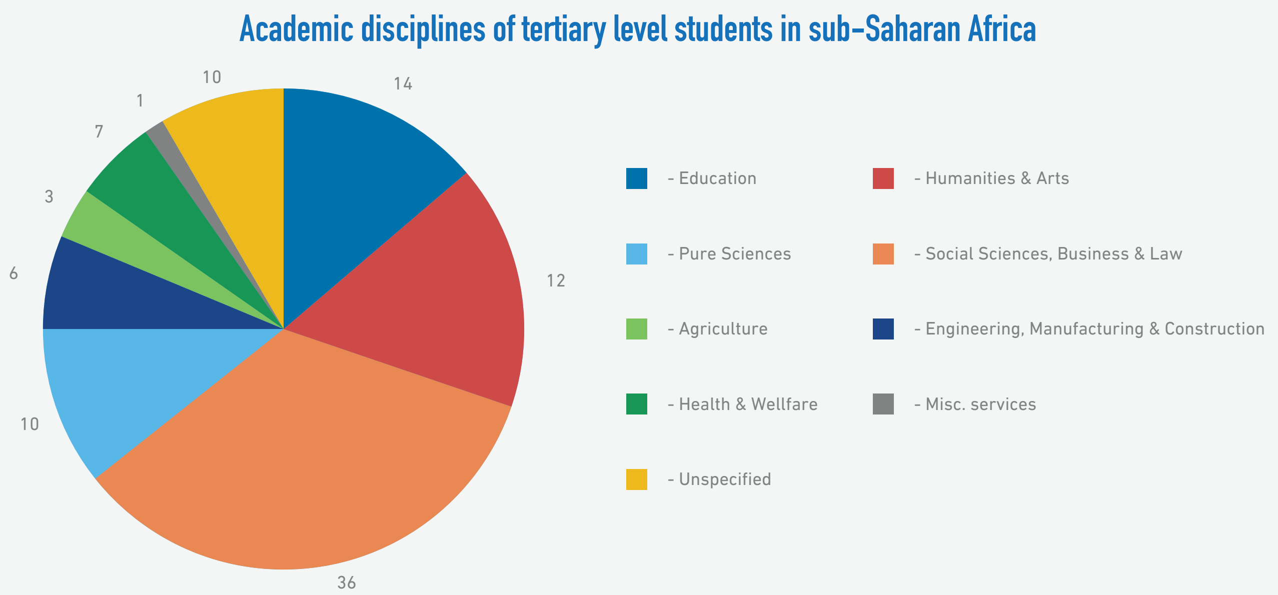


Exhibit 16: Almost 75 percent of students enrolled in tertiary education in sub-Saharan Africa focus on social sciences, 36 percent on business & law, 12 percent on humanities & arts, 14 percent on education and10 percent on the pure sciences. Only 6 percent are in engineering and related fields, 7 percent in health, and 3 percent in agriculture. (Source: UNESCO, 2012)

Industries in Africa with the greatest opportunity for future job placement

Ranked by share of recent economic growth versus employment multiplier

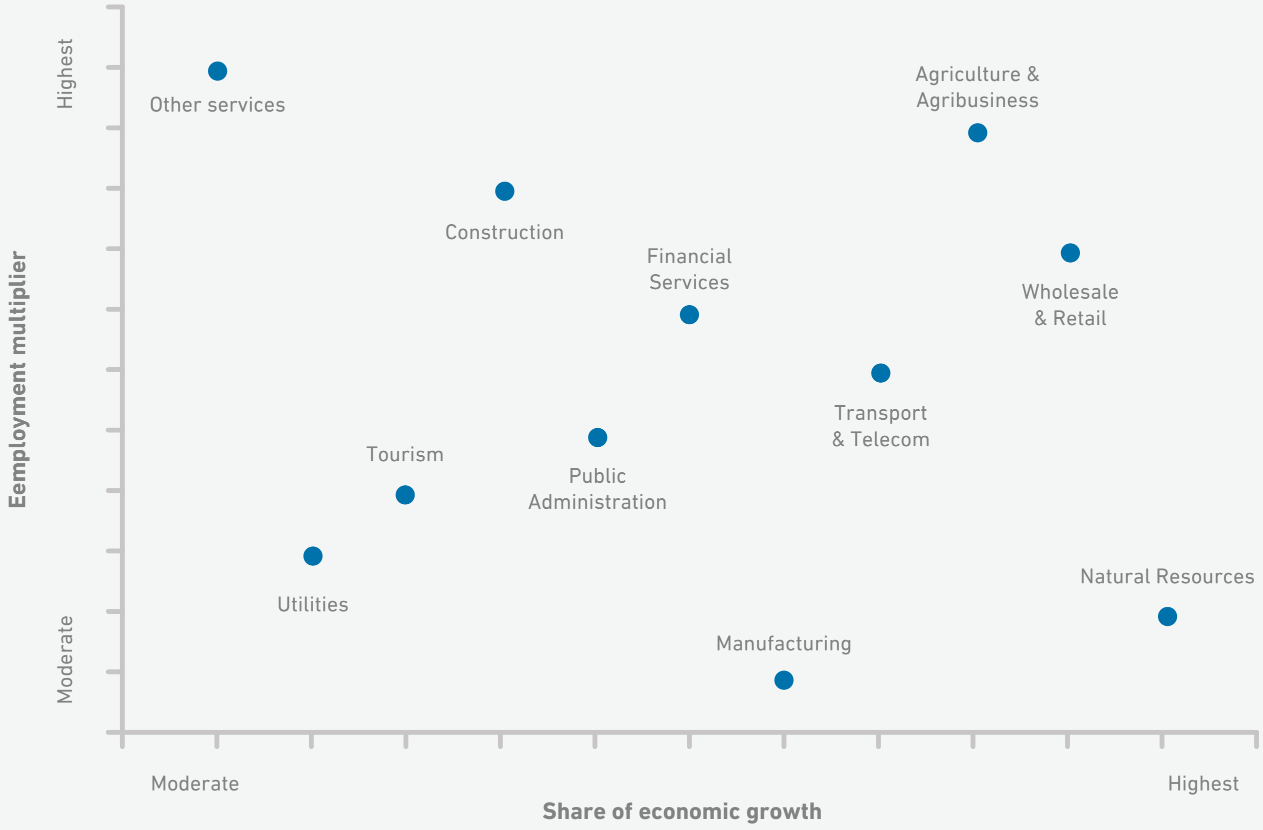


Exhibit 17: Illustrative analysis mapping industries based on their potential for creating local jobs along two dimensions. The agriculture and agribusiness and the wholesale and retail sectors offer the best opportunity, while the natural resources and manufacturing sectors are growing strongly without creating many local jobs[3] (Source: ITT analysis)

Cross-referencing the tertiary enrollment data (**Exhibit 16**) against the industries which offer the best opportunities for employment (**Exhibit 17**) in Africa, shows that fewer than half of the students who invest in tertiary education in sub-Saharan Africa receive the education they need to meet the human capital needs of the industries that offer the best job prospects (**Exhibit 18**).

Not surprisingly, many multinational corporations in Africa have trouble finding local talent to fill executive roles and seek expatriates from other countries (typically from the United States or from the European Union) to fill such roles (Chynoweth, 2012).

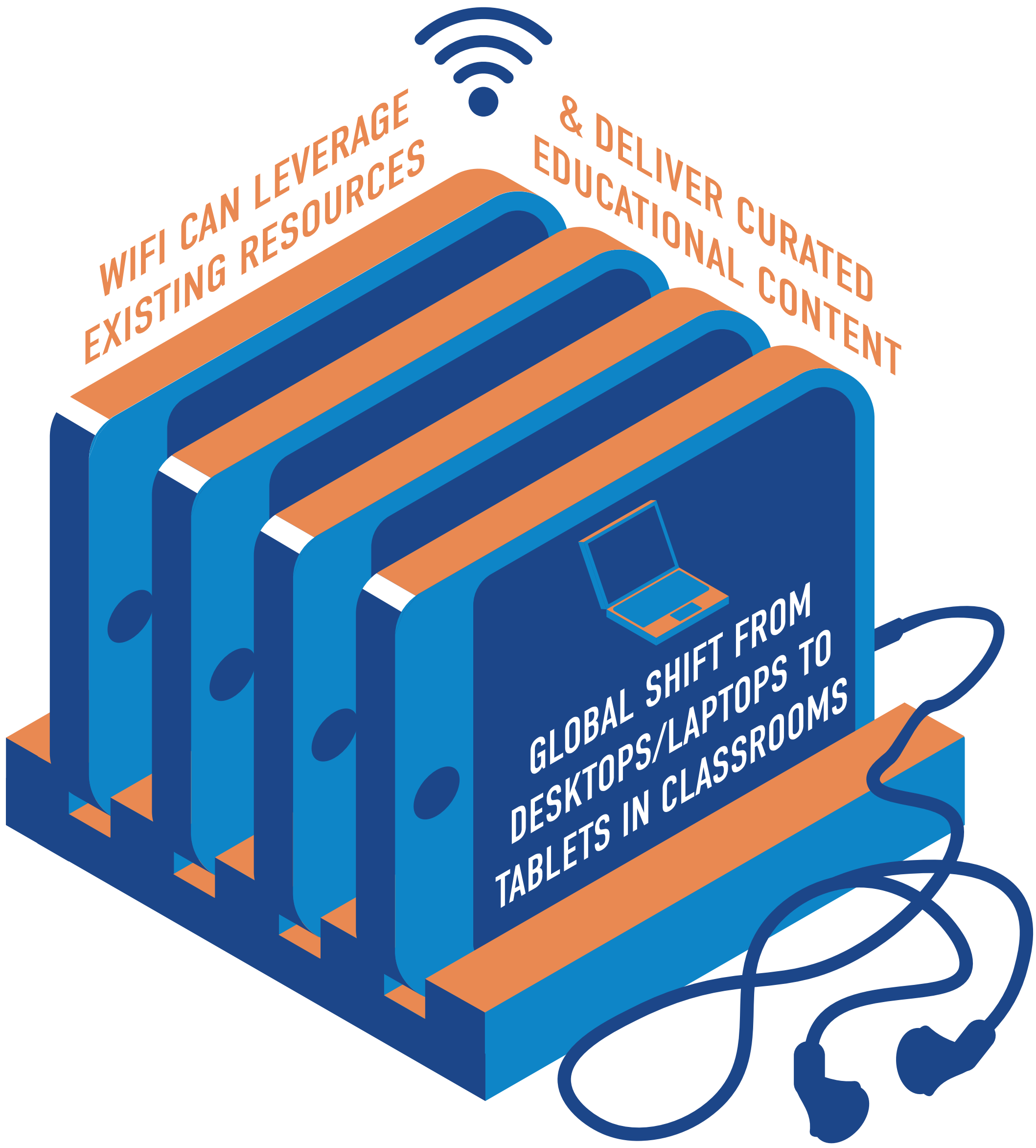
[3]This illustrative analysis uses incomplete data from multiple sources and is not meant to be the kind of rigorous assessment required for a comprehensive education policy.

Cross-reference of current tertiary enrollment in Sub-Saharan Africa against needs of high-potential industries

Assessment of how well the tertiary education system meets industry human capital needs

HIGH-POTENTIAL INDUSTRIES	ACADEMIC DISCIPLINE OF ENROLLED STUDENTS							
	Education	Humanities & Arts	Social Sciences, Business & Law	Pure Sciences	Engineering, Manufacturing & Construction	Agriculture	Health & Wellfare	Misc. services
Agriculture & Agrubusiness	Low	Low	Medium	Low	Low	High	Low	Low
Wholesale & Retail	Low	Low	High	Low	Low	Low	Low	Medium
Transport & Telecom	Low	Low	Medium	Low	High	Low	Low	Low
Financial Services	Low	Low	High	Low	Low	Low	Low	High
Construction	Low	Low	Low	Low	High	Low	Low	Low
Public Administration	Low	Low	Medium	Low	Low	Low	Medium	High
Natural Resources	Low	Low	Low	Medium	High	Low	Low	Low
Tourism	Low	Low	Low	Low	Low	Low	Low	High
Manufacturing	Low	Low	Low	Low	High	Low	Low	Medium
Utilities	Low	Low	Low	Low	Medium	Low	Low	Medium
Health Care	Low	Low	Low	Low	Low	Low	High	Low

Exhibit 18: Tertiary education systems in sub-Saharan Africa do not appear to be geared toward the human capital needs of the industries that offer the highest opportunities for employment. (Source: ITT analysis)



DIGITAL TECHNOLOGY IN EDUCATION

DIGITAL TECHNOLOGY IN EDUCATION

11. There is a proliferation of digital devices for improved content delivery in schools

Within the last decade there has been a large push to place educational tablets in classrooms around the world. In countries like Brazil, Indonesia, Malawi and Kazakhstan, the governments have mandated large-scale purchase and deployment of "tablet-as-textbooks", first on a pilot and then an at-scale basis (Gondwe, 2013; Mari, 2013; Cosseboom, 2015). The sudden increase in the popularity of tablets is influenced by a variety of technological, economic, cultural and aesthetic factors.

There has been a significant global shift from desktops to laptops and finally tablets within the last decade. This trend has influenced educational practices in emerging economies. From a political standpoint, many countries have emphasized a simultaneous push for in-country innovation and manufacturing to build the necessary devices to service this need.

As a result, local innovators are developing technology and content to compete with internationally acclaimed brands, such as Samsung and Apple. The tablet's ease-of-use, resemblance to textbooks and significantly lower cost than laptop and desktop computers have all enabled this movement to take shape (World Bank Blog, 2015).

One example of the potential of a "smart textbook" led approach to content delivery can be see in Bridge Academy schools in India, Uganda, Kenya and other countries around the world.

The wireless teacher guides, and tablet-based customized content delivery, cover some of the critical features highlighted above. The innovation is focused both on supporting students as well as providing state-of-the art teacher training support through the tablets and digital platform.

Another example is Zaya Labs, an Indian technology organization, which has developed "SchoolWiFi" systems to beam secure, digital content into smartphone, tablet and personal computer devices in underserved government and private schools.

With student performance tracking, content specific to classes and regions, supporting material for teachers and support systems both offline and online, School WiFi offers an innovative means to leverage existing resources while also delivering advanced and curated content. Other similar models, such as Omega Schools in Ghana and APEC schools in Philippines, use technology to varying degrees to make technology-enabled content delivery more effective.

That said, the innovation is facing a number of the key challenges listed earlier in the chapter. For instance, the Ugandan government is cracking down on the 60 schools that Bridge Academy set up around the country, citing non-adherence of national guidelines and use of unrecognized teachers in classrooms.

From a technology perspective, the tablet-based content, although effective, could still be developed significantly in trying to cater to a broad spectrum of age-groups and learning levels, as is often the case in under-resourced classrooms.

12. Data analytics, artificial intelligence and machine learning are emerging technologies with potential to improve education

The various infrastructural, policy, behavioral and workforce issues that plague the education systems of emerging countries are unlikely to be solved through technology innovations alone. This includes such breakthrough areas as artificial intelligence (AI) and machine learning. Given the broad resource constraint in underserved areas, the likelihood of radical innovations such as robots replacing human teachers is very small (Edwards, et al., 2018).

That said, there are a number of second order, support service initiatives that machine learning and AI-based algorithms could enable:

- Incentives for families (such as conditional cash transfers) to invest in children's education (a la Brazil's Bolsa Familia program). Robust data and analytics can be very useful in designing optimal programs and incentive packages.

- Incentive programs for schools and teachers, closely linked to educational outcomes, investment in teacher training and other quality and access improvements. As with incentives for families, robust data and analytics can be very useful in designing optimal programs and incentive packages.

- Student loan programs, especially for vocational training and entrepreneurship. Reliable data and analytics can help understand the success rates of various training programs and shape loan and incentive programs accordingly.

Similarly, as more data is captured and is available for analysis, smart textbooks can be even more powerful if supported by a robust AI-based algorithm as the backbone. AI, machine learning and big data are discussed further in the Emerging Technologies chapter.

KEY CHALLENGES

Primary Education

There are a number of reasons why such a large number of children in lower income countries do not receive adequate education at the primary school level. The entire spectrum of challenges can be split across two overarching issues. First, the lack of access to an education. Second, the quality of education.

1. Lack of access to education is driven by seven factors

- **There simply aren't enough schools**
  Many remote, sparsely populated and isolated areas simply do not have schools within reasonable reach. Public school systems in poorer countries are not adequately funded, leading to an overall lack of infrastructure. Annual public spending per student in sub-Saharan Africa and South Asia is $331 and $396, respectively, a small fraction of the thousands of dollars per student spent in higher income regions (**Exhibit 19**).

Furthermore, only a portion of that budget actually goes to directly educating children while the rest of it goes toward paying for system overhead (for example, the education ministry, administrators, etc.). Even as there is limited data to show the actual distribution of funding between direct instruction-related activities and system overhead, the dismal condition of many schools is indicative of the allocation and distribution of funds.

Many primary schools in Sub-Saharan Africa do not even have basic amenities, such as electricity (only 35 percent), potable water (44 percent) and toilets (61 percent) (UNESCO, 2018) (**Exhibit 20**). South Asian primary schools are somewhat better equipped, with 51 percent with electricity, 84 percent with water and 82 percent with toilets. In addition, there is a severe lack of textbooks; 2.6 and 2.3 students, respectively, have to share a single textbook for Mathematics and Reading. It is important to note that in these lower income countries, there are also examples of school systems, which appear to provide quality education for $100 or less per year per student (Kristoff, 2010).

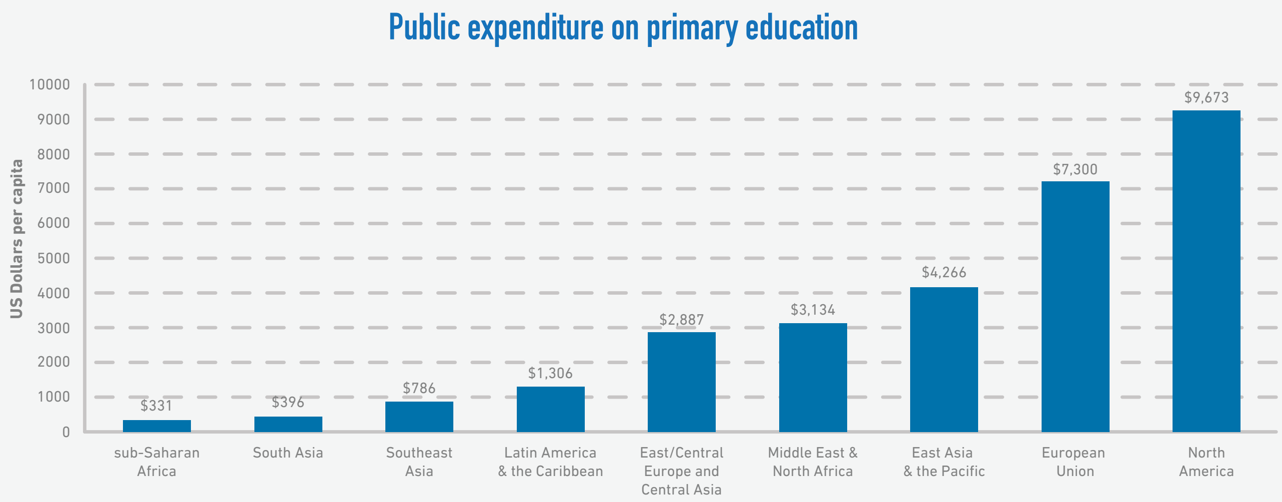


Exhibit 19: Government expenditure on primary education in sub-Saharan Africa and South Asia is a small fraction of that in wealthier countries. (Source: UNESCO, 2012)

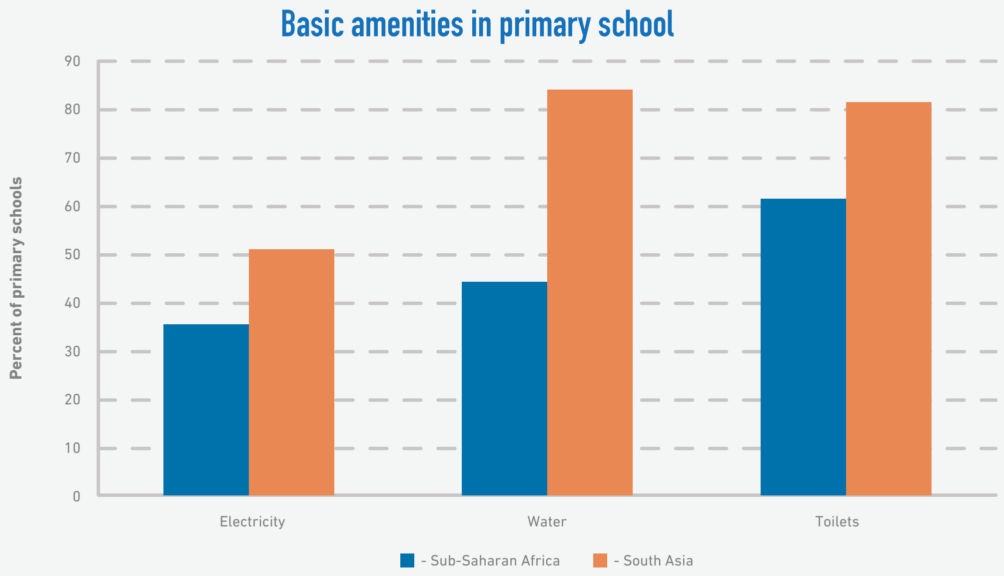


Exhibit 20: Most primary schools in sub-Saharan Africa and many schools in South Asia do not have basic amenities like electricity, potable water and toilets. (Source: UNESCO, 2018)

- **There is a low (perceived or actual) value of education, especially compared with the opportunity cost of attending**
  The relatively low levels of financing notwithstanding, there is strong evidence suggesting that even the available funds are not spent efficiently or effectively in many countries (Lutyens, 2011; Tooley, 2009) leading to schools of very poor quality. As a result, many parents do not find schooling attractive or useful in any way and simply pull their children out of the schools.

- **A large number of children cannot afford school and are engaged in child labor**
  Globally, more than 300 million children between the ages of 5 and 17 are engaged in employment (ILO, 2010a), most of whom work to financially support their families. Child labor is a significant contributor to children being out of school. A study conducted across a number of African countries (Gibbons, et al., 2005) found that an average of 21 percent of out-of-school children are engaged in labor (**Exhibit 21**).

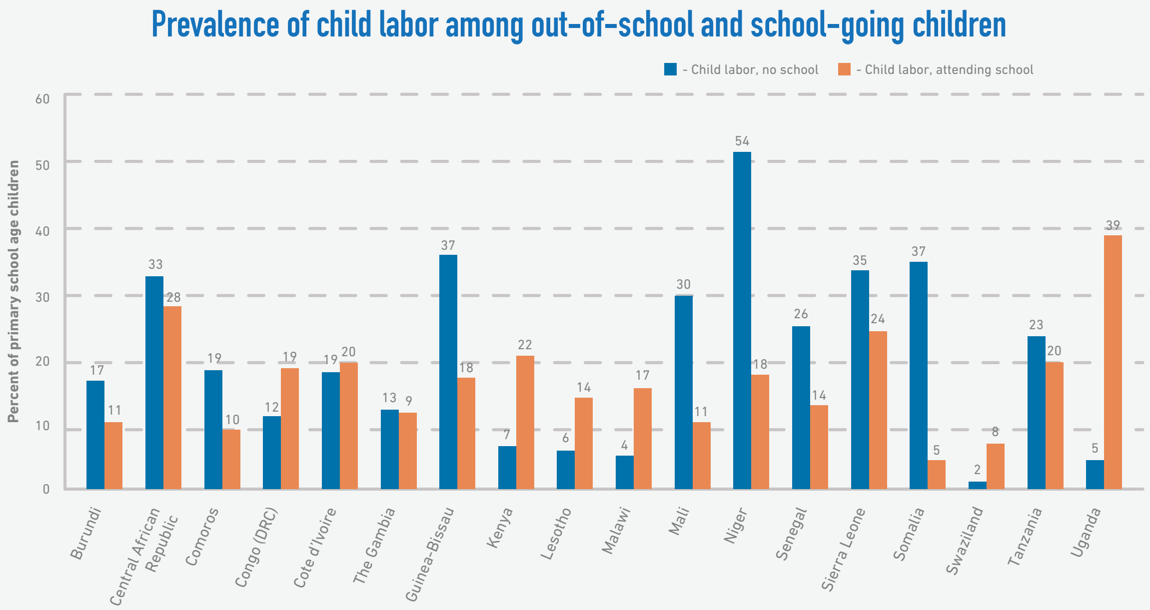


Exhibit 21: A study across a number of African countries shows approximately 21 percent of out-of-school children are engaged in child labor. (Source: Gibbons, et al., 2005)

- **Minority groups are often excluded, intentionally or through neglect**
In many countries with high ethnolinguistic fragmentation, many minority groups find themselves disenfranchised and their children deprived of educational opportunities. This can happen either because of the government is passively underinvesting in particular geographies where the ethnic minorities are concentrated or because of active discrimination (IRIN, 2011).

- **Some cultures do not value education**
Some communities have traditionally not considered participation in formal education a priority. For example, throughout South Asia, which has one of the highest out-of-school populations in the world, formal education of girls is discouraged (Latif, 2000). In addition, nomadic populations across the world also tend to de-prioritize formal education (Carr-Hill, 2005).

- **Poor health and nutrition can prevent children from going to school**
While there is limited data on how many children stay out of school because of ill health, a number of programs (NUEPA, 2008; Chege, 2012) have found that providing hot, nutritious meals to children on school-days markedly increases their participation in schooling.

- **There are a number of hurdles specific to some population segments**
The challenges described above tend to affect children living in different contexts, and from different population segments, in different ways.

Remote and hard-to-reach areas
For children who live in remote or hard-to-reach rural areas, access is a core concern. The majority of people in sub-Saharan Africa and South Asia live in rural areas. Less than 20 percent of the roadways in these areas is paved (World Bank, 2011).

These areas typically have a low density of schools, few qualified teachers (with limited incentives for qualified teachers from urban areas to relocate), little in the way of transportation to help students reach schools in nearby towns and poor local governance to oversee the quality of education. There is also a high incidence of child labor in rural areas. More than 60 percent of all children work in agriculture, two-thirds of whom work, unpaid for their families (ILO, 2010a).

Urban slums
The situation is markedly different for children living in urban slums. Urbanization is a growing phenomenon in sub-Saharan Africa and South Asia. Children in poor, urban settings face a range of issues, which are different from issues poor children face in rural settings (Mander, 2009).

People living in urban slums are often separated from their communities and (typically informal but traditional) social safety nets. The physical environments in which the urban poor are forced to live in are more vulnerable (with few assets and little security for the assets they do own) and degraded than those in rural areas. Because urban economies tend to be more monetized than rural economies, the urban poor find themselves needing to pay cash for many more things than their rural counterparts.

The urban poor also tend to be subject to far greater levels of violence from state actors (such as the police) as well as criminals. Children are often also subjected to many forms of exploitation or violence, with many of them being forced to beg. Children of first-generation migrants to urban areas can be even worse off since they do not have a permanent place of residence or necessary documentation.

This indirectly excludes them from being able to access whatever little they otherwise can in the form of state-provided education and healthcare facilities. All of this put together, creates a very precarious environment for children to live and grow in, let alone seek an education in.

Refugee and displaced populations
Even more vulnerable are children among refugee and internally displaced populations. Refugees and displaced people living in refugee-like situations do not have access to many services provided to populations living under more normal conditions. They are far removed from their own homes and assets and often do not have a clear legal status where they live (whether in camps or urban settings).

The number of displaced children has increased significantly in recent years (**Exhibit 22**). As of 2017, there were about 10 million children who were displaced, including refugees, asylum seekers and internally-displaced persons (UNHCR, 2018). In 2017, 61 percent of refugee children were enrolled in primary school, versus 89 percent globally. At secondary level, 23 percent attended school, compared to 66 percent globally.

This means nearly two thirds of refugee children who attend primary school do continue to secondary school. Since refugees usually do not have a steady source of income, most of the services they (and their children) receive, are provided by charitable agencies and basics like shelter and food take precedence over education.

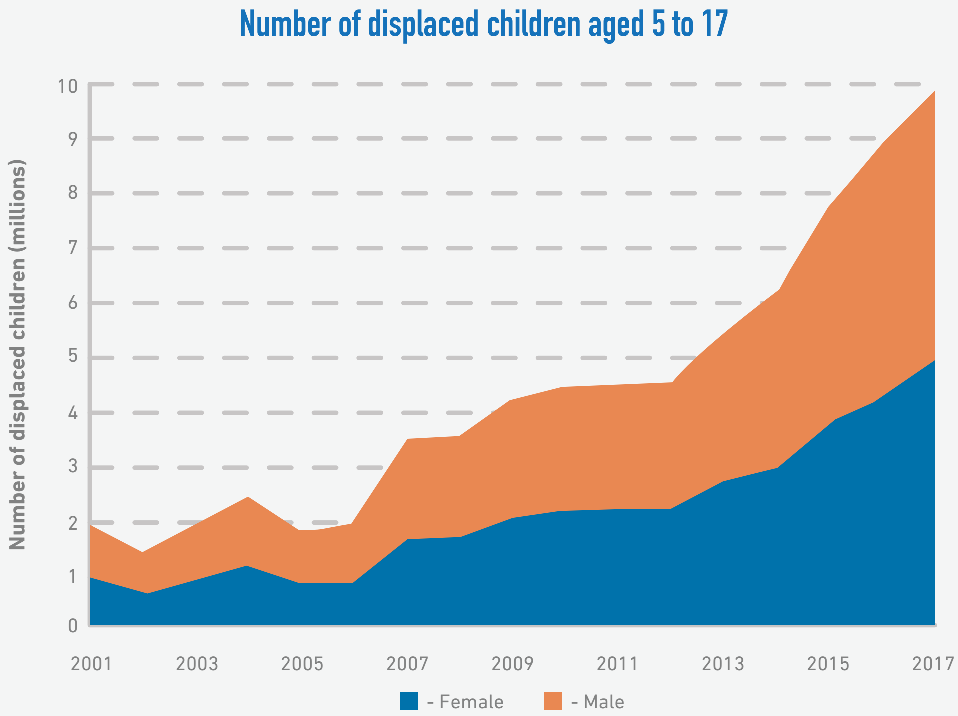


Exhibit 22: The number of displaced children has increased significantly in recent years. (Source: UNHCR, 2018)

2. Quality of education remains poor and there is limited emphasis on outcomes

The gains made through the increasing rates of access and enrollment are undermined if the quality of teaching is subpar, schools are mismanaged and learning outcomes achieved by children fall below minimum required age-appropriate benchmarks. A few factors play a central role in the overall quality of education that children receive.

- **There aren't enough well-trained teachers**
  As **Exhibit 5** and **Exhibit 6** illustrate, the required minimum qualifications for primary school teachers in most developing countries are low and there is very limited on-the-job training once they begin teaching.

- **Accountability and incentives are often not aligned with actual education outcomes**
  A commonly cited problem, especially in government-run school systems, is that neither the school systems nor the teachers are accountable for actual education outcomes.

  Studies have found that the root causes for this lack of accountability are the excessive power of teachers' unions and the general bureaucratic challenges that any large public system faces (Tooley, 2009; Lutyens, 2011). In addition, parents with low-income are often not in a position to evaluate the quality of education and rely on external indicators, such as cleanliness of the buildings and toilets.

- **Teachers do not have adequate tools for instruction**
  Teachers need a range of tools—building blocks, maps and a variety of books, photographs and ideally computers—to offer the breadth and depth of knowledge children require to be competitive in the long run. As **Exhibit 20** shows, many schools across Africa do not even have basic amenities, such as electricity, potable water and toilets (UNESCO, 2018). There are also severe shortages of textbooks and other school supplies. Tools, such as computers, are available only to students attending the most elite schools.

Secondary Education

Globally, most hurdles that make primary education for the poor challenging also apply to secondary education. In addition, there are four hurdles specific to secondary education.

3. There can be a high opportunity cost to secondary schooling

152 million youth are from households below the poverty line of $1.25 per day (ILO, 2010b). For youth living in such or even somewhat better conditions, there can be a significant opportunity cost to attending school. Income generated by these youth often constitutes a significant portion of their families' aggregate income. Not surprisingly then, 43 percent and 54 percent of youth in South Asia and sub-Saharan Africa, respectively, work to support themselves and their families (Betcherman, et al., 2007).

4. Secondary education is often not perceived as adding value

Almost by definition, the job market in low income countries is meager. Almost a quarter of unemployed people in sub-Saharan Africa and South Asia have a secondary education (ILO, 2010b). This creates a disincentive for investing time in secondary education, especially considering the opportunity cost of forgone income. For most of these youth, formal secondary level education is not viewed as relevant for dramatically increasing incomes.

5. In the past, the global community has not emphasized youth education

There has not been as much emphasis—in global or national agendas—on youth education as there has been on primary schooling. For example, the Millennium Development Goals, enacted in 2000 for achievement by 2015, aimed for universal primary education but did not consider secondary education.

6. Gender discrimination grows, as girls enter youth

Gender-based discrimination begins to play an increasingly major role as girls enter adolescence and early youth. Traditional practices force many young women from low income families to marry or take on other household responsibilities including caring for younger siblings or the elderly.

Tertiary Education

The challenges of providing affordable, quality and relevant tertiary education to low-income populations in developing countries are an extension of the challenges in secondary education.

7. There is a very high opportunity cost to higher education

Low-income individuals older than 19 face an extremely high opportunity cost of spending years in school rather than earning a living.

8. Curricula are not aligned with employment opportunities

The majority of colleges and universities do not prepare students for the demands of the job market with respect to growth industries, or functional specialization. As a result, many of the most attractive roles in the private and NGO sectors are occupied by expatriates from industrialized countries.

9. There are not enough jobs

The economies in most countries in sub-Saharan Africa are not strong enough to absorb a large number of graduates with advanced degrees. Consequently, there are few clear incentives for individuals to invest in higher education. This, in turn, creates a vicious cycle with the two aforementioned challenges.

SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

Solving the broad problem of education requires fundamental, systemic improvements on three key fronts. First, we require proper infrastructure—construction of a large numbers of schools with appropriate amenities. Second, we need to invest in human capital—training and certification of all teachers. And third, there needs to be policy changes to ensure the system is accountable to students and parents and to ensure the curricula are relevant.

In all likelihood, achieving this will require a combination of both private and public systems, with the former leading the charge in innovation and the latter ensuring universal and equitable access. While the role of technology may not be central here, one breakthrough can play a powerful part in achieving dramatic improvements in overall access to quality education and learning outcomes.

Breakthroughs:

1	2	3	4	5	6	7	8	9	10
11	12	13	14	15	16	17	18	19	20
21	22	23	24	25	26	27	28	29	30
31	32	33	34	35	36	37	38	39	40
41	42	43	44	45	46	47	48	49	50

18 Smart electronic textbooks that dynamically adapt content for different skill levels, languages and other user specific needs

While smart devices like touchscreen phones and increasingly powerful tablets are well on the path to becoming as ubiquitous as the basic mobile phone, digital educational content has not kept pace. There are isolated pockets of excellent content (for example, videos by the Khan Academy), but there is very little in the way of curated and structured material which is suited to country-specific curricula for various stages of education and ready for use off-the-shelf. Grade-specific 'smart' electronic textbooks with well-designed applications can be a very powerful way of compensating for systemic gaps in infrastructure, human capital and policy. Important features include:

• Digitized textbooks across all disciplines, based on the curricular standards established by existing school systems (such as international standards like A-level/O-level and International Baccalaureate and national standards like ICSE or CBSE in India)

• A repository of regularly refreshed supplementary material that may be curated from 'best of' writings, recordings of experiments, instructional videos, research papers and recordings of historical or public events

• A dynamic, interactive, personalized, and adaptive learning mechanism in which students' performance on problem sets determines the pace of content and learning, using a rules engine, which inserts introductory material and remedial problem sets, as required

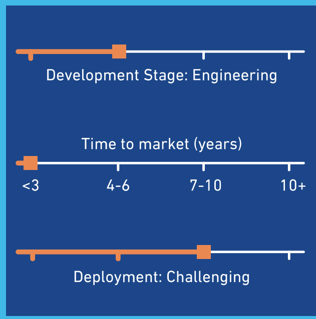
• A peer-to-peer 'wiki' collaboration platform, which allows students and teachers to exchange ideas, engage in virtual Q&A and share relevant curated or created content, including local language and gender-inclusive content and videos

In principle, all ecosystem ingredients are already present to create such e-textbooks and various versions are available in industrialized markets. However, the control exerted by publishers and local school boards in markets like the United States appears to have contributed to the relatively slow emergence of disruptive innovations in content delivery. As a result, there are few platforms that can be immediately transplanted to a developing country context. Still, with targeted investment and collaboration we believe something like this should be market-ready within two to three years.

Meanwhile, tablet computers are becoming increasingly affordable and readily available. Tablets, and to a somewhat smaller extent, smartphones with touchscreens, offer the perfect platform through which such a breakthrough can be deployed on a large scale. Both devices have significant advantages over traditional keyboard-based computers, especially for children. Not only are they light, portable and very easy to carry (even by small children), their touchscreen interface makes them more intuitive to use.

Compared to keyboards, which require a certain literacy level and can be very cumbersome for children or other users who are unfamiliar with them, tablets are easy to interact with and handle.

Current State

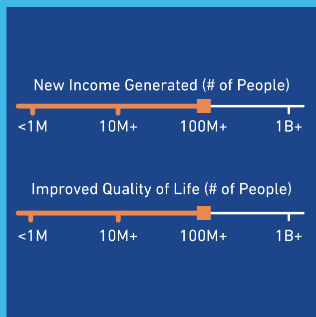


Associated 50BT Chapters

Education

SDG Alignment

Impact



Commercial Attractiveness

- **Attractive for industrialized markets (high profits)**
- Attractive for emerging markets (lower profits)
- Emerging markets potential; requires derisking (sustainable)
- Non-commercial (unprofitable)

Already existing, standard applications make it possible to access, and easily share, visually rich and dynamic content on the web. Utilizing built-in tools, applications and other programs, children can easily customize and share pictures they take or content they create. This creates a rich, highly personalized and empowering experience for children.

As technology advances, tablets will come with higher storage capacities, making them conducive for processing large amounts of data and content and—like personal computers and laptops—capable of storing individual and customized usage histories.

Although there is still a long way to go before tablets and smartphones can be considered affordable for the very poor, they are close to being affordable at a community level, so that they can be shared by groups of students in a school. The Digital Inclusion chapter discusses the prospects of truly affordable devices, and what it will take to achieve them.

Despite the momentum in the global information and communication technology revolution, there will be a number of challenges that smart textbooks will have to overcome once they are introduced to the market.

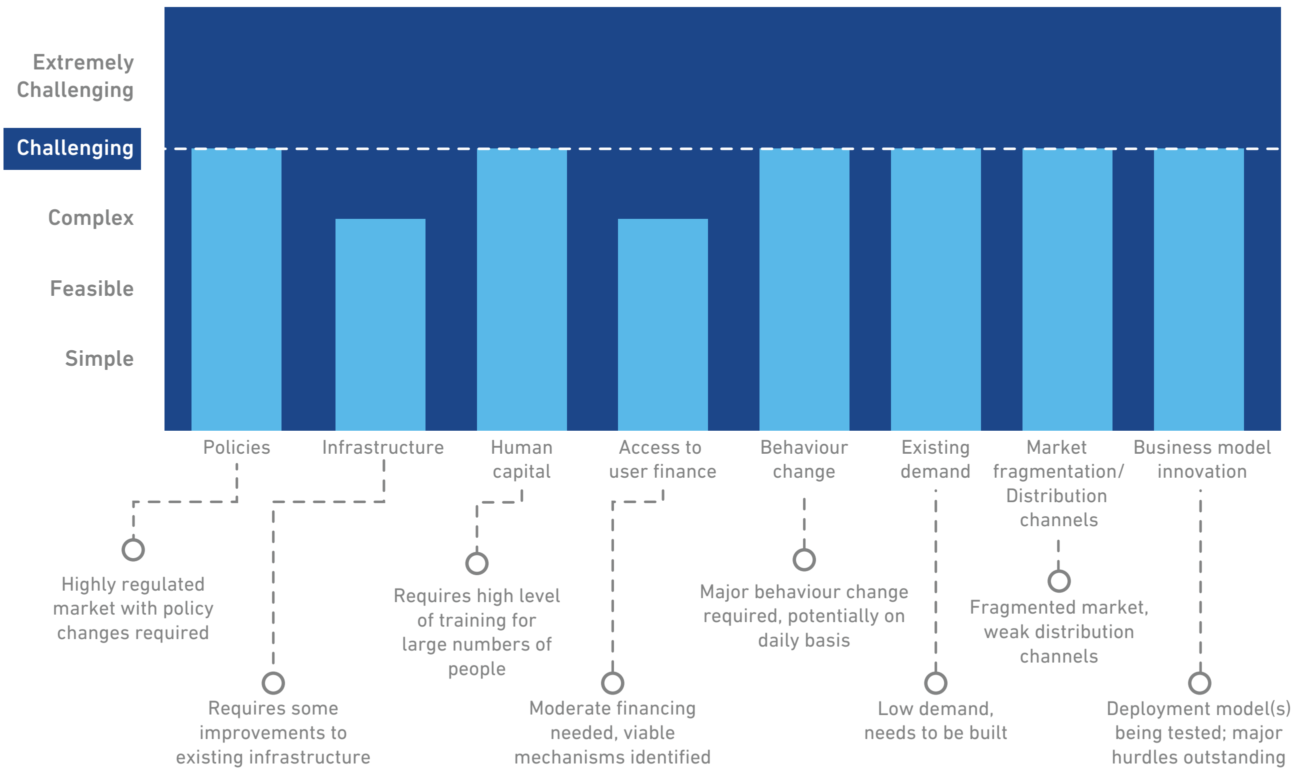
Educational ministries and school systems will need to recognize the value of such a technology and its compatibility with existing curricula.

Demand will need to be built with teachers and students, who will need to change daily behavior and learn to use devices effectively. Rapid adoption of mobile technologies suggests this is possible.

Some effort will be required to ensure the availability of electrical power (to charge the devices) and wireless connection. Despite the falling costs of tablet devices, financing will be necessary for lower income students. Even though school systems, especially public schools, operate through some form of centralized control, the market is still highly fragmented.

There is no business model precedent, and deployment models will need to very innovative to address all aforementioned hurdles. Considering all of the above factors, we believe that deployment will be CHALLENGING.

Breakthrough 18: Difficulty of deployment



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GENDER EQUITY

GENDER EQUITY

INTRODUCTION

It is fair to say that gender equity—defined as "a state wherein women and men are treated alike, in terms of rights, benefits, obligations and opportunities" (UNESCO, 2000), by custom, by law, and in practice—does not exist.

Not in wealthy countries and certainly not in developing countries. The root causes are many: religious and cultural beliefs, the persistence of societal stereotypes and more so deep-seated existence of a male-dominated society, the dearth of female perspective in legislation even in the 21st century and a host of other male-dominated influences. Even in interventions aimed at poverty alleviation, the solutions—technological or otherwise—are more often than not designed by men without enough understanding of the real needs of users, the majority of whom are often women.

This inequity, away from the spotlight for many years, manifests itself on women in a number of ways. Women do most of the world's work but earn only a fraction of the compensation that men do. They frequently face violence and abuse at home, at the workplace and by men in other positions of power; too often, they have no recourse. They are vulnerable to a number of health risks that men are not but do not have access to the necessary healthcare. The majority of women do not have a voice in how they spend the money they earn and cannot invest in technologies and tools that can alleviate their condition.

Clearly, none of these problems can be addressed without fundamental changes in societal values and attitudes, complemented by strictly enforced legal protections. While technology itself will not be a definitive or permanent solution, we believe it can play a supplemental yet vital role. We have identified six technology breakthroughs, some of which have been identified as breakthroughs in other sections of this study, that can have a direct effect in enhancing gender equity.

- Breakthrough 7: Affordable (less than $50), lightweight, energy-efficient, solar-powered irrigation pumps
- Breakthrough 19: Affordable healthy homes that are resilient to extreme weather events
- Breakthrough 20: A simple point-of-use, low cost DNA-based rape kit capable of delivering rapid results
- Breakthrough 24: Microbicides to provide a method of protection for those who are otherwise vulnerable to HIV/AIDS infection by their partner
- Breakthrough 46: Advanced biomass cookstoves that are desirable, affordable, robust and very clean
- Breakthrough 47: Novel ways of converting household or village waste products into clean cooking fuel or electricity

Historically, most societies have been dominated by men. Religious institutions, from every major faith around the world, have been the exclusive preserve of male leadership and perspective. Men have been able to dictate laws and traditions to their own benefit, often ignoring the perspectives of women, and sometimes manifestly suppressing female rights. While we've seen significant improvements in both law and practice in recent decades, even the most educated and economically advanced societies are still male-centric; lower income countries, more so. Not surprisingly then, from an early age, girls and women around the world experience inequities in virtually every aspect of life: access to education; conforming to what constitutes acceptable dress and speech; opportunities for employment; appropriate working conditions and fair wages; land and other economic rights; the right to decide when to marry; the right to choose their partner; the right to contraception; the right to choose if, when, and how many children to have; the share of the responsibility for managing their household work and caring for children; protection from health hazards; security from harassment, abuse and violence; and access to adequate healthcare.

CORE FACTS AND ANALYSIS

Women and girls account disproportionately among the very poor and bear the brunt of extreme poverty. The following discussion analyzes specific hurdles females face along the key aspects of development: basic human rights, education, economic, social and political, health and day-to-day life.

Although these challenges exist throughout the world and across economic classes, our analysis focuses on developing countries and low-income populations.

Human rights

1. There are more than 90 million "missing women", primarily in Asia

Sex-selective abortions are common in countries where there is a strong preference among parents for boys and girls are perceived as an economic burden. In many countries such as India, this is due to social ills like the practice of dowry, as well as a general belief that only boys grow up to support parents in their old age.

Other countries have variations of such beliefs. This pressure is further exacerbated by reduced fertility rates, with families now wanting fewer children--and at least one son. China's "one-child policy" was an extreme example of external pressure that appears to have compelled parents into sex selective abortion. Increased access to technologies, such as antenatal ultrasound, has increased the ability of would-be parents to determine the sex of a fetus and selectively terminate pregnancies (Kulkarni, 2007; Hvistendahl, 2011).

As a result, the ratio of male-to-female births in a number of Asian countries, particularly China, India, Pakistan, Bangladesh, Afghanistan, Taiwan and South Korea, is well above the expected ratio. For example, in India and China the ratio is about 107 boys for every 100 girls, with some regions in India going over 155, and some regions in China going as high as 135 (Hudson & Boer, 2005; World Economic Forum, 2012).

This, combined with other health factors, appears to have contributed to a large number of "missing women", estimated at 90.3 million as of 2005 (Hudson & Boer, 2005), with China and India accounting for the majority (**Exhibit 1**). This phenomenon is discussed in greater detail later in this chapter.

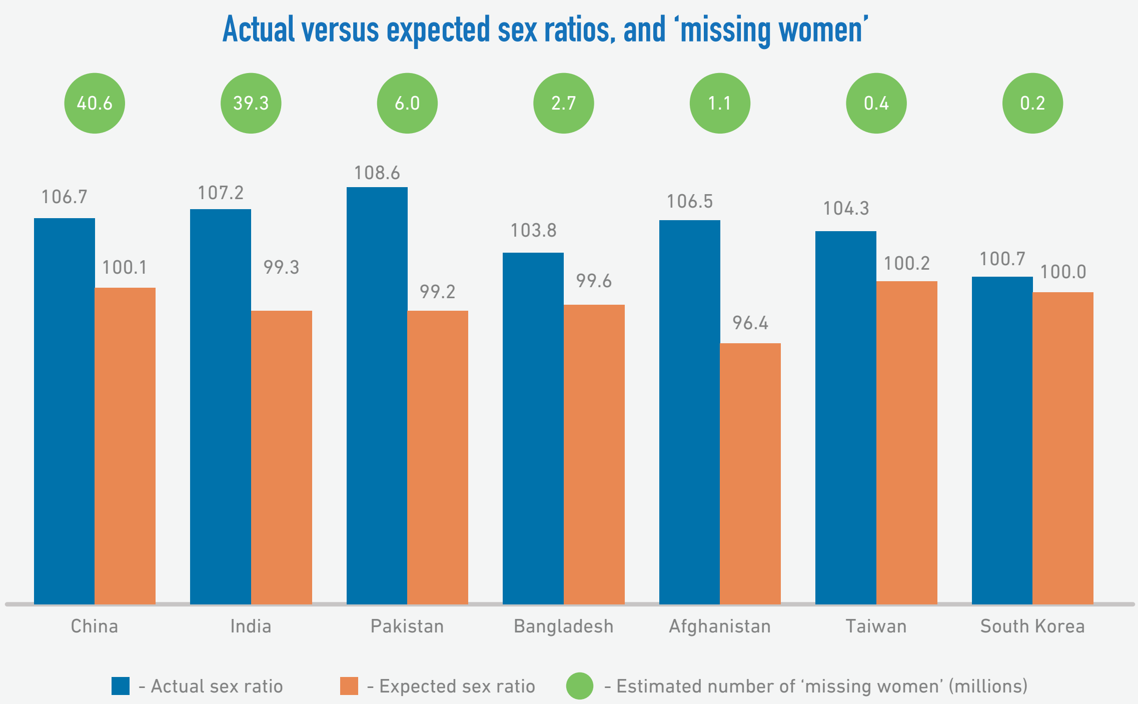


Exhibit 1: Sex-selective abortion, combined with other factors, has led to a higher-than-expected male-female sex ratio in a number of Asian countries. There are as many as 90 million "missing women" in these countries. (Source: Hudson & Boer, 2005)

2. Violence against women and girls is common in many parts of the world

Violence and abuse against women and girls is all too common an occurrence and takes place in many forms—physical, sexual and psychological. While men also face violence, the violence and abuse faced by women is gendered, in that it is usually perpetrated by men and often in the context of a one-sided power dynamic.

Physical and sexual violence

A large proportion of women from countries around the world are subjected to physical violence by their partner at least once in their lifetime, many of them in the last 12 months (UN, 2015) (**Exhibit 2**). Women also face high rates of sexual violence, with more than 20 percent of women in Cameroon, Uganda and Zimbabwe reporting assault, not including non-violent incidents of sexual harassment, at least once in their lifetime (**Exhibit 3**) (UN, 2015).

Physical and sexual violence occurs on all continents, but the highest rates are in Africa. Equally troubling is that in many countries, violence against women is perceived as acceptable or justifiable, even by the women themselves.

Nearly 30 percent of women in the surveyed countries agreed that wife beating is justified for arguing with the husband, 25 percent believed it is justified for refusing to have sex and 21 percent believe it is justified if the wife accidentally burns the food while cooking. In Guinea, as much as 60 percent of surveyed women found it permissible to be beaten for refusing sex and in Ethiopia 81 percent of women agreed with at least one of these reasons for wife beating (World Bank, 2012).

Proportion of ever-partnered women aged 15 to 49 experiencing intimate partner physical and/or sexual violence at least once in their lifetime and in the last 12 months

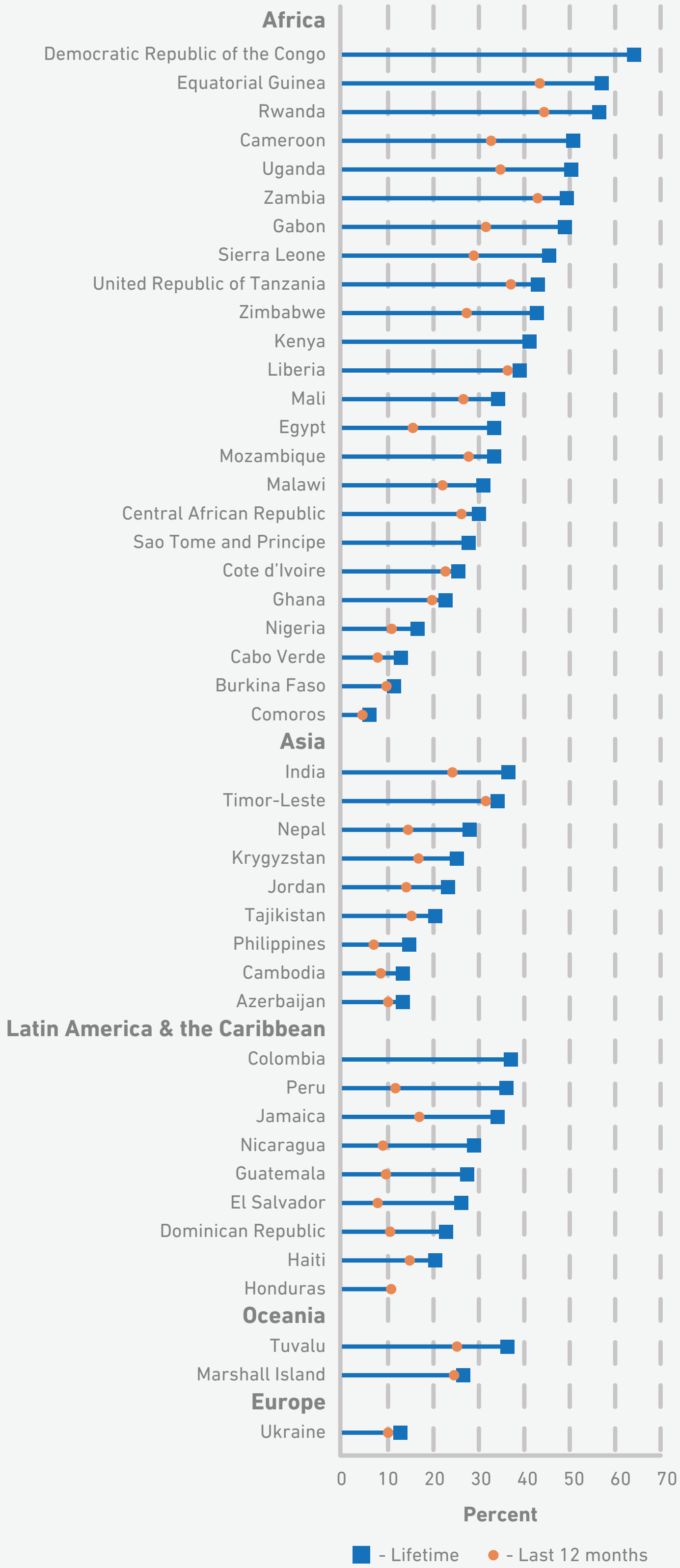


Exhibit 2: Millions of women from many countries have reported experiencing physical or sexual violence by their partner at least once in their lifetime. For many, it has happened within the last year. (Source: UN, 2015)

Proportion of women aged 15 to 49 experiencing sexual violence (irrespective of the perpetrator) at least once in their lifetime and in the last 12 months

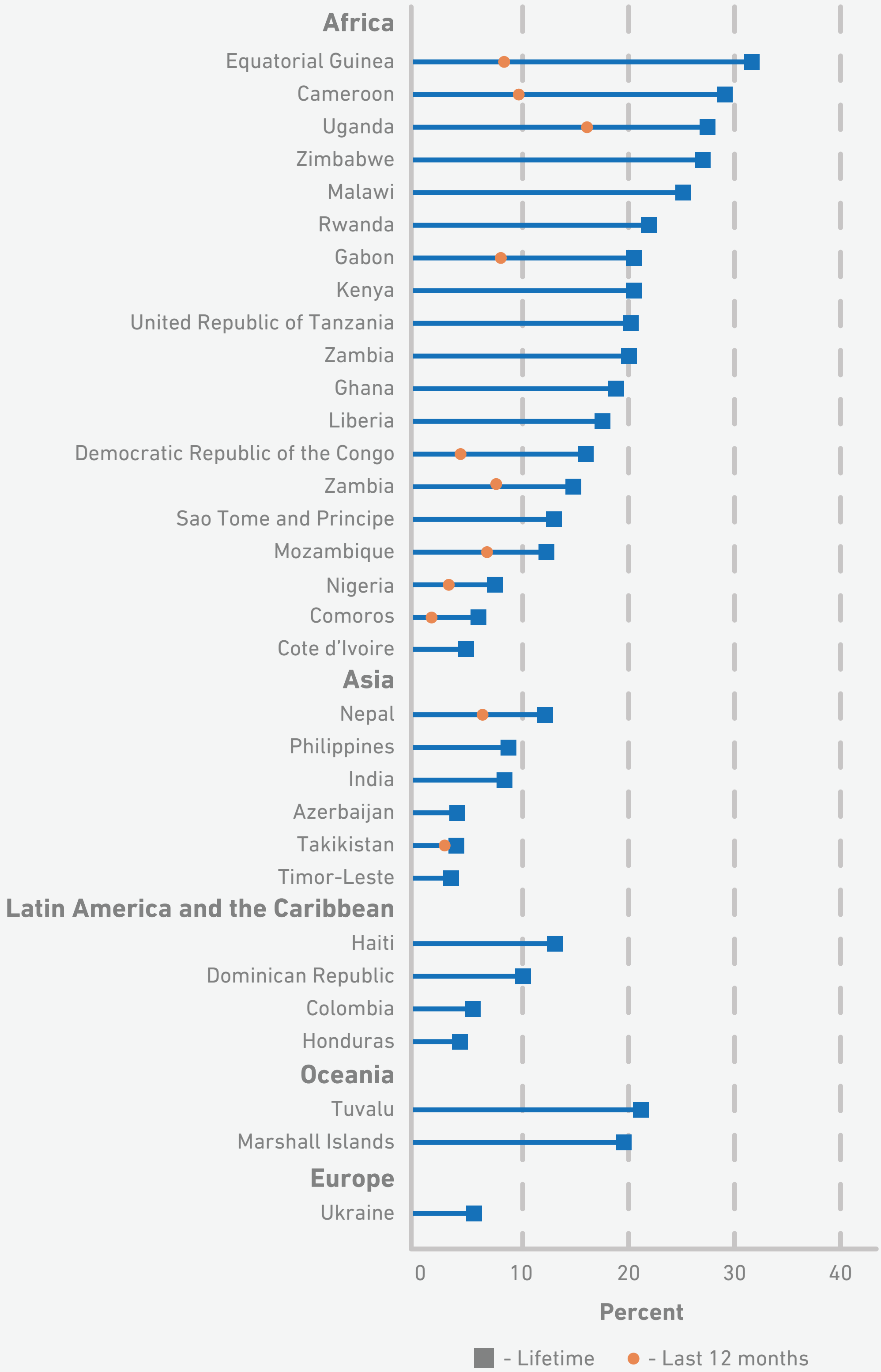


Exhibit 3: In some developing countries, more than 20 percent women reported facing sexual violence at least once in their lifetime. Note that statistics for the last 12 months are not available for all the countries. (Source: UN, 2015)

Human trafficking

Human trafficking for sexual exploitation and forced labor is the fastest growing form of organized crime in the world, and the third largest form of criminal enterprise globally (FBI, 2014). There are more than 20 million victims, of whom more than 12 million are women, trafficked for sexual exploitation (UN-ECOSOC, 2010).

Genital mutilation and other culturally sanctioned violent practices

In a number of countries girls face specific forms of culturally sanctioned violence. While some practices like breast flattening typically take place to keep young girls from showing any outward signs of puberty and 'keep them safe from rape', others like 'sexual cleansing' (by paying an older man to have intercourse with girls as young as 9) occur to prepare girls to enter adulthood (The Guardian, 2012, 2014).

Another major form of violence against girls and young women is female genital mutilation (FGM), which refers to a range of procedures involving removal or partial cutting of external female genitalia for non-medical reasons.

A traditional ritual in many cultures, FGM rates are higher than 80 percent in Guinea, Egypt, Eritrea and Mali (UN-ECOSOC, 2010). In the face of advocacy and awareness campaigns, however, the rates have dropped somewhat in the last decade (**Exhibit 4**).

Percentage of girls aged 15 to 19 who have experienced any form of female genital mutilation

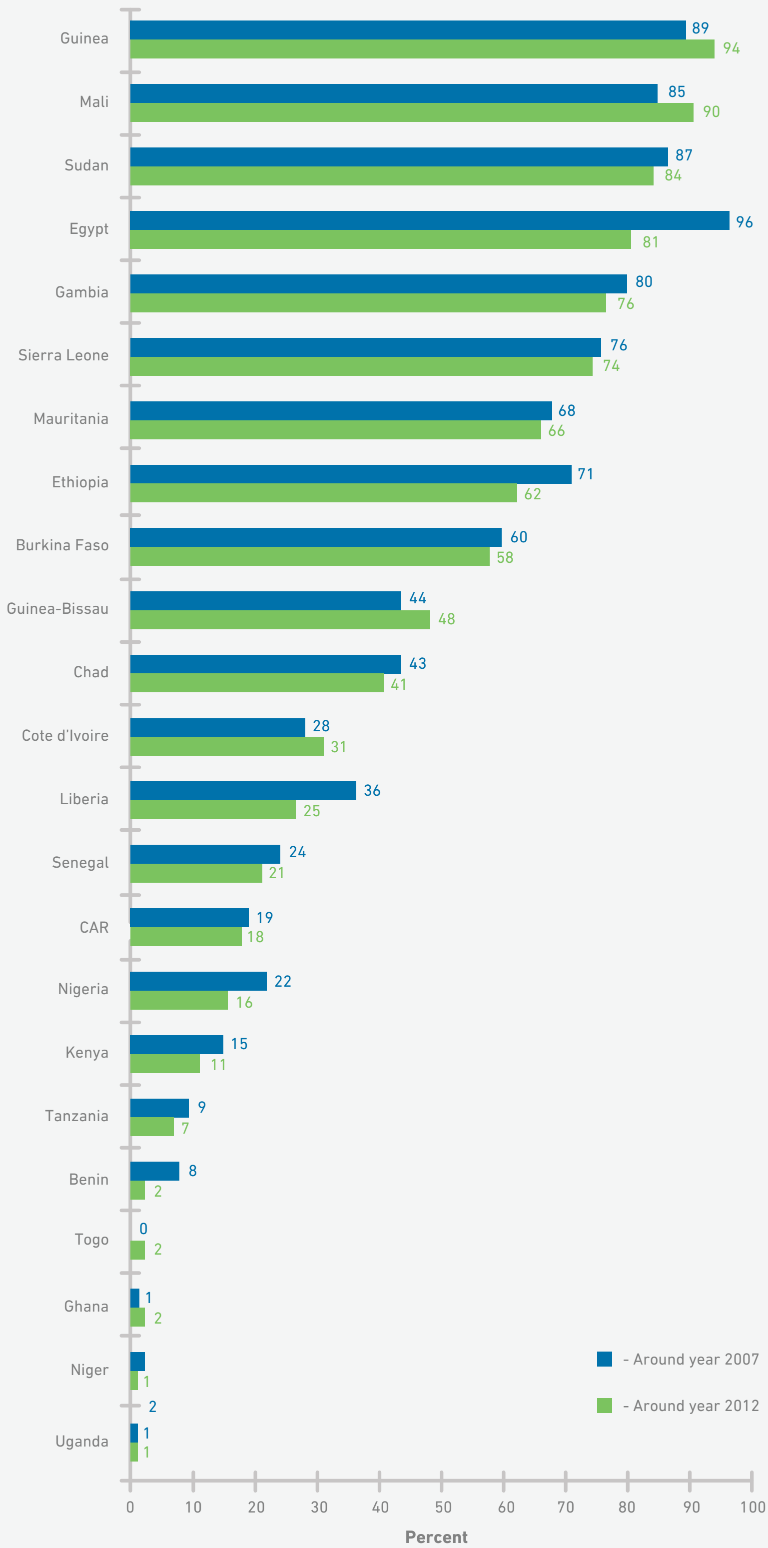


Exhibit 4: Female genital mutilation is a major problem in a number of countries, even though recent campaigns have resulted in minor improvements in some countries (UNFPA, 2015).

Honor killings

Each year, an estimated 5,000 women and girls are violently killed by members of their own family or community in so-called honor killings (UNFPA, 2000). Concentrated in South Asia and the Middle East, such violence is perpetrated on women who are considered to have defied traditional norms and embarrassed their family usually through acts of intimacy before marriage, by marrying someone outside of the community or for committing adultery.

Rape as a weapon of war

Many conflicts, especially those with an ethnic or religious rift, involve widespread sexual violence against women and girls perpetrated by combatants or civilians. According to a UN Security Council resolution, "Women and girls are particularly targeted by the use of sexual violence, including as a tactic of war to humiliate, dominate, instill fear in, disperse and/or forcibly relocate civilian members of a community or ethnic group" (UN Security Council, 2008).

Recent examples of large-scale sexual atrocities include the conflicts in the former Yugoslavia, Rwanda, the Democratic Republic of Congo and Liberia. Seemingly, the motivations range from a desire to humiliate the enemy by impregnating "their" women, to use HIV as a weapon or to just brutally exercise power over civilians with neither protection nor recourse (Aginam & Rupiya, 2012). Positive recent signs include the 2018 Nobel Peace Prize awarded to Nadia Murad and Denis Mukwege for their efforts to end the use of sexual violence as a weapon of war and armed conflict (Nobel Committee, 2018). A less progressive sign was the 2018 overturning of the International Criminal Court's conviction of Jean-Pierre Bemba, the warlord from DR Congo responsible for widespread raping and killing (BBC, 2018).

Education

3. Despite recent progress in enrollments at the primary school level, gender disparities persist in higher education

A quality education is critical for every girl's ability to access economic opportunities later in life. Moreover, educated women also take better care of, and invest more in their children, who are then more likely to become well educated themselves. Women are also much more involved in teaching children than men are, both as formal teachers and as mothers (World Bank, 2012).

In Pakistan, for example, children whose mothers have even a single year of education spend an extra hour studying every day and do better at school. In addition, children of educated women are more likely to be immunized and have good nutrition, lowering the rate of child mortality.

As shown in the education chapter, in recent years we have seen considerable increases in female enrollment rates in sub-Saharan Africa and South Asia. **Exhibit 5** shows the increases in the relative number of girls and women enrolled across various levels of education. However, gender parity is far from being a reality at the higher levels of education. Only 42 percent and 47 percent of tertiary enrollees in sub-Saharan Africa and South Asia, respectively, are women (UNESCO, 2018).

While the male-female ratio is more even in primary school, traditional beliefs and opinions about gender roles leads parents to discourage their daughters from pursuing an education as they grow older. As **Exhibit 6** and **Exhibit 7** show, these disparities are pronounced in lower income regions of the world, especially in poorer population segments. In some parts of the world, discouragement of girls' education can even turn violent, as events in Nigeria and Pakistan have shown (The Guardian, 2014).

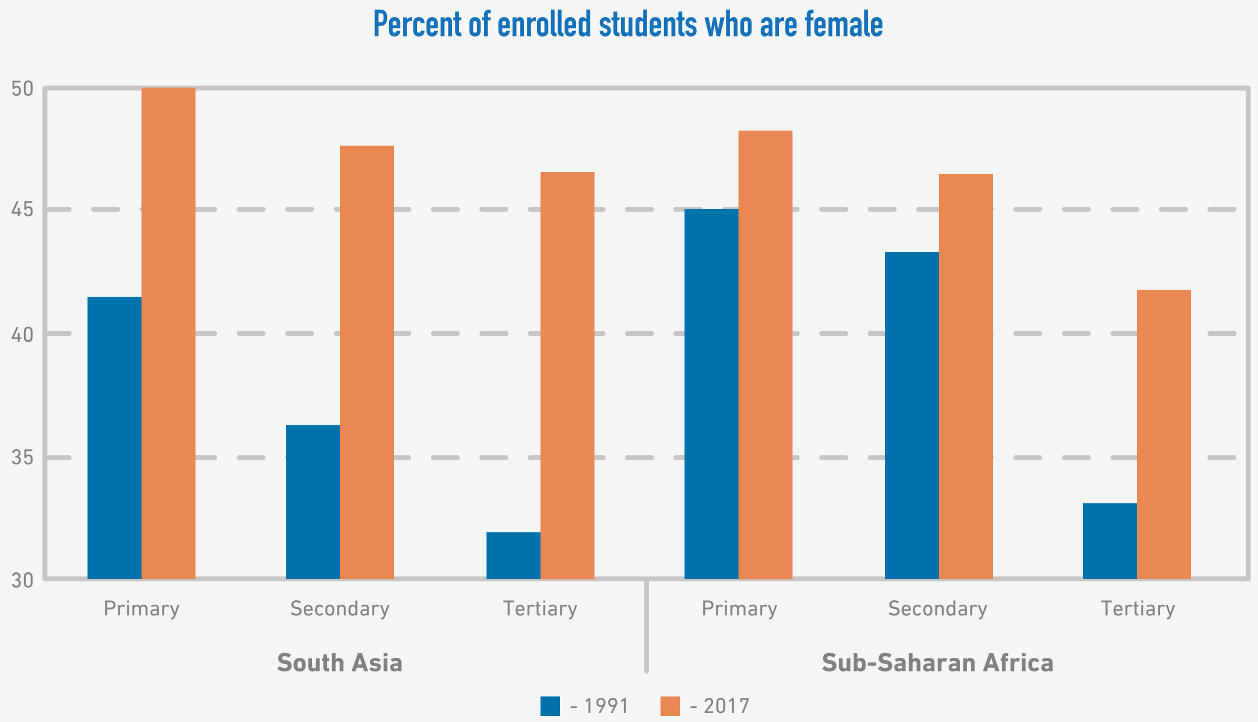


Exhibit 5: Although between 1991 and 2017 female enrollment for all levels of education increased more rapidly than for males, women still comprise a small proportion of total enrollees, especially in sub-Saharan Africa. (Source: UNESCO, 2018)

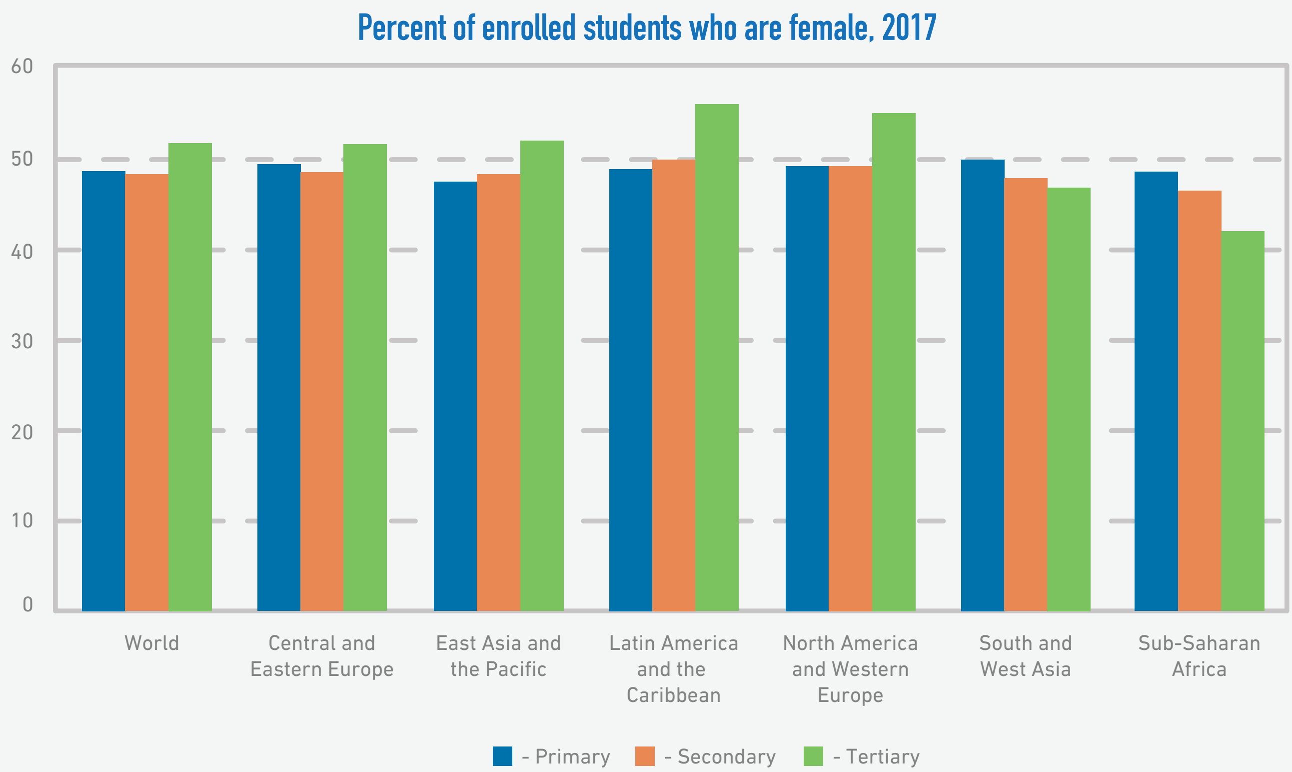


Exhibit 6: South Asia and sub-Saharan Africa trail the rest of the world when it comes to secondary and tertiary education for women. (UNESCO, 2018)

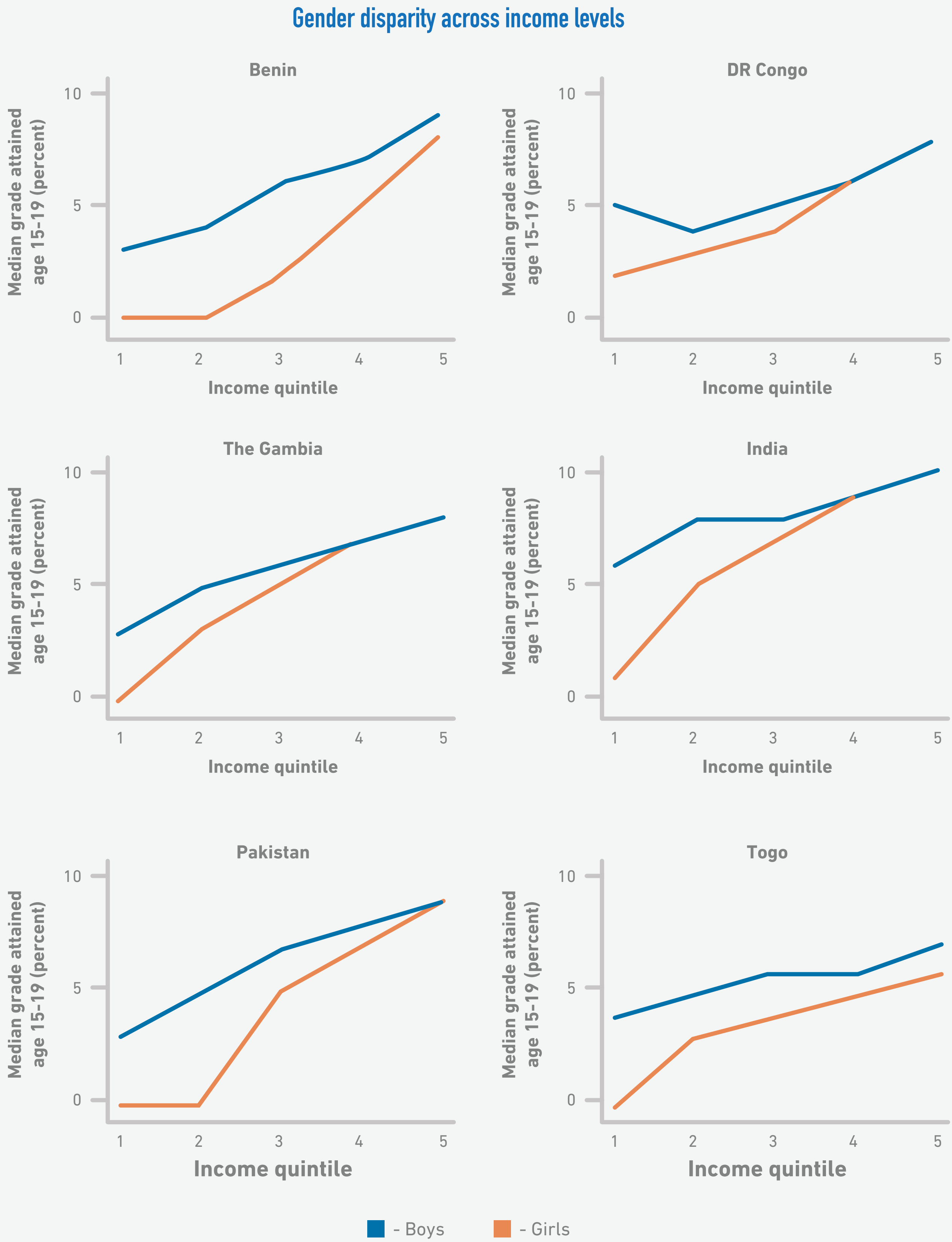


Exhibit 7: In a number of countries in South Asian and sub-Saharan Africa, gender disparities are more conspicuous in lower income population segments. The wealthiest (5th) quintiles have close to equal school enrollment in the 15 to 19-year age group, while the poorest (1st) quintiles consistently have the highest disparity. (Source: World Bank, 2012)

While gender disparity, especially in early education today, may seem to be driven more by economic factors than outright gender discrimination (World Bank, 2012), inequality exists and manifests itself in many ways:

- Women today account for two-thirds of the 774 million illiterate adults in the world, a proportion that has remained unchanged since 1990. There are 130 million illiterate women in Africa and 341 million in Asia (UN-ECOSOC, 2010).
- In Africa, 41 percent of women have never attended school, compared with 24 percent of men. Only 21 percent of women in Africa have obtained secondary or tertiary education, compared with 30 percent of men; in Asia, only 25 percent of women are completing secondary or tertiary school, compared with 41 percent of men (World Bank, 2012).
- In developing countries, fewer women than men have access to the internet. The gap between male and female internet users is 8 percent in Asia, 6 percent in Africa, and is 7 percent in the least developed countries as a whole (ITU, 2017) (**Exhibit 8**).

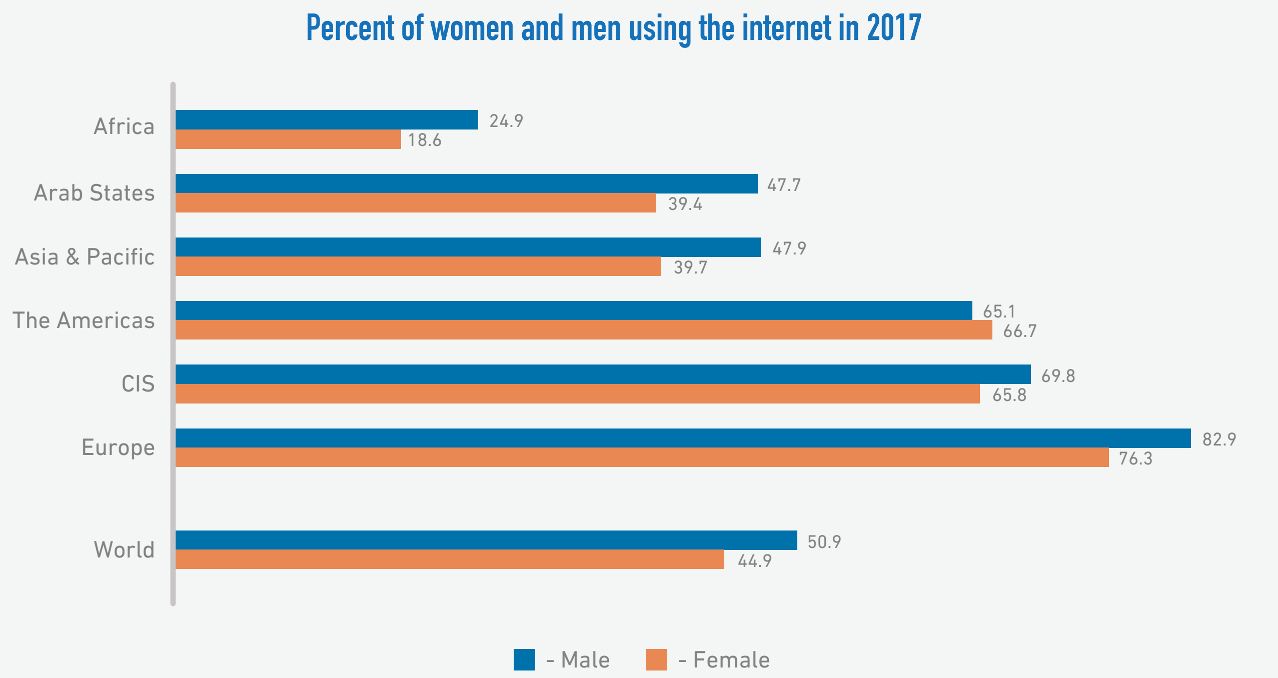


Exhibit 8: Women have less access to the Internet than men in all global regions except the Americas. (Source: ITU, 2017)

Economic opportunity

4. Women are responsible for more work than men, often in the form of unpaid household work or manual labor, especially in the agriculture sector

Women perform two-thirds of the world's work, yet earn only 10 percent of the world's income. This is largely because women continue to bear the primary responsibility for the home, spending twice as much time as men on unpaid work, such as caring for children and dependent family members, preparing meals and performing housework like cleaning, washing, gathering firewood and fetching water.

More than 50 percent of rural households and 25 percent of urban households in sub-Saharan Africa lack easy access to drinking water—and it is typically women who collect the water, a task that can involve walking many miles and take up the better part of a day. The time women spend on such domestic and otherwise unpaid activities keeps them from schooling and earning (UN-ECOSOC, 2010; World Bank, 2012).

Table 1 shows the share of time women and men spend on various categories of activities. As **Exhibit 9** shows, agriculture represents the single largest form of economic activity for women in South Asia and sub-Saharan Africa (ILO, 2014). They work as producers, laborers, processors and traders in domestic markets. Women contribute to a substantial portion of total agricultural labor, ranging from 26 percent in Nigeria to 87 percent in DR Congo (FAO, 2018) (**Exhibit 10**).

While men perform much of the heavy manual labor, such as plowing fields and driving draft animals, women do most of the weeding, fertilizing and harvesting and contribute to a significant share of the workload in food production. In aggregate, women are responsible for 50 percent of food production worldwide (FAO, 1995; UN, 2007).

Type of work men and women engage in

Region		Women				Men			
		Wage & salaried workers (percent)	Employers (percent)	Own-account holders (percent)	Contributing family workers (percent)	Wage & salaried workers (percent)	Employers (percent)	Own-account holders (percent)	Contributing family workers (percent)
Africa	Northern Africa	46	2	19	33	58	8	22	12
	Southern Africa	76	3	17	4	82	7	9	2
	Eastern and Western Africa	20	1	47	32	24	1	57	18
Asia	Eastern Asia	86	2	7	5	79	7	13	1
	South-Eastern Asia	52	2	23	23	52	4	34	10
	Southern Asia	30	1	22	47	44	3	41	12
	Western Asia	80	1	6	13	79	5	14	2
	Central Asia	45	1	39	15	50	3	40	7
LAC	Caribbean	80	2	16	2	68	3	28	1
	Central America	65	3	25	7	64	6	24	6
	South America	63	3	28	6	62	6	29	3
Europe	Eastern Europe	84	2	10	4	78	4	17	1
	Northern Europe	93	2	4	1	84	5	10	1
	Southern Europe	81	3	10	6	75	6	17	2
	Western Europe	88	3	6	3	84	7	8	1
Other	Other developed regions	89	2	7	2	83	5	11	1

Table 1: Women spend a disproportionate share of their time taking care of their households (compared with men) rather than on income-generating activities. The countries with the greatest disparities are in Africa and South/ Southeast Asia. (Source: UN-ECOSOC, 2010; World Bank, 2012)

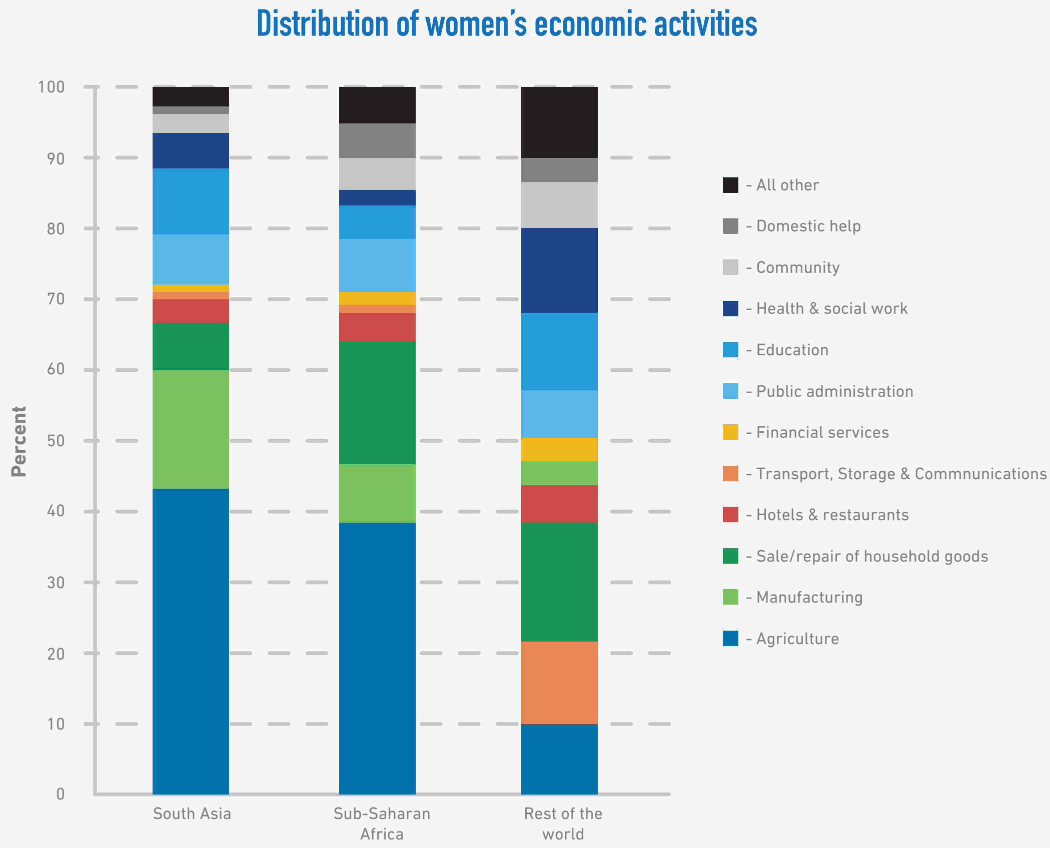


Exhibit 9: Women contribute a substantial portion of agricultural labor in both South Asia and sub-Saharan Africa, far more than in the rest of the world. (Source: ILO, 2014)

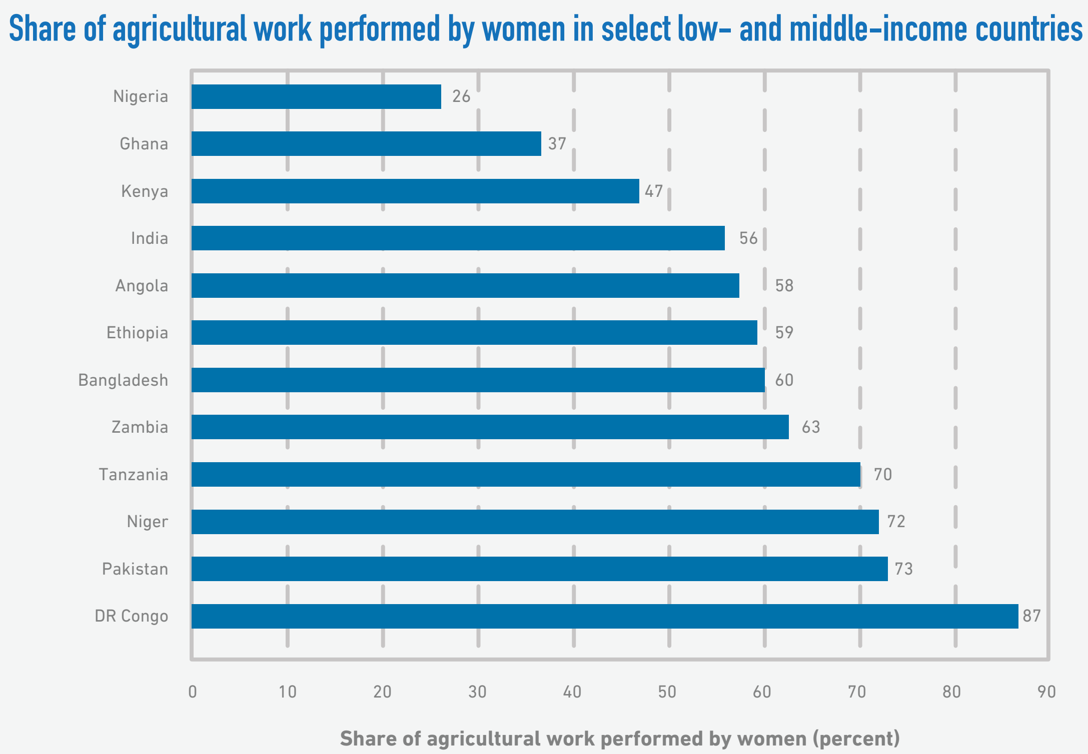


Exhibit 10: Women contribute to a substantial portion of total agricultural labor, ranging from 26 percent in Nigeria to 87 percent in DR Congo. (Source: FAO, 2018)

Advancing towards the goal of gender equity can contribute significantly to greater economic growth. Eliminating the global gender gap at work could contribute $12 trillion to the economy considering the 'best-in-region' scenario which translates to 11 percent increase in global GDP. The full economic potential of such a transformation is estimated at greater than $25 trillion (McKinsey, 2016).

Research indicates that gender diverse organizations tend to outperform organizations that rate in the lowest quartile of gender diversity. A truly gender diverse organization not only embodies equity in hiring but also in employee management and takes cases of harassment or pay gap very seriously. In recent years, the profile of both of these issues have been raised with the boom of social media-led mass campaigns like the #MeToo movement (McKinsey, 2015).

Gender diversity has a strong impact on innovation in the workplace and promotes inclusive entrepreneurship. A more inclusive approach to women as customers, employees and employers will translate to higher efficiency and outputs. Given that women control a substantial share of consumer spending worldwide, they are a critical consumer segment that companies need to better understand, design for and market to if they want to experience market growth. To ensure that modern organizations truly match the needs of this large consumer base, it is critical to have women take on roles across the value chain.

5. Women do not benefit from income parity, lack control over income earned and are deliberately excluded when it comes to owning or inheriting property

Even when women are paid for their work, a persistent remuneration gap exists. There is disparity in income, both because women work fewer hours in the paid economy than men, and because women get paid less per hour worked than men. Women's wages represent only 70 to 90 percent of men's wages in the majority of countries (UN-ECOSOC, 2010). In many countries, women earn much less income than what men earn (**Exhibit 11**).

In Bangladesh, women earn only 12 cents ($0.12) for every dollar earned by men (World Bank, 2012). To make matters worse, women have limited control over how the income they earn is spent. This is particularly true in lower income countries and even more so in lower income segments of the populations in those countries (**Exhibit 12**).

Married men and women aged 15 to 49 who earned any cash labor income in the last 12 months, by urban and rural areas, 2005 to 2012

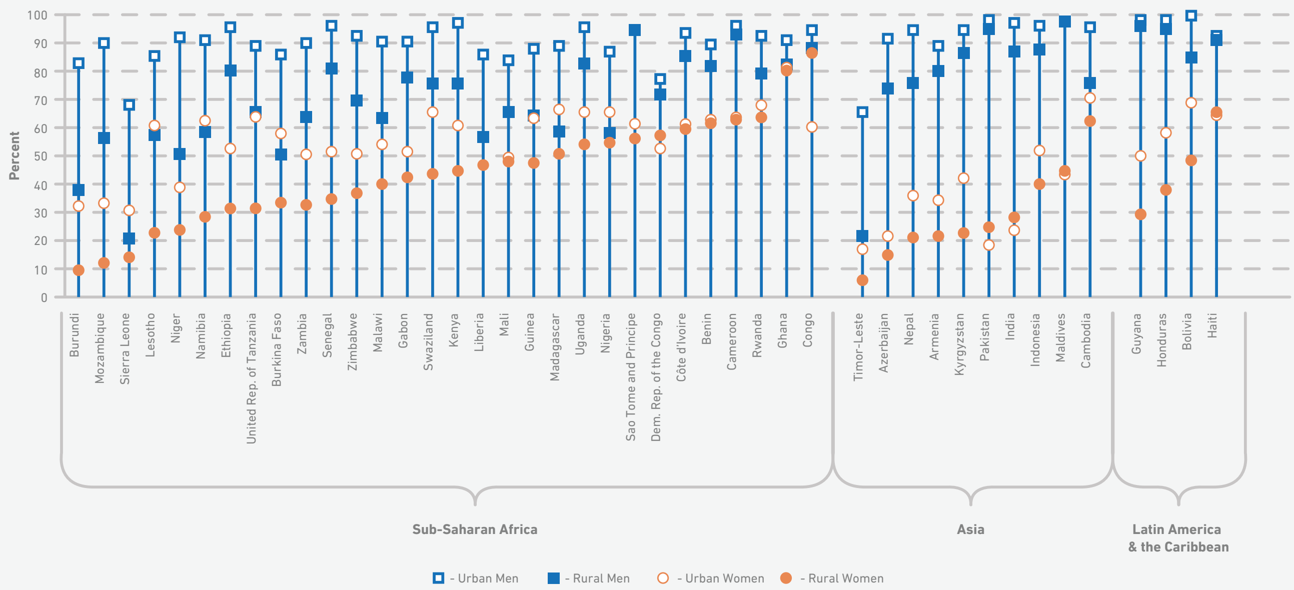


Exhibit 11: In most countries, women earn much less cash income than what men earn. (Source: UN, 2015)

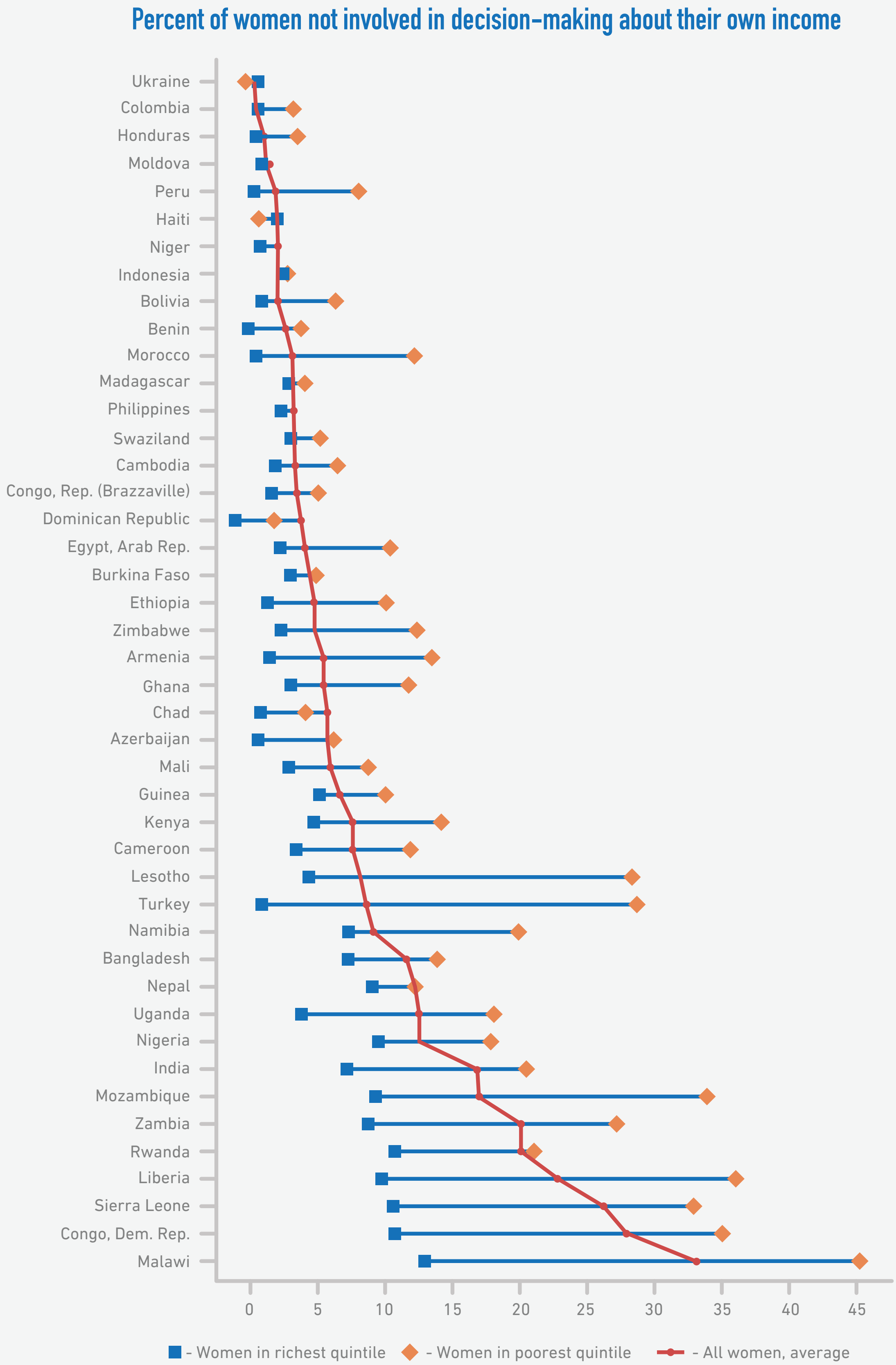


Exhibit 12: Women in lower income segments of the population have limited say in how they spend their own income. (Source: World Bank, 2012)

Women are also disadvantaged with respect to land and property rights, whether through inheritance or marriage. In many countries in Africa and Asia, only men are allowed to own land, by both law and tradition. Additionally, in many countries, women do not have the legal right to a share in paternal or matrimonial property.

The consequence of this systemic bias is obvious: women in Kenya represent only 5 percent of registered landowners and in Brazil and Paraguay, they own only 11 percent and 2 percent of registered land, respectively. Moreover, women's land holdings are far smaller than those of their male counterparts: in Ghana, for example, the average land holding for a man is three times the size of that for a woman (World Bank, 2012).

Without land or another non-movable asset as collateral, women have very limited access to credit. Without credit, they cannot purchase seeds, fertilizer, irrigation equipment or other mechanisms for increasing farm productivity. Globally, women receive only 10 percent of small farmer credit and only 5 percent of agricultural extension services (World Economic Forum, 2012).

There is an inverse correlation between fertility rates and engagement of women in the workforce of a country. In high-fertility countries, particularly the least developed countries, women's enrolment in the labor force as wage and salaried employees remains low: 20 percent in South Asia and 22 percent in sub-Saharan Africa (UNFPA, 2017).

6. Legal systems of a few countries can directly or indirectly deprive women of economic opportunities and equal pay

In 18 countries, men can legally prevent their wives from working outside the home (UN, 2015). Gender inequality is also present in laws regarding property ownership and inheritances. In rural work, women have less access to credit and agricultural inputs when they lack secure land tenure. This results in women having lower agricultural yields—and the corresponding earnings from them—than men.

Furthermore, laws protecting women against "economic violence" are rare. Economic violence occurs when a woman is deprived of the economic means to leave an abusive relationship because her partner either controls the economic resources or prevents the woman from having or keeping a job.

These issues can only definitively be solved by a strong shift in policies and organizational structures to be further accepted by the society. While technology cannot solve for these issues directly, it can act as a pillar to the major initiatives.

Health

7. While women have a higher life expectancy, there are 3.9 million 'excess female deaths' each year due to factors like selective abortion, maternal mortality, HIV/AIDS, and indoor air pollution

In every region of the world, and in nearly every country (except Botswana, Mali and Swaziland), women outlive men. As **Exhibit 13** shows, globally the average female life expectancy (74 years) is 4 years higher than that for men (70 years).

While the specific reasons are not clear, studies point to the higher incidence of heart disease among men, driven by a combination of genetic factors, as well as behaviors like smoking that are more prevalent among men (Waldron & Johnston, 1976; Waldron, 1983). The difference, however, dwindles in South Asia (70 for women versus 67 years for men) and sub-Saharan Africa (62 years for women versus 59 years for men) (World Bank, 2018).

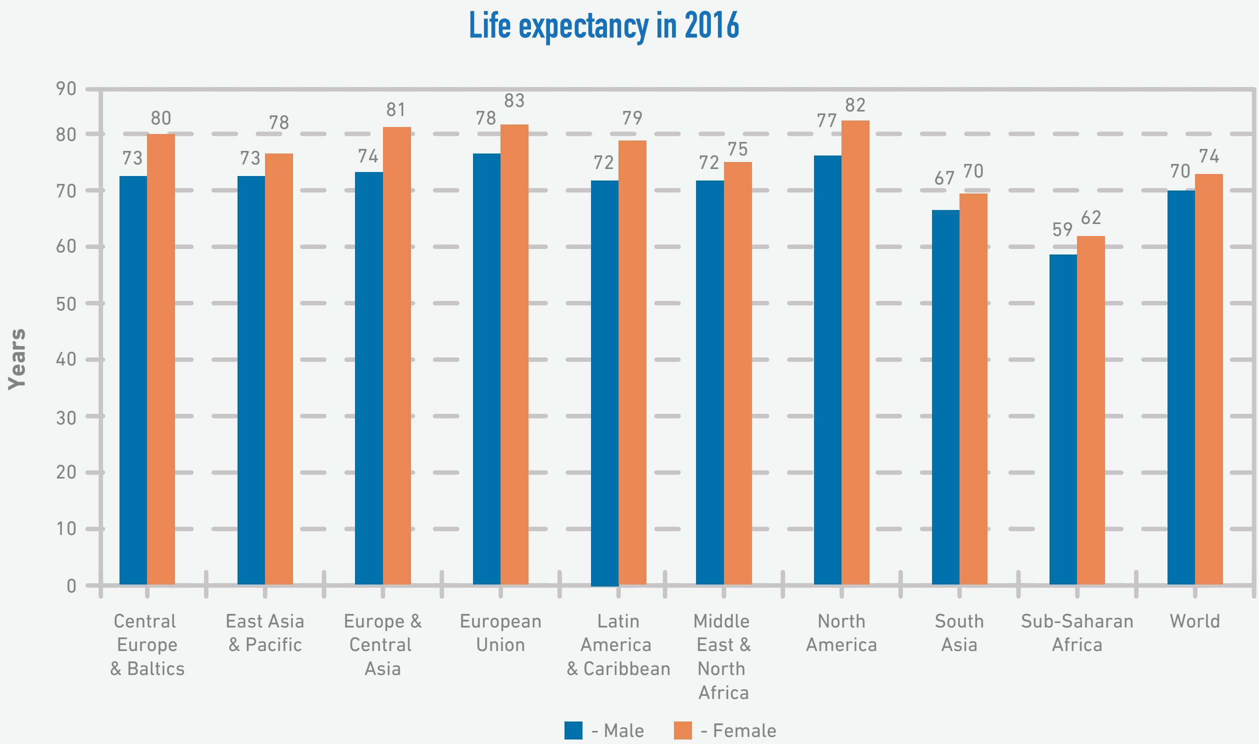


Exhibit 13: Life expectancy of females is higher than that of males in every region of the world. (Source: World Bank, 2018)

These advantages notwithstanding, it is estimated that each year there are 3.9 million cases of "excess mortality" among girls and women (World Bank, 2012). These deaths (**Table 2**) are concentrated in East Asia (primarily China), sub-Saharan Africa and South Asia (primarily India). Of these 3.9 million deaths, 1.43 million occur at or before birth due to selective abortion; another 617,000 occur in girls under 5; 158,000 between the ages of 5 and 14 years; 1.35 million in the 15 to 49-year age range; and 334,000 excess deaths occur between the ages of 50 and 59 years. The main factors leading to female deaths in post-birth age groups are highlighted in the following discussion.

Excess female deaths in the world by age and region (in thousands)

Region	Birth	Under 5	5-14	15-49	50-59	Total
sub-Saharan Africa	53	203	77	751	99	1,182
South Asia	258	323	65	389	126	1,161
East Asia	1,096	78	14	169	76	1,433
Middle East & North Africa	6	7	1	24	15	52
Europe & Central Asia	14	1	0	4	3	23
Latin America	0	5	1	10	17	33
Total	**1,427**	**617**	**158**	**1,347**	**334**	**3,882**

Table 2: "Excess mortality" among women and girls is concentrated in South Asia, East Asia and sub-Saharan Africa. (Source: World Bank, 2012)

Child mortality

The reasons for the 617,000 excess deaths of girls under 5 are not clear. While some studies have implicated delays in seeking healthcare for girls (Tarozzi & Mahajan, 2007; World Bank, 2005), a World Bank study on gender equity (World Bank, 2012) did not find conclusive evidence to show why girls in low income populations are worse affected than boys.

Exhibit 14 shows data from World Bank (2012) suggesting that there are no meaningful differences between healthcare provided—vaccination, being taken to a health facility for respiratory illness, or stunting—to boys and girls in countries with higher rates of mortality among girls.[1]

That study concludes that excess female mortality in childhood "is a result not so much of discrimination as of poor institutions that force households to choose among many bad options, particularly regarding water and sanitation" (World Bank, 2012).

[1]Polio and measles are not major drivers of childhood mortality. However, it is likely that children who are vaccinated for these diseases are also vaccinated for other diseases. Respiratory conditions like pneumonia are among the leading causes of mortality among children under five. Stunting is one of the leading symptoms of malnutrition among children.

Key health statistics for boys versus girls, across a large number of low-income countries

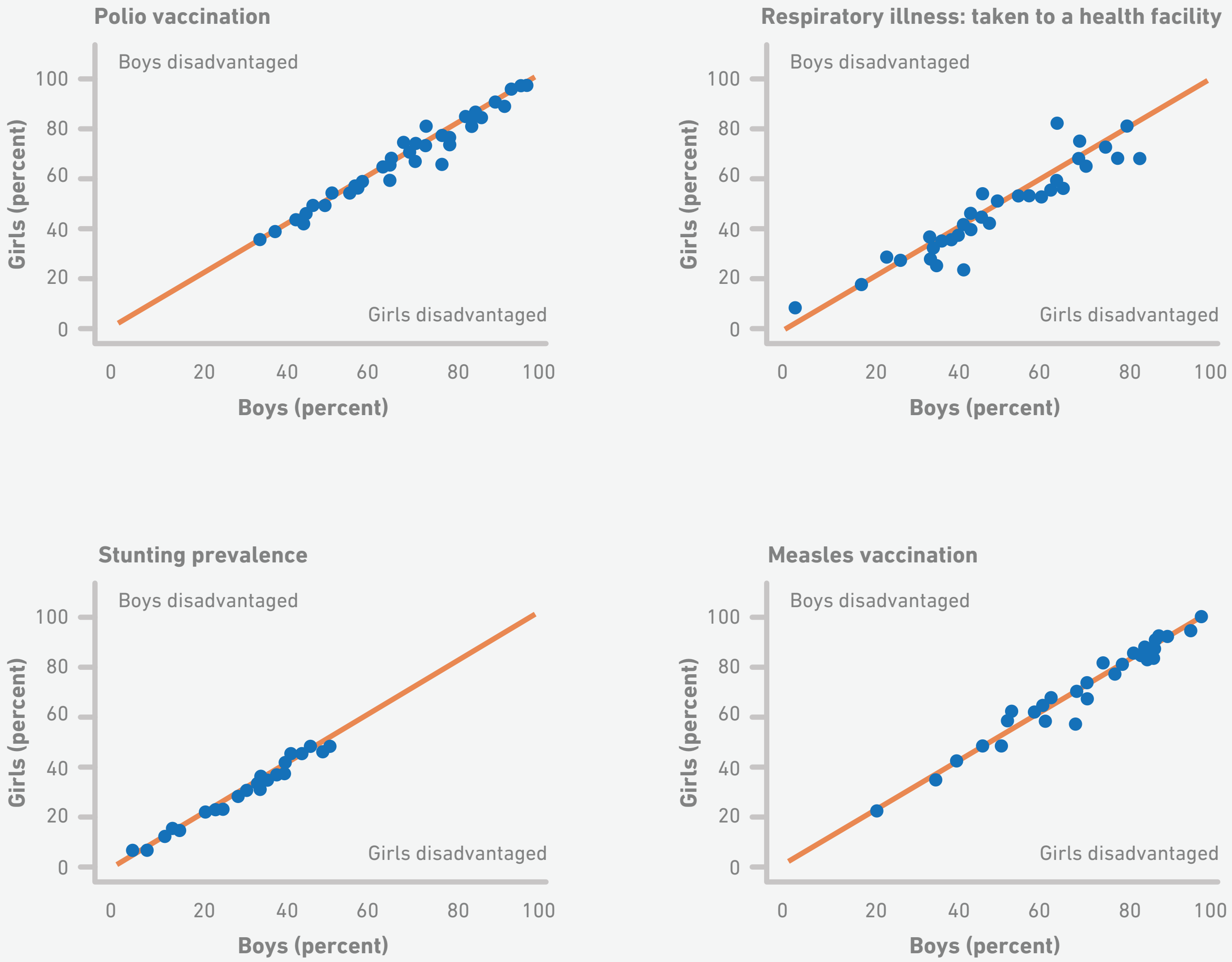


Exhibit 14: There appears to be little gender disparity among children with respect to vaccination rates, nutrition outcomes, or use of health services. This makes it difficult to explain the causes behind the 617,000 "excess deaths" of girls under five. (Source: World Bank, 2012)

Maternal mortality

Women in developing countries are much more likely to die during pregnancy compared to women in higher income countries (World Bank, 2018) (**Exhibit 15**).

As the section on maternal mortality in the Global Health chapter of our study discusses, about 300,000 women die each year during childbirth (WHO, 2015). It is one of the leading causes of death among women of childbearing age in South Asia and sub-Saharan Africa. Among the main drivers of maternal mortality is the fact that a large number of births take place at home and are administered by untrained traditional birth attendants.

There is a systemic absence of maternal healthcare in low income countries without enough adequately equipped clinics, trained clinicians, or means of escalation in the event of complications.

In fact, across the largest countries in South Asia and sub-Saharan Africa, only 37 percent pregnant women receive at least four antenatal care visits as require by WHO, which are crucial for determining the health of both mother and the unborn child. While the majority of maternal deaths are due to weak healthcare systems, 10 to 15 percent of maternal deaths are caused by unsafe abortions in countries where abortion is restricted or inaccessible.

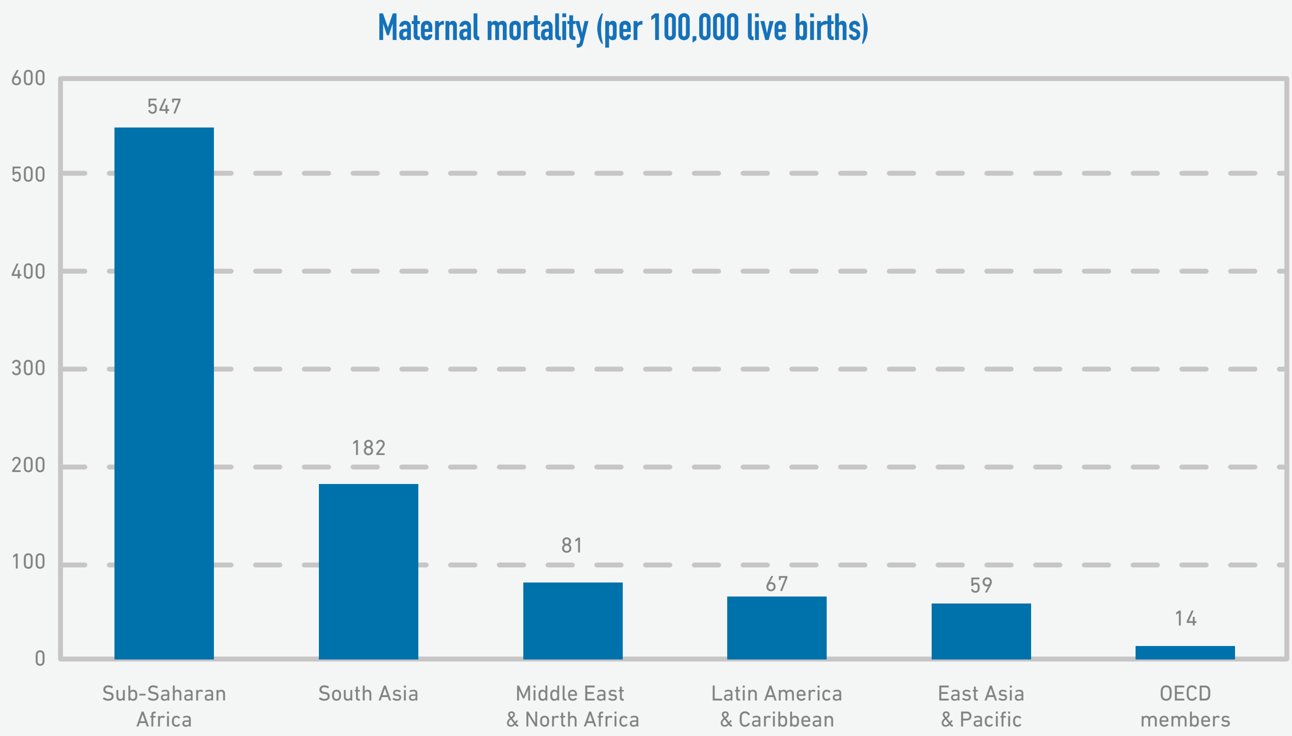


Exhibit 15: Women in Sub-Saharan Africa are much more likely to die during childbirth than women in high income countries. (Source: World Bank, 2018)

HIV/AIDS

Women are more susceptible to HIV/AIDS due to both sociological and biological factors. The latter include the surface area of the cervix and vagina (compared to the surface area of the male penis); the increased likelihood of tears along the surface of the vagina, particularly in younger women who tend to have immature genital tracts (compared with parts of the penis); the higher fluid volume of semen entering the woman's body (compared with the volume of vaginal secretion entering the man's body); the higher viral concentration in semen (compared with that in vaginal secretion); and the warm, moist environment inside the vagina, which is ideal for the HIV virus to thrive.

Sociological factors include notions about masculinity, due to which men tend to have a higher number of and younger female sexual partners (than the other way around); the unwillingness of men to use condoms or get circumcised; and the practice of douching (washing the vagina with soap), which destroys natural protective bacteria (UNAIDS, 2011; World Bank, 2012; Canada AIDS Society, 2014).

The prevalence of HIV among women in sub-Saharan Africa is almost twice that among men: 2.0 percent versus 1.1 percent, respectively (World Bank, 2018) (**Exhibit 16**). Women account for 60 percent of HIV infections, with the gender gap greatest among young adults. After age 34, HIV prevalence rates are similar for men and women. Prenatal care, care during childbirth and children's vaccination rates have suffered most in regions and areas where HIV rates are the highest.

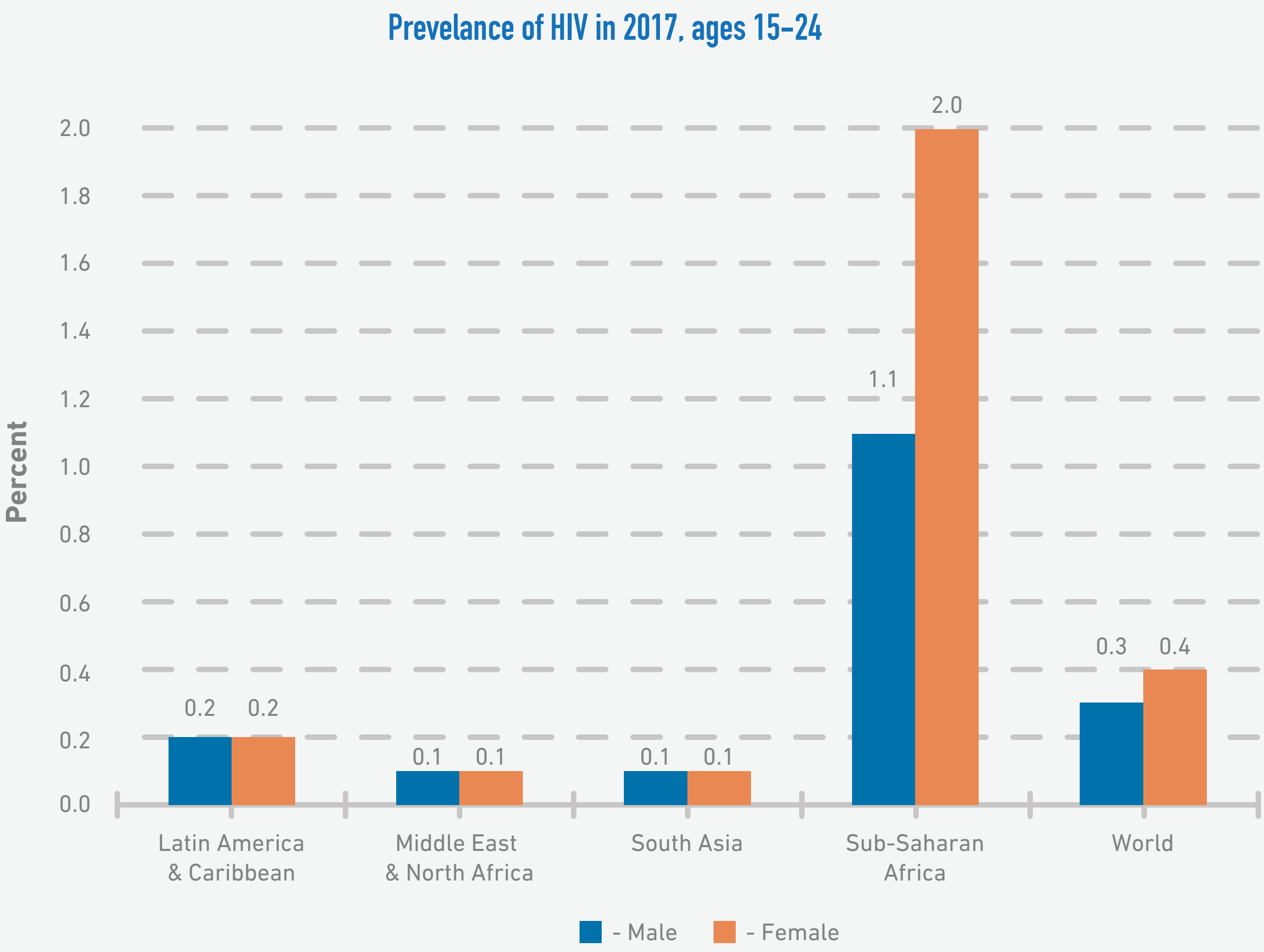


Exhibit 16: In sub-Saharan Africa the prevalence of HIV among women is almost twice that of men. In other parts of the world, prevalence among men and women is roughly the same. (Source: World Bank, 2018)

Cervical cancer

Every year, over 270,000 women die from cervical cancer, which is caused by the Human Papillomavirus (HPV). The infection is acquired through sexual contact and is the single most common form of viral infection of the reproductive tract. HPV is most widespread in the early years of sexual activity, can be spread by skin-to-skin contact and does not necessarily require penetrative intercourse for transmission.

Most cases of HPV infection heal by themselves in a few months and do not lead to life-threatening disease. However, the lesions caused by infection can lead to cervical cancer in women over the course of 15 to 20 years, based on a number of risk factors: weak immune system; age at first intercourse with an infected partner; multiple sexual partners; and tobacco use. HPV vaccines for both men and women, recommended prior to first sexual encounter, are available for the strains most commonly linked to cervical cancer.

However, these vaccines are either not broadly available in developing countries or are unaffordable. Once the cancer sets in, the only methods for treatment are those similar to other forms of cancer, such as surgery, radiation therapy and chemotherapy (WHO, 2014).

Household (indoor) air pollution

Women do most of the household cooking around the world. In developing countries, low income women cook over traditional stoves using fuels like wood or biomass, which emit high levels of smoke. This pollution causes respiratory infections, heart disease and lung cancer, leading to 4.3 million deaths each year. Of these, 3.1 million deaths occur in South and Southeast Asia, 600,000 in sub-Saharan Africa and 200,000 in the Middle East and North Africa.

While women face greater exposure to indoor air pollution, men account for a higher share of the mortality from respiratory and lung diseases due to higher underlying disease rates: 46 percent of the deaths (1.99 million) are those of men, and 41 percent (1.77 million) are women; 13 percent (534,000) are children (WHO, 2014).

Household air pollution disproportionately affects women and children due to the greater amount of time they spend cooking and preparing food in households, compared to men (Putti, et al., 2015) (**Exhibit 17**). Globally, women experience an estimated 5 percent more exposure to risk from solid fuel household air pollution than men. However, the effects of this exposure discrepancy vary significantly between regions (GBD Risk Factor Collaborators, 2016).

In recent decades, a number of fuel efficient and clean cookstoves have been developed but virtually none have been scaled to make significant impacts. One of the main reasons is that these stoves are competing against a free and long-standing alternative—the traditional three-stone or mud hearth.

While there is clearly a health imperative in reducing household air pollution through cleaner stoves, it is not clear that there is demand for them. Presumably, this is because those most exposed to high indoor air pollution do not see any short-term value in cleaner stoves, especially considering their economic means. In a number of urban markets, liquefied petroleum gas (LPG) stoves appear to be gaining traction (GACC, 2013).

More details on cooking fuels and household air pollution can be found in the Energy Access chapter.

Gender-disaggregated health impacts associated with household air pollution

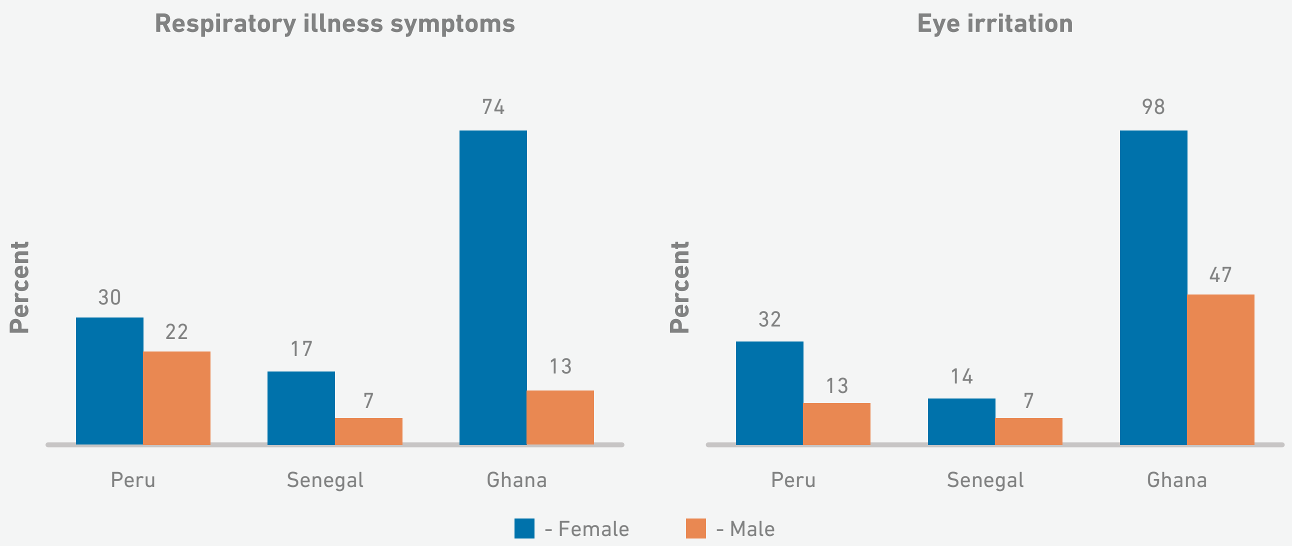


Exhibit 17: Household air pollution disproportionately affects women and children due to their greater amount of time spent cooking and preparing food in households, compared to men.
(Source: Putti, et al., 2015)

Sanitation and menstrual hygiene

There are several other issues, which disproportionately affect low income women but often do not receive adequate recognition in the conversation about global health. Due to the lack of sanitation and safe toilets, millions of women have to urinate and defecate in the open.

In addition to compromising women's basic dignity and hygiene, not having safe toilets also makes women and girls vulnerable to sexual abuse and violence when they use public facilities or venture out in darkness to relieve themselves (BBC, 2014a).

Another major issue is the lack of affordable sanitary pads. Without these, women and adolescent girls have to either stay home, or use uncomfortable cloth rags that lead to poor menstrual hygiene and may cause reproductive tract infections.

Lack of access to suitable sanitary care products causes many girls to interrupt their schooling (sometimes even drop out of school) and older women to interrupt their work and livelihood (BBC, 2014b). More than 70 percent of menstruating women in India can't afford usable products (Times of India, 2011). Evidence suggests that the problem is similarly severe in many other low-income African countries (One Foundation, 2014).

8. Women and girls in low income populations have limited voice in critical decisions regarding marriage and family planning

The lack of agency in the context of family life begins at an early age and is particularly prevalent among lower income families. As **Exhibit 18** shows, women in lower income populations tend to be married at a significantly younger age than their wealthier counterparts (World Bank, 2012).

Many girls from low income families are not able to exercise choice in the use of contraception or in having children. Among these populations, one of the main reasons for low contraceptive use is the refusal of condom use by men (despite significant improvements in access) and the lack of female condom availability.

Such factors lead to significantly higher fertility rates among women in lower income groups.

As **Exhibit 19** shows, women in the poorest quintiles of many countries have twice as many (or more) children as women in the wealthiest quintile. The poorer the country, the greater the gap is between the fertility rates of the rich and poor.

Encouragingly, only 18 percent of women today live in countries where average fertility is above 3 births per woman. This trend is important because lower fertility rates—and the ability of women to have a say in how many children they have, how early they begin having them, how long they wait between pregnancies and when to stop having children—has proven critical to their own health and wellbeing, as well as that of their children and families (World Bank, 2012).

It is also encouraging that long-acting reversible contraceptives (LARCs) like intrauterine devices (IUDs) are becoming increasingly available and affordable in developing countries.

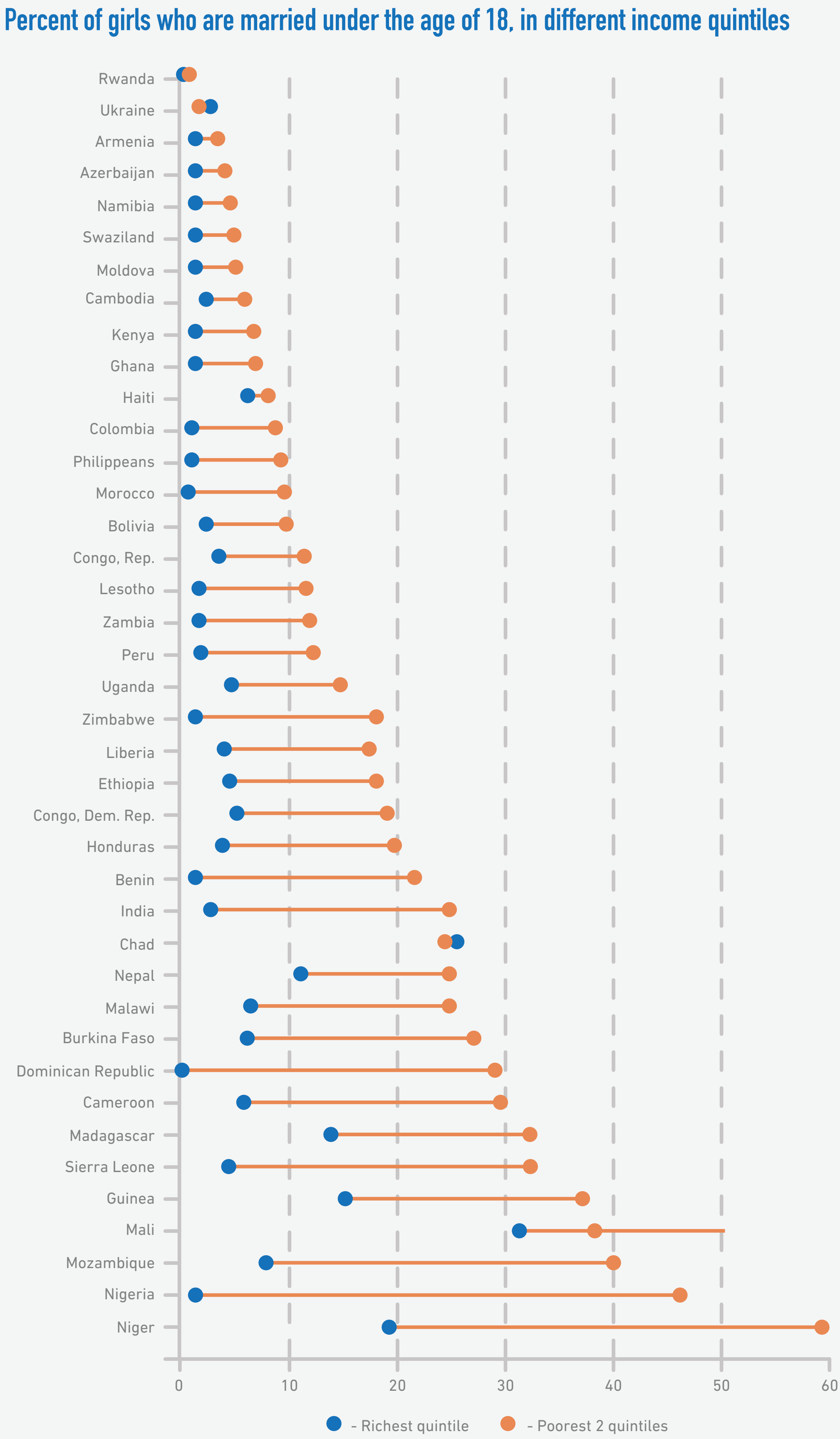


Exhibit 18: Underage marriage is a common phenomenon in many countries, particularly among low income families. (World Bank, 2012).

Fertility rates across different income quintiles

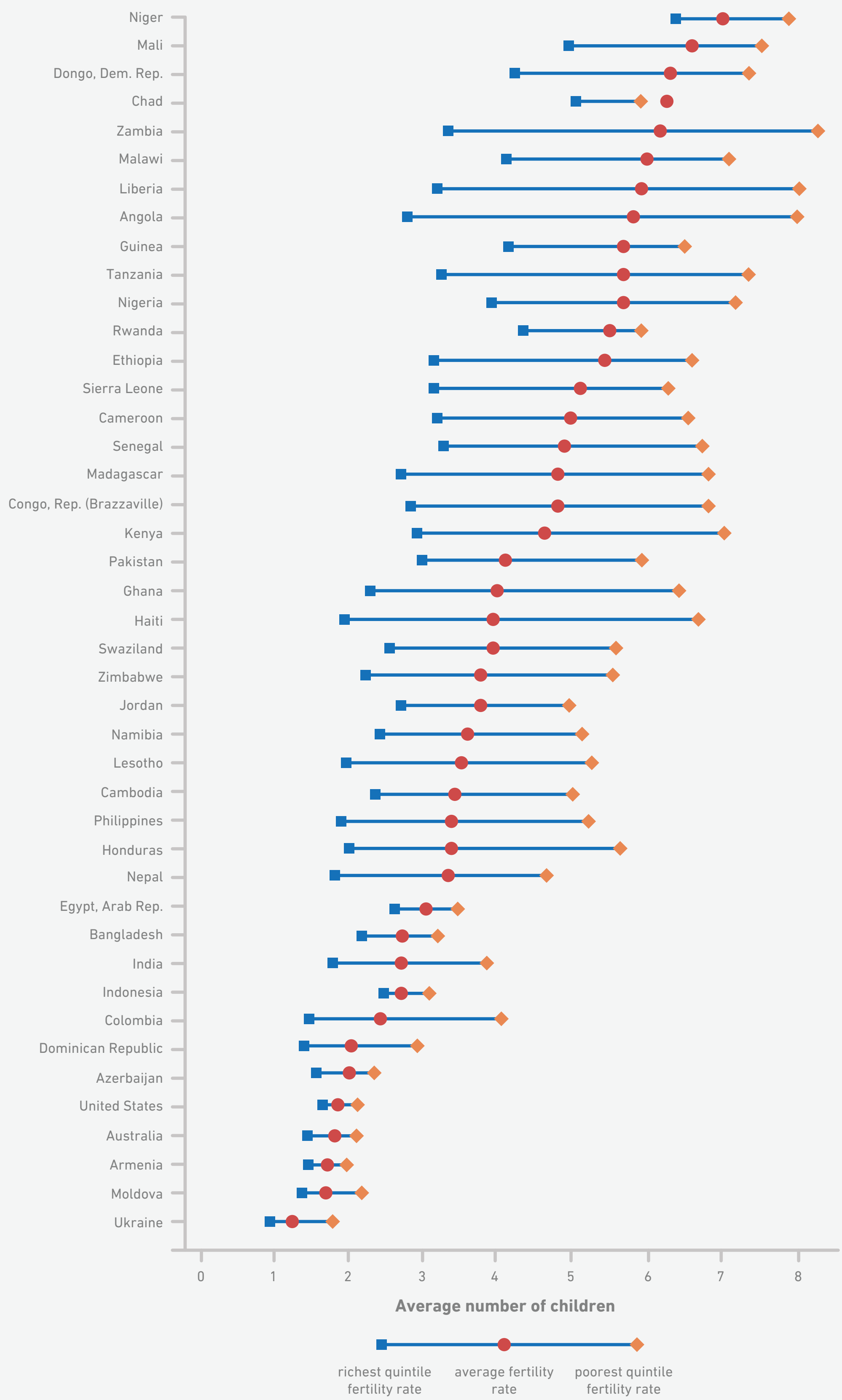


Exhibit 19: Fertility rates vary by a factor of two between the wealthiest and poorest income quintiles in many countries. (World Bank, 2012).

KEY CHALLENGES

There are many reasons why gender equity does not exist in the world today. Some of these explanations are obvious, while others are complex and nuanced. Some are seemingly addressable, while others are deep-rooted and threaten to be an ongoing struggle. Some reasons affect women across income groups, while others are particular to low income populations. The following is a summary—admittedly oversimplified—of the reasons why gender disparities exist among low income populations.

1. Laws to ensure gender equity and protection of women, already weak or poorly enforced in many countries, are even more poorly enforced for low income women

Laws are typically written by male-dominated legislatures and do not reflect the context and challenges faced by women; sometimes, they are outright discriminatory.

For example, equal pay for equal work had not been fully guaranteed by law in the US until recent legislation like the Lilly Ledbetter Fair Pay Act of 2009 (United States Senate, 2009). On the other hand, acts like Kenya's 2014 polygamy law (The Guardian, 2014), allowing men to marry multiple wives, are actively creating barriers against equity.

Even when fair laws are on the books, there is strong evidence to suggest that they are not enforced, especially for low income women (World Bank, 2012; Mehta, 2013). In most regions of the world, fewer than one-fourth of national parliamentarians are women (**Exhibit 20**).

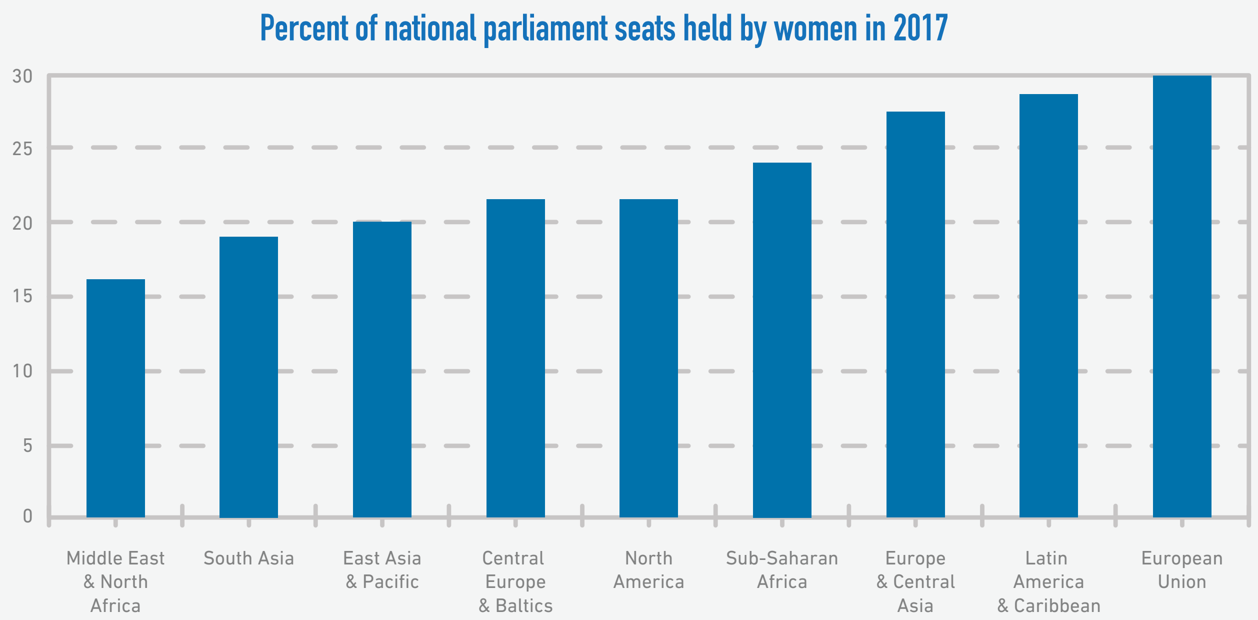


Exhibit 20: Throughout the world, women comprise a small portion of national parliaments. (Source: World Bank, 2018)

2. Customary practices, often discriminatory, coexist with formal constitutional laws

A number of countries have plural legal systems, in which traditional laws and practices coexist with more modern constitutions and legal frameworks. To be clear, not all traditional laws are necessarily discriminatory towards women, nor do modern constitutional laws necessarily guarantee more protections.

Still, it is reasonable to assume that newer laws, based on international standards and legislative debates and under higher levels of scrutiny from the media, tend to be more inclusive than traditional practices.

As **Exhibit 21** shows, almost all countries in sub-Saharan Africa recognize traditional laws, and a substantial number of them are either silent on discriminatory practices or explicitly exempt women from nondiscrimination (World Bank, 2012).

Plural legal system in sub-Saharan Africa

Exhibit 21: Customary laws are part of the formal legal system in most countries in sub-Saharan Africa. This leads to discriminatory practices and laws in much of the region. (Source: World Bank, 2012)

In Pakistan and other Islamic countries there is heavy pressure from religious leaders to impose Sharia Law (which can inflict many restrictions on girls and women, including denial of education). Similarly, the legal systems in countries like India and Israel have also created separate laws for different religious groups.

Often, such laws based on interpretation of religious scripture—rather than on modern constitutional principles—tend to discriminate against women (Amien, 2006; ACLU, 2018). Across the board, wealthier urban populations and the women who live in them, tend to have access to better legal protections from these traditional laws and practices.

3. There are a range of barriers preventing women from seeking available services, leading to a lack of transparency into the condition and specific needs of individual women

Even when women are subjected to physical abuse or other forms of violence, they very often do not seek available remedial services.

There are a number of reasons: stigma associated with filing claims; lack of awareness about their rights or the services available; lack of trust in the system to deliver effective results; inconvenience of the process involved, household and other responsibilities; lack of support from the family or community; and the threat—implicit or explicit—of additional violence. **Exhibit 22** shows that, according to surveys conducted in several countries, only a small portion of the women subjected to domestic violence sought recourse (World Bank, 2012).

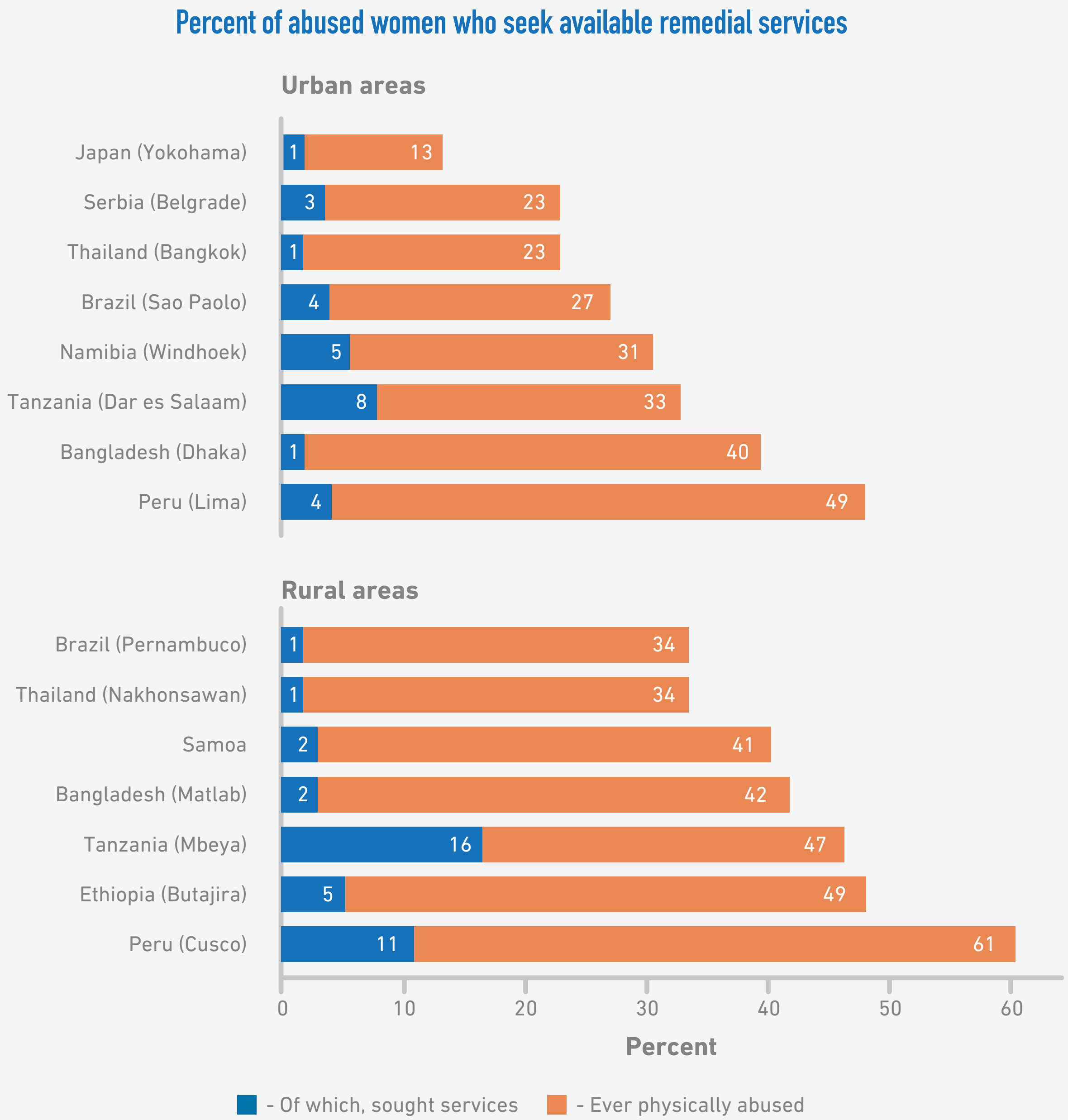


Exhibit 22: In domestic violence cases the vast majority of women do not seek available remedial services. This reluctance is driven by cultural practices, social stigma (or, inversely, support, and interpersonal family dynamics. (Source: World Bank, 2012)

4. Technologies aimed at combating poverty are typically not developed with women in mind, even in the face of evidence that women constitute the majority of users

There is growing research to more accurately account for the quantum of work women do, whether or not they are compensated for it and their contribution to broader economic and social development. Women constitute the majority of farmers, health workers and educators in many countries, but technologies are often not designed with women users in mind.

Too frequently, new technologies are designed by men for men. For example, manual treadle pumps used for irrigation in much of Africa have been reported to be too strenuous and inconvenient for women to use. Thus, women often have to employ young men to operate the pumps for them (Kay & Brabben, 2000).

When designing new technology, developers don't always take into account critical factors, such as women's physical strength, size, mobility, traditional clothing constraints, whether or not they carry children with them during their workday, as well as cultural constraints. Another important consideration not factored into product design is the distance women travel routinely while carrying various types of. loads.

By some estimates, over the course of a year, the average rural African woman transporting water, fuel or produce will carry more than 80 tons over a 1 km distance, while men carry about 10 tons over a 1 km distance (Ashby, et al., 2008). Solutions, such those powered by solar or other renewable energy, can be adapted to the needs of women in rural or semi-rural areas.

One such examples is the solar rickshaw in India (India Today, 2012), which already exist on the market and is slowly converging toward an accessible price point. With the right financial and regulatory support, such a product could go a long way in improving the quality of day-to-day life for rural women.

5. There are significant systemic gaps in basic healthcare, which disproportionately impacts women

While health conditions have generally improved in recent decades, there is still inadequate healthcare infrastructure in many countries, especially in rural or remote areas. There are far too few functional clinics and adequately trained clinicians to operate them and far too little funding to build and support the infrastructure. Today, significant gaps in basic healthcare exist in much of rural Africa and South Asia.

The physical traits unique to women increases their vulnerability to specific health conditions and the absence of essential health services disproportionately impacts them. Specifically, lack of adequate maternal care increases the risk of complications and mortality during childbirth; and the nature of women's reproductive organs increases their vulnerability to sexually transmitted infections like HIV and HPV. As a result, each year, 300,000 women die during childbirth and another 270,000 die from cervical cancer. Also, the prevalence of HIV in sub-Saharan Africa among women is almost twice that among men.

Exposure to a number of health hazards is exacerbated by the poor quality of homes. In particular, inadequate ventilation combined with high levels of indoor air pollution from using traditional cookstoves is a major driver for respiratory diseases. The absence of private toilets exposes women to significantly greater levels of inconvenience and increases the risk of abuse and violence when women are forced relieve themselves in the open or use unsafe public facilities.

The lack of affordable sanitary care products during menstruation increases the risk of reproductive tract infections. While in recent years there has been an increasing effort towards making very low-cost sanitary pads available for women, no single product has yet been scaled to have a broad enough reach. We believe affordable products will become available within the coming years but distribution and adoption, much like other products aimed at the low-income retail market, will be a challenge.

6. Although social media campaigns have successfully created awareness about the scale of sexual violence faced by women, they have failed to overcome these issues

The #MeToo movement is an example of a social media campaign that has drawn attention to the problems of sexual harassment that women face. Originally started in 2006 in the United States, the movement was intended to help survivors of sexual violence, particularly young women of color from low wealth communities.

The movement's twofold objective was meant to address the dearth of resources for victims of sexual violence and to build a community of advocates, driven by survivors who will be at the forefront of creating solutions to interrupt sexual violence in their communities.

The movement came into the limelight in 2017 when Hollywood mogul Harvey Weinstein was accused of sexual misconduct and actress Alyssa Milano encouraged victims to tweet their personal experiences of sexual harassment, essentially providing a sense of the problem's magnitude.

Technology, especially the proliferation of social media channels like Twitter and Facebook, played a pivotal role in echoing the message of millions of women and bringing the movement broad recognition. The usage across social media platforms during first 12 hours of the movement shows that the initial reception of the movement was much stronger in the industrialized parts of the world than in the developing parts (The Telegraph, 2018) (**Exhibit 23**).

Spread of #MeToo movement during the first 12 hours

Exhibit 23: Global social media spread of #MeToo movement focused mainly in North America and Europe during the first 12 hours. (Source: The Telegraph, 2018; © Telegraph Media Group Limited 2018)

Although the movement is having some consequences in parts of the industrialized world, the #MeToo movement has failed to achieve impact in developing countries like India, Kenya, Ghana and South Africa. Even in the developed world, most of the women who've come forward are primarily from middle- to upper- class white communities. There are several reasons why social media campaigns like the #MeToo movement have failed to meaningfully impact lives of women in developing countries:

- Survival and defense against life threatening physical and sexual violence are immediate issues facing women in these countries. Although social media campaigns might advance the overall movement forward, they do not make any tangible difference to the immediate lives of women.

- Women in developing countries have limited access to internet and social media platforms (see **Exhibit 8**). For example, in India only 25 percent of daily internet users in rural areas are women, and 40 percent of urban users are women (IAMAI, 2017).

- A lack of robust legal systems and processes to hold perpetrators accountable leads to women feeling helpless as avenues of getting justice either do not exist or the bureaucracy deters the women from filing complaints.

SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

Technology will not overcome deep-seated and archaic societal attitudes that predominantly dictate women's roles and entitlements and underlie almost every challenge women face.

However, when it comes to some disadvantages faced specifically by low-income women in developing countries, the following six breakthrough technologies can have targeted impact.

Breakthroughs:

1 2 3 4 5 6 7 8 9 10
11 12 13 14 15 16 17 18 19 20
21 22 23 24 25 26 27 28 29 30
31 32 33 34 35 36 37 38 39 40
41 42 43 44 45 46 47 48 49 50

7 Affordable (less than $50), lightweight, energy-efficient, solar-powered irrigation pumps

Irrigation is one of the most significant levers for increasing on-farm yield. However, currently available manual irrigation pumps (for example, treadle pumps) are quite strenuous to use and often not suited to the needs of women farmers. Motorized pumps available on the market are even more expensive, and the cost hurdle is compounded by the recurring cost of diesel fuel. In remote areas, the paucity of distribution networks for diesel is an additional constraint.

A solar powered pump that costs under $50, and pumps enough water for a typical smallholder farm, could dramatically increase access to irrigation. Direct-drive photovoltaic solar pumping can be quite efficient, as all harvested power is used for pumping and there is no need for batteries and associated losses.

Modern positive displacement pumps have efficiencies of up to 70 percent. Nevertheless, a significant barrier to the scale-up of PV-powered irrigation pumps is the high upfront cost of PV systems, which are typically 10 times that of conventional pumps. Despite the very low operating costs of solar irrigation pumps, the high capital cost leads to untenably-long economic payback times. Strongly reducing cost, while ensuring reliable service, is thus essential.

Considering the effort being dedicated to this problem and the pace with which this market is developing, it is likely that low-cost market-ready pumps will become available within the next four to six years. A number of organizations are developing solar pumps, a small number of which are already being used in India and other developing regions.

The biggest hurdle appears to be throughput: the greater the volume of water pumped, the larger and more expensive the solar panel needs to be.

Development Stage: Engineering

Time to market (years)

<5 5-7 7-10 10+

Deployment: Complex

Associated 50BT Chapters

Water Security

Food Security

SDG Alignment

2 ZERO HUNGER

6 CLEAN WATER AND SANITATION

Impact

Increased Access to Food (# of People)

<1M 10M+ 100M+ 1B+

New Income Generated (# of People)

<1M 10M+ 100M+ 1B+

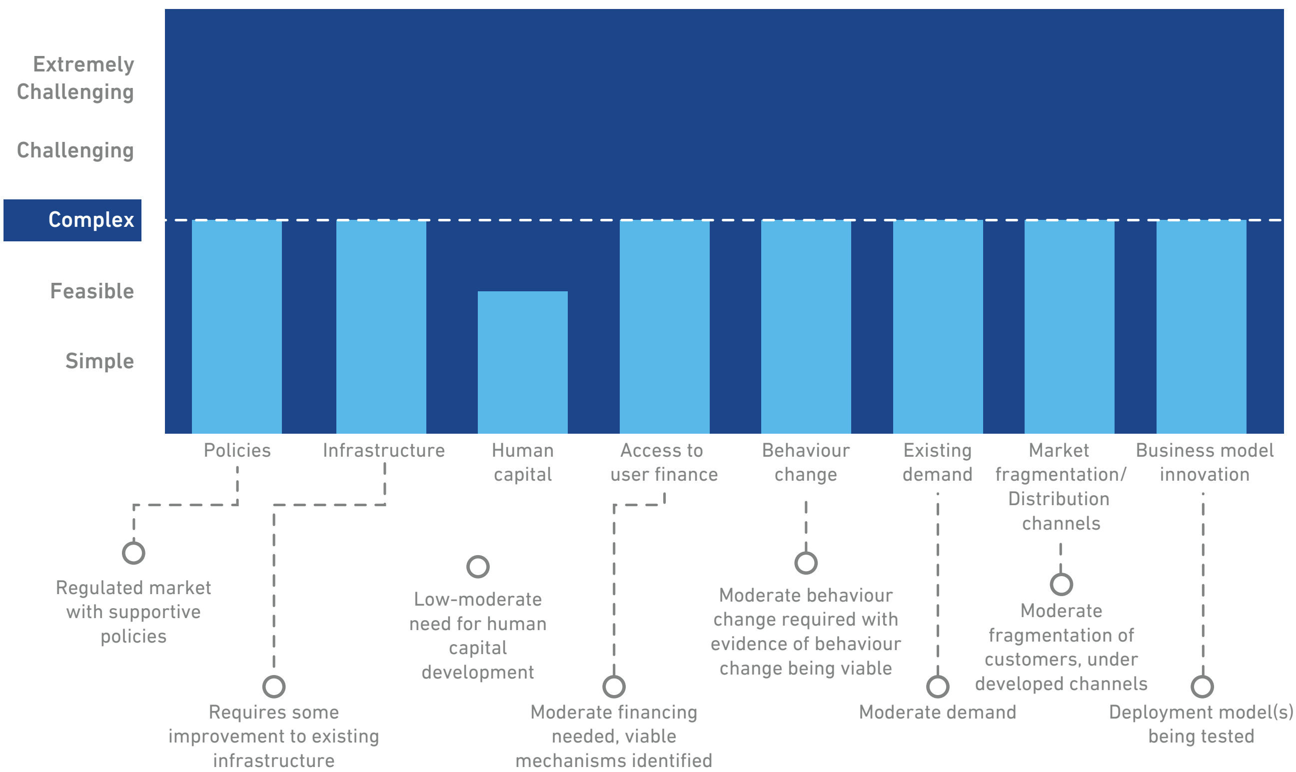
Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- **Attractive for emerging markets (lower profits)**
- Emerging markets potential; requires derisking (sustainable)
- Non-commercial (unprofitable)

However, even if solar pumps become available, there are a number of deployment hurdles: the majority of African farmers are still extremely poor, live in remote areas and are accustomed to rain-fed farming. Considerable effort will be required for creating demand and providing financing and training. A critical lesson from the decades of agricultural development in South Asia is that water can easily be overused and groundwater easily depleted.

Since there is zero marginal cost for solar water pumping, there is a risk of unrestrained aquifer depletion if the technology is scaled up in the absence of rational water allocation systems. Enforcing any such system will be very challenging. Hence, we believe that deployment will be COMPLEX.

Breakthrough 7: Difficulty of deployment



19 Affordable healthy homes that are resilient to extreme weather events

Shelter is a fundamental human need, but a large segment of the world's population is either homeless or lives in very poor housing conditions. Almost 70 million people are refugees or displaced persons who have been forced to flee their homes and find shelter elsewhere.

More than 800 million people reside in urban slums, often living in improvised dwellings with insecure land tenure. Long-term trends towards urbanization suggest that the urban population in less developed regions, currently less than 3 billion, will exceed 5 billion people by 2050. Creating adequate housing to accommodate this number of people will be challenging.

A growing challenge is the increasing frequency and intensity of extreme weather events, due to global climate change, which are expected to alter the habitability and safety of homes. A comprehensive and lasting solution to the problem of inadequate shelter requires concerted action in the political, economic and technological spheres. In particular, technology-related advances are needed to develop robust, affordable and environmentally compatible housing materials and designs that can scale-up to meet global demand.

Constructing housing with traditional building materials used in rural areas, such as grass and earth, cannot scale up sufficiently in urban areas with much higher population densities. The only option for poorer segments of the population is to create provisional shelter from found materials such as cardboard and plastic sheets. Due to their exposure to physical insecurity and unsanitary living conditions, life is precarious for this segment of the population.

A breakthrough is needed to develop a functional and very low-cost housing system accessible to the global poor that is resilient to extreme weather events. Applied research is needed to identify appropriate types of building materials and the scale and location of manufacturing facilities in different social, geographical and cultural contexts.

Trade-offs may exist between large-scale centralized production versus smaller-scale decentralized production closer to end users. Trade-offs may also exist between production automation and local employment opportunities. The potential use of locally-available raw materials suggests that various geographically specific solutions may exist.

Development Stage: Engineering

Time to market (years): <3 | 4-6 | 7-10 | 10+

Deployment: Complex

Associated 50BT Chapters

Global Change

Gender Equity

SDG Alignment

Impact

Improved Quality of Life (# of People): <1M | 10M+ | 100M+ | 1B+

Health Improved (# of People): <1M | 10M+ | 100M+ | 1B+

Commercial Attractiveness

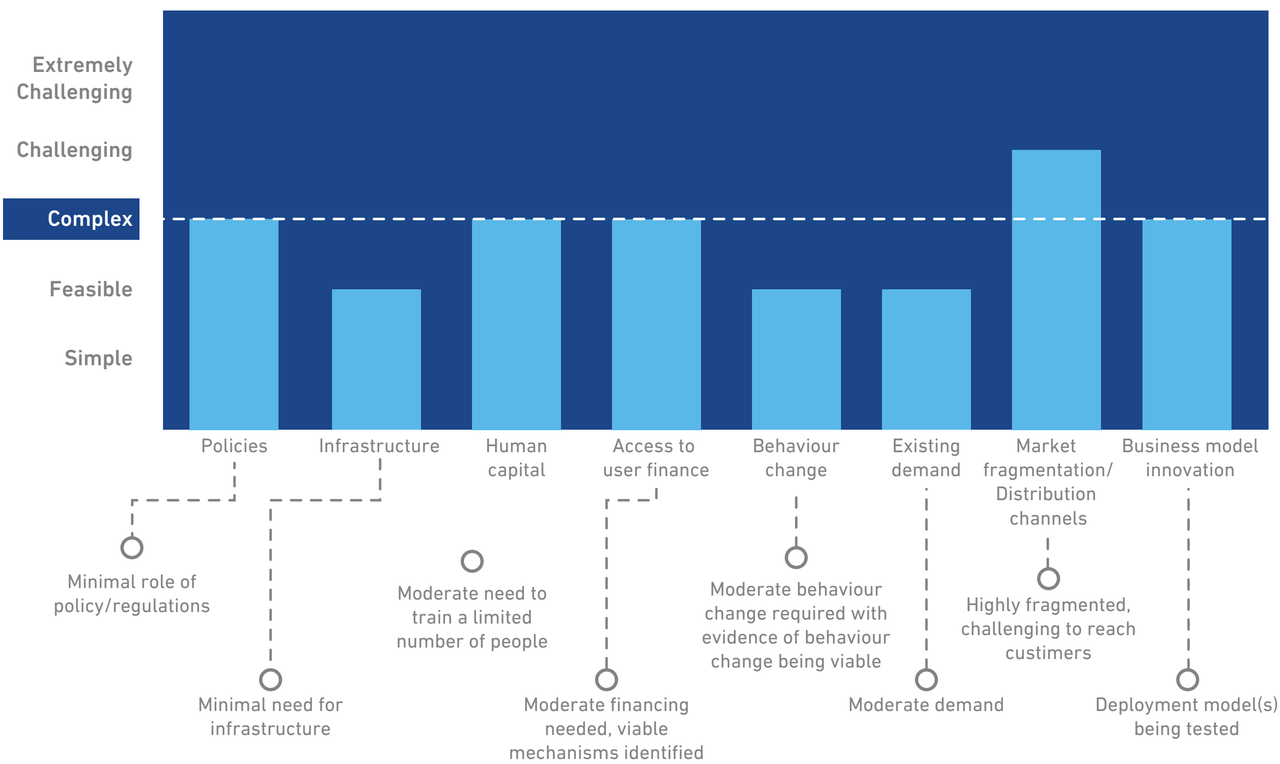
- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

Beyond material properties, sensitive design work is required to produce robust, efficient, comfortable and culturally-appropriate housing solutions that can scale to the extent needed. Potential integration of renewable energy technologies, such as photovoltaic or solar-thermal collectors, could allow synergies between human development goals.

While broad in scope, if resources were allocated to allow adequate research and development efforts, we expect that it will take five years for this breakthrough to be deployment ready.

Significant deployment challenges include a fragmented building industry with multiple actors and components, access to finance for both producers and end users and municipal and national policies supporting urban poor. The difficulty of deployment would be COMPLEX.

Breakthrough 19: Difficulty of deployment



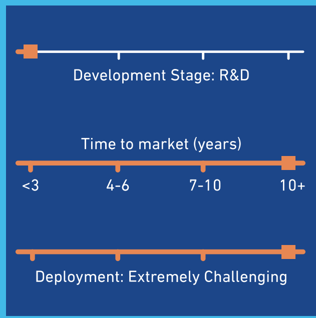
20 A simple point-of-use, low cost DNA-based rape kit capable of delivering rapid results

Sexual violence occurs for a whole host of reasons, including gender discrimination, societal and interpersonal power dynamics and impunity that comes from the lack of accountability.

A major challenge is that even if a person overcomes the stigma associated with being a victim of sexual violence and lodges a formal complaint, there is limited evidence to make a robust legal case. Rape kits to preserve semen and other degradable biological tissue and conduct DNA analysis to match against potential perpetrators are becoming increasingly common in higher income countries.

However, these require skilled technicians and a sophisticated, expensive laboratory to analyze the samples. To be useful in low resource or conflict settings, a rape kit would have to be very low cost (less than $10 per test, with the processing equipment not more than a few hundred dollars), usable off-grid and not require much clinical training to use. In addition, the analysis should be rapid, with the ability to digitize and transmit relevant data for secure (presumably cloud-based) storage.

Similar low-cost DNA-based technologies being prescribed and developed for medical diagnostics, are approximately three to five years from becoming available on the market. In principle, a DNA-based rape kit should not take more than five years beyond that.



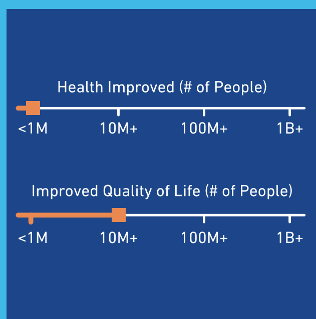
Associated 50BT Chapters

Human Rights

Gender Equity

SDG Alignment

Impact



Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- Emerging markets potential; requires derisking (sustainable)
- **Non-commercial (unprofitable)**

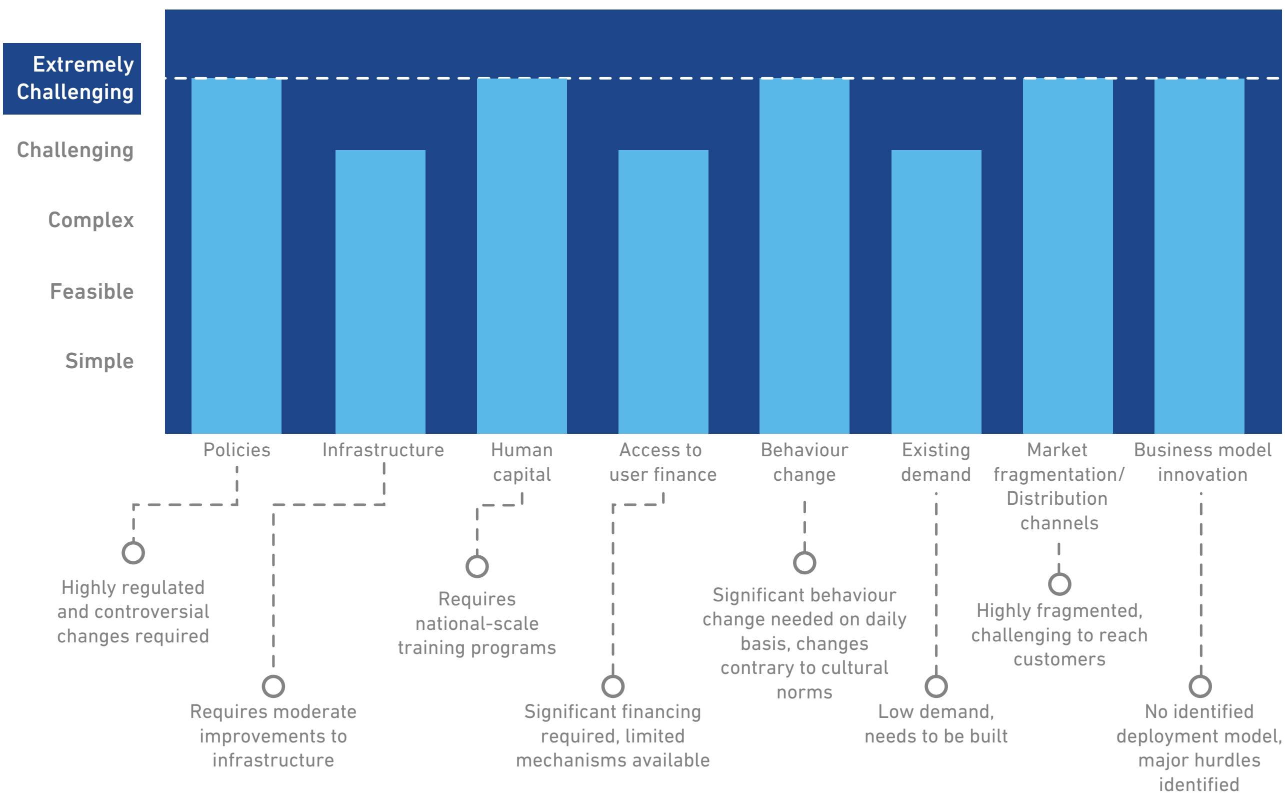
However, once developed the technology will face significant challenges in deployment along virtually every dimension. Enough facilities (such as health clinics) will need to have the device at hand, those administering the test will require some level of training, and financing will be necessary to cover the costs involved.

Without financing it will also be very difficult for health facilities to ensure a steady supply of the kits and maintain the processing equipment.

Moreover, policy changes will be necessary to determine how the judicial systems of different countries can best use such evidence in their legal proceedings.

Furthermore, rape kits can be administered only if a victim seeks help immediately after the incident while the biological evidence is still intact. For these reasons, deploying such a technology will be EXTREMELY CHALLENGING.

Breakthrough 20: Difficulty of deployment



24 Microbicides to provide a method of protection for those who are otherwise vulnerable to HIV/AIDS infection by their partner

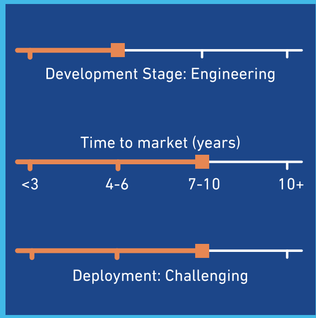
Women, especially those living in societies and situations plagued by gender and income inequality, are often limited in their ability to ensure that their sexual partners use condoms. This risk is exacerbated in places with high rates of sexual violence and prevalence of polygamy. Specific high-risk populations, like sex workers and transgender people, also find themselves restricted in their ability to use protection during sexual contact.

Microbicides are currently under development as vaginal or rectal products designed to protect healthy men and women from HIV/AIDS infection. These products are being tested in multiple forms—vaginal and rectal gels that can be used at the time of sexual contact and vaginal film, tablets or rings that can slowly release the microbicide drug to provide preventative coverage for up to a month.

Unlike vaccines, an effective microbicide must be made into a commodity that individuals will want to and can safely use, on a regular basis. Ideally, microbicides would be discreet, easy to use, long-lasting and easy to distribute.

There are several different microbicide candidates currently being studied. Between 2012 and 2016, two Phase III trials were conducted on the dapivirine vaginal ring and showed that ring use reduced the rate of new HIV infections by 56 percent among the women who used it as instructed (AVAC, 2018). Regulatory decisions are expected by end of 2018.

A couple of other studies are looking into how young women use the ring. Even after regulatory approval, the ring will take a few years before it becomes available for use. It will also take time to work out the best formulation and dosage, find a suitable delivery method and identify appropriate distribution channels before the product can be made available to the public.



Associated 50BT Chapters

Global Health

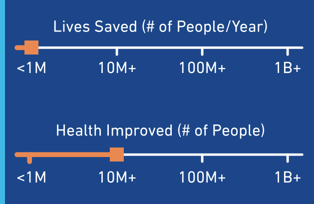
Gender Equity

SDG Alignment

3 GOOD HEALTH AND WELL-BEING

5 GENDER EQUALITY

Impact



Commercial Attractiveness

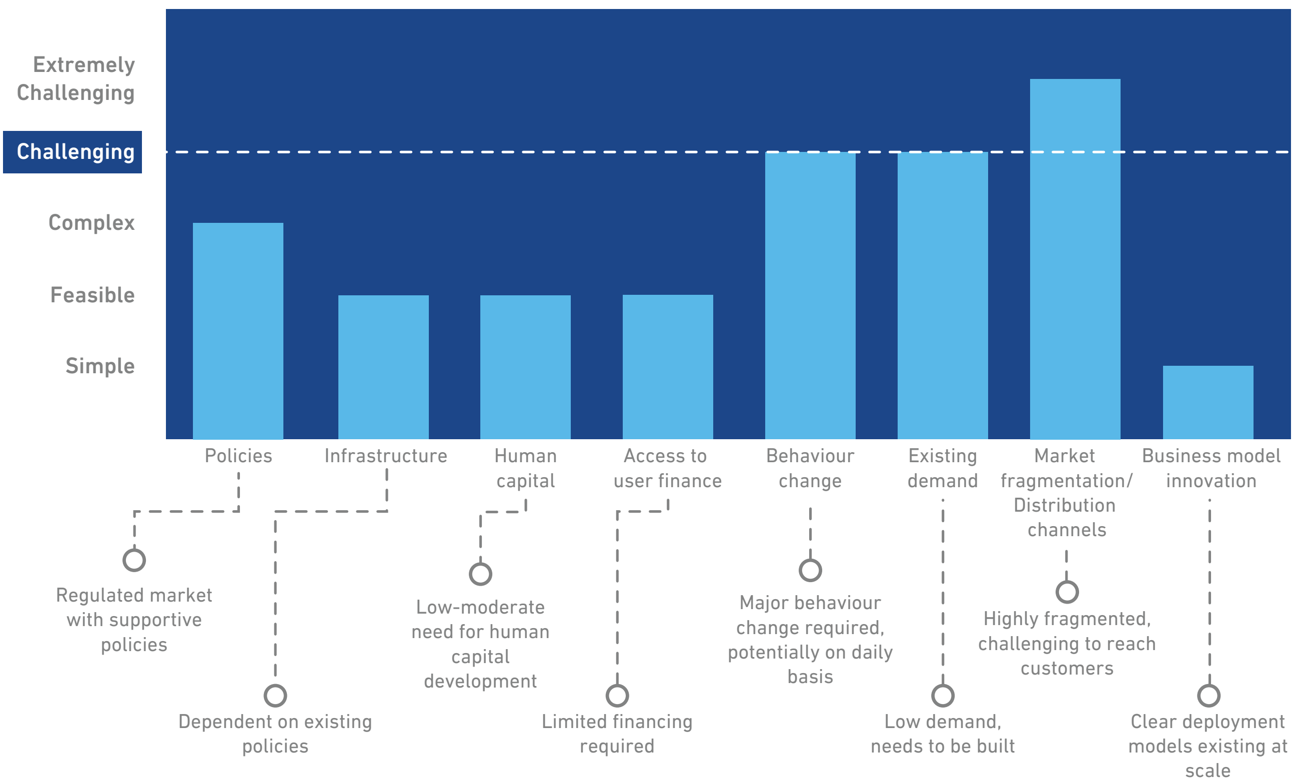
- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

Difficulty of deploying microbicides, once available, will depend on human factors, including how easy and convenient they are to use (microbicides require regular reapplication) and whether they are made available to consumers over the counter or by prescription only.

To ensure microbicides are widely available to people in LMICs, the price will have to be affordable, and this may mean that profit margins have to be kept low.

Based on the above assessment, the projected time to market readiness is one to five years and the level of difficulty for deployment is CHALLENGING.

Breakthrough 24: Difficulty of deployment



46 Advanced biomass cookstoves that are desirable, affordable, robust and very clean

Biomass such as wood, straw and dung is the primary cooking fuel for about 2.5 billion people, or a third of the world's population. Household air pollution caused by these fuels causes millions of deaths each year, due to illnesses such as lower respiratory infection, lung cancer, ischemic heart disease, stroke and chronic obstructive pulmonary disease.

Despite major initiatives to extend access to cleaner cooking fuels like gas and electricity, more households currently use solid fuels for cooking today than at any time in human history, due to growing population size. It is likely that billions of people will continue to cook with biomass for the foreseeable future, due to economic, logistical and cultural barriers to change.

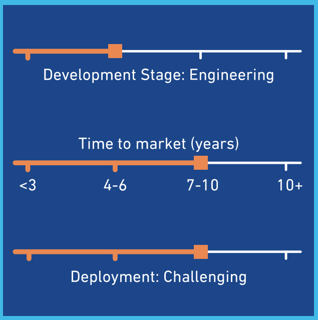
Design and deployment of improved biomass cookstoves has been an important goal of global development efforts for many decades. A wide range of biomass cookstove improvements have been proposed and trialed, with significant reduction in emissions of air pollutants like particulate matter and carbon monoxide.

Some of these improved stoves have reached moderate levels of deployment in low-income countries. However, recent research has shown that the exposure-response relationship for household air pollution is non-linear, thus the large reduction in emissions from current improved stoves brings only a modest decrease in health risk.

To effectively eliminate the serious health risk of household air pollution, stove emissions must be reduced much further than is possible with current biomass stove designs.

A new generation of advanced biomass cookstoves is needed, with greatly reduced emissions so they have low health risk that is comparable to other clean cooking solutions like gas and electricity. Advanced biomass cookstoves typically use complex, multiple stage combustion methods in order to burn fuel efficiently and minimize harmful emissions.

Current versions of advanced biomass cookstoves often have high upfront costs, offer less cooking flexibility, need pre-processed fuels and require an electricity supply to power built-in fans, yet still do not reliably achieve emission levels low enough to eliminate health risk in people's kitchens.



Associated 50BT Chapters

Access to Energy

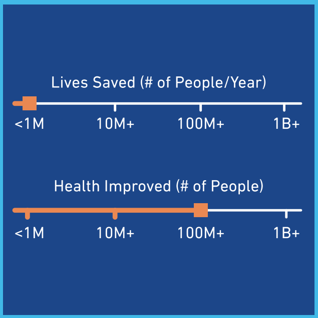
Gender Equity

SDG Alignment

3 GOOD HEALTH AND WELL-BEING

7 AFFORDABLE AND CLEAN ENERGY

Impact



Commercial Attractiveness

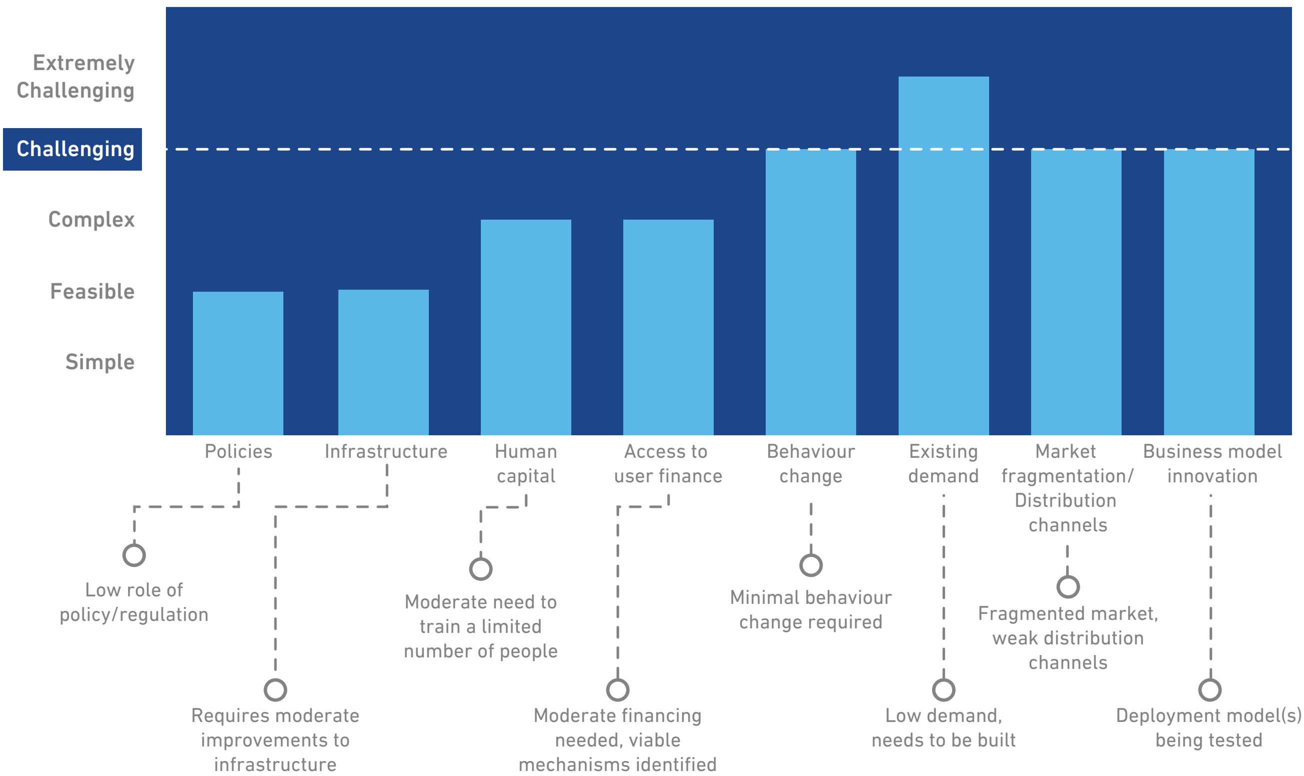
- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

An effective advanced biomass cookstove must be durable, low-cost and low maintenance. It will preferably use unprocessed fuel, or fuels that can be processed locally with available equipment. It will be compatible with traditional foods and cooking styles and not require major behavioral change by the users. Above all, it must employ extremely efficient combustion processes and emit very low levels of dangerous pollutants.

This breakthrough will require significant advances in thermodynamic and combustion sciences, as well as outstanding user-centric design. Innovative business models will be required, and significant outreach will be needed in some regions to ensure sufficient demand.

The projected time to market readiness of a breakthrough advanced biomass cookstove is five to seven years, and the difficulty of deployment is CHALLENGING.

Breakthrough 46: Difficulty of deployment



46 Novel ways of converting household or village waste products into clean cooking fuel or electricity

Gas and electricity are recognized as very clean and safe cooking fuels, yet their usage remains very low in rural areas of developing countries. This is mainly due to the high cost and logistical challenges involved in extending the required infrastructure to these areas. Liquified petroleum gas (LPG) is typically transported in cylinders, which requires an adequate road network and sufficient truck fleet that are lacking in many areas. Natural gas is typically transported in pipelines, which are very expensive and therefore limits the use of natural gas in areas distant from gas wells.

The price volatility of LPG and natural gas makes it difficult for low-income households to have consistent access to the fuels. Electrification of rural areas is a longstanding challenge, and even in areas that are nominally connected to the power grid, electric cooking is seldom practical due to unreliable supply and the high power requirement of electric cookers.

Decentralized production of biogas by means of anaerobic digestion of organic materials such as manure and crop waste is an established practice, but is used by only a small fraction of households, mainly in China where it is supported by government subsidies. Use of anaerobic biogas digesters requires a large upfront cost, and most biogas systems require skilled installation and maintenance which is unavailable in most developing countries.

While clean cooking fuel is lacking in rural regions, many areas have abundant organic waste materials such as human waste, animal waste, crop residue or household garbage. A breakthrough is needed in the form of an affordable, robust process to convert diverse organic waste products into clean and reliable gas or electricity for cooking. Such a process would not only provide clean cooking fuel, but would safely dispose of waste products and result in cleaner surroundings. In principle, this could be achieved by various conversion routes, such as biochemical, thermochemical or electrical.

- Biochemical processes would use living organisms to produce biogas. This could take the form of improvements to existing anaerobic digestion processes to make them less capital-intensive with easier installation and maintenance. Advances in genetic editing might be used to create microorganisms capable of digesting a wider range of input materials. If human waste were used as input material for fuel production, cultural concerns among some population segments would need to be addressed.

Development Stage: Engineering

Time to market (years)

<3 | 4-6 | 7-10 | 10+

Deployment: Challenging

Associated 50BT Chapters

Access to Energy

Global Health

Gender Equity

SDG Alignment

3 GOOD HEALTH AND WELL-BEING

7 AFFORDABLE AND CLEAN ENERGY

Impact

Lives Saved (# of People/Year)

<1M | 10M+ | 100M+ | 1B+

Health Improved (# of People)

<1M | 10M+ | 100M+ | 1B+

Commercial Attractiveness

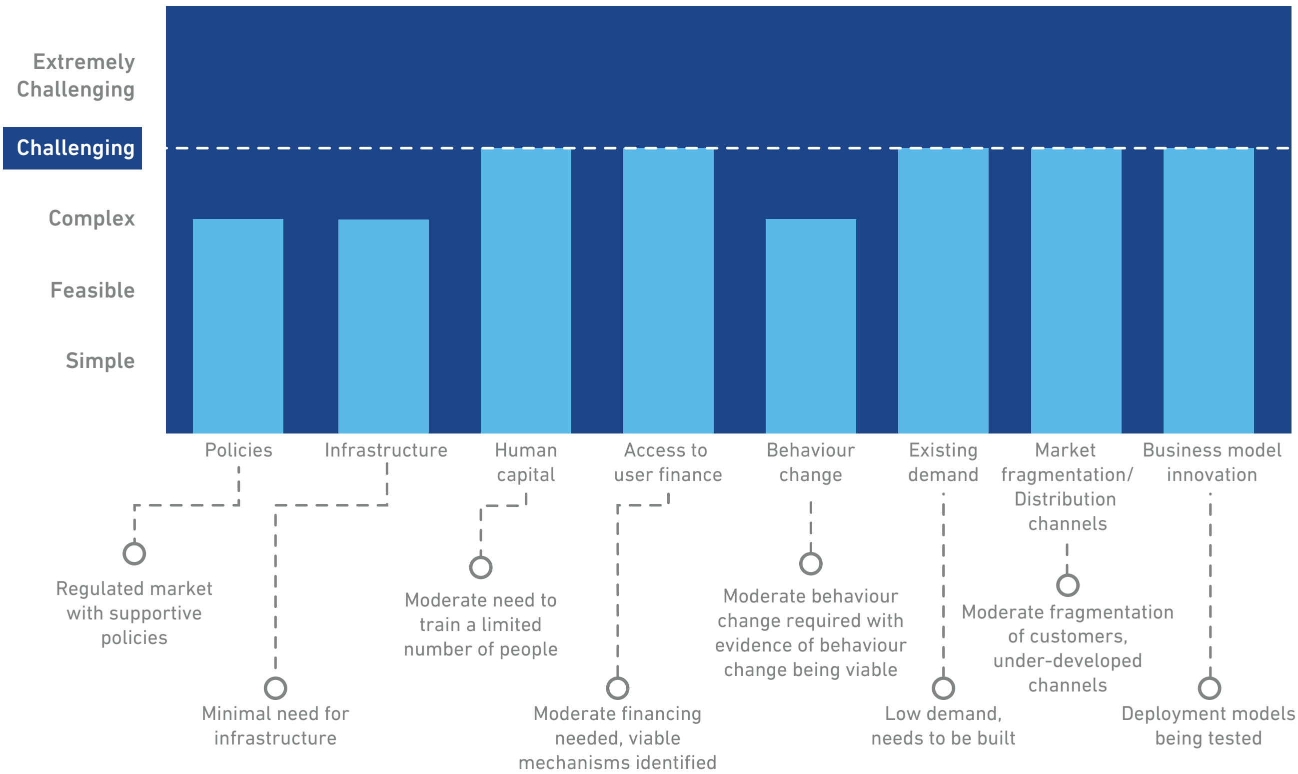
- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

- Thermochemical methods, such as pyrolysis or gasification, use high-temperature processing to produce syngas. These methods are well established at industrial scales, but are less well developed at smaller scales suitable for villages and households. Current small-scale methods are quite polluting, and are relatively complex and require skilled operation and maintenance. In addition to cooking fuel, thermochemical processes typically produce biochar that could be used as a soil amendment.

- Electrical methods would convert the chemical energy of the waste products into electricity, which is a clean and safe form of cooking. Because cooking requires a relatively high electric current, and is typically practiced only at certain times during the day, the most suitable form of village-level electricity production for cooking may be a small-scale "peaker plant" that only operates during limited hours when meals are prepared, and would supplement a solar powered mini-grid that provides continuous power for lighting and other uses. For example, a batch-fired thermochemical gasifier could be combined with an electrical generator to provide a village with sufficient electricity for cooking during several hours in the morning and again in the evening.

There are numerous technology pathways by which this breakthrough could be realized. It will likely require advances in relevant disciplines, such as biological or mechanical engineering. It will also require a thorough understanding of the needs and wishes of the users, and innovative design and implementation to ensure satisfaction. Appropriate business models will be needed to provide economic sustainability. The projected time to market readiness of this breakthrough is seven to 10 years, and the difficulty of deployment is CHALLENGING.

Breakthrough 47: Difficulty of deployment



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HUMAN RIGHTS

HUMAN RIGHTS

INTRODUCTION

The enjoyment of basic human rights is a core goal of global development efforts.

Human rights in a formal sense refer to a set of legal entitlements accorded by states that have signed and ratified specific international laws and protocols, usually translated into domestic legislation. They include civil, political, economic, social and cultural rights, protections for specific vulnerable populations, and restrictions of particular actions or weaponry in the context of conflict.

Adoption of the Universal Declaration of Human Rights and subsequent international legal instruments have led to a marked improvement in the protection of human rights around the world. Still, universal respect for human rights is far from being a reality. Severe violations of the rights of individuals and communities are common at the hands of state or non-state actors. Interventions aimed at either preventing the abuse of human rights or ensuring accountability for perpetrators, tend to diminish in scope and effect especially when faced by the systemic absence of rule of law, real or perceived impunity, lack of rapid-response preventative mechanisms and the difficulty of collecting adequate evidence for prosecution.

In recent years, new information and communication tools—particularly digital photography and social media platforms—have played a very important role in increasing transparency and collecting and collating various types of evidence. Our analysis concludes that more progress can be achieved with the help of three technological breakthroughs.

- Breakthrough 20. A simple point-of-use, low cost DNA-based rape kit capable of delivering rapid results
- Breakthrough 21. Low cost (less than $50) wearable, or otherwise easily concealable, cameras with automatic geocoding and timestamps, capable of SOS data preservation (such as via satellite)
- Breakthrough 22. Low-cost aerial vehicles to capture high-resolution imagery for use by civil society groups, to document large-scale human rights violations

Human rights, as a standardized, broad, international construct, were developed formally after the Second World War. The Universal Declaration of Human Rights—embracing the notion that "All human beings are born free and equal in dignity and rights"—was adopted by the United Nations General Assembly in December 1948. The declaration, even today, remains the foundation of international human rights law.

CORE FACTS AND ANALYSIS

Since its adoption in 1948, the Universal Declaration of Human Rights has inspired a multitude of instruments (more than 80 declarations, treaties, covenants, conventions and bills), with various degrees of enforceability under national or international law. Some of the constructs within these instruments still remain aspirational. **Table 1** summarizes the chief instruments that embody the broad set of human rights as codified into various legal instruments (Weissbrodt & de la Vega, 2007). These include:

- The International Bill of Human Rights, which is comprised of the Universal Declaration of Human Rights, the International Covenant on Civil and Political Rights and the International Covenant on Economic, Social and Cultural Rights
- Six core treaties, which specify protections for specific vulnerable populations like children, migrants and the disabled, and the Convention Against Torture
- A range of Humanitarian Laws governing the conduct of armed conflict including the Geneva and Hague Conventions
- A number of topic-specific treaties, such as the ban on landmines and cluster bombs, and the Rome Statute, which created the International Criminal Court (ICC) to prosecute war crimes, crimes against humanity and genocide

A summary of key human rights instruments

Internation Bill of Human Rights	1. Universal Declaration of Human Rights: equality, liberty, fair trial, privacy, nationality, marriage, religion, employment, clothing, medical care, free/compulsory elementary education, etc. 2. International Covenant on Civil & Political Rights: self-determination, life, cruel/inhuman/degrading punishment, slavery, liberty/security of person,treatment of prisoners, legal rights, etc. 3. International Covenant on Economic, Social & Cultural Rights: economic/social/cultural self-determination, subsistence, working conditions, standard of living, housing, education, etc.
Six core Human Rights treaties	1. Convention on Elimination of [_] Racial Discrimination 2. Convention on Elimination of [_] Discrimination Against Women 3. UN Convention Against Torture 4. Convention on the Rights of the Child 5 Convention on the Rights of Persons with Disabilities 6. International Convention on the Protection of the Rights of all Migrant Workers and Members of their Families
Humanitarian Law (governing conflict)	1. Geneva Conventions (on conduct of war) • Four conventions (treatment of wounded & sick, prisoners of war, protection of civilians) • Two amendment protocols (protection of victims of international armed conflict, non-international armed conflict and adoption of additional emblem (for medical services) 2. Hague Conventions (prohibition of chemical & biological weapons, etc.)
Other topic-specified treaties	1. Mine Ban Treaty 2. Convention on Cluster Munitions 3. Rome Statue of the International Criminal Court (for genocide, war crimes, crimes against humanity)

Table 1: Human rights instruments can be roughly grouped into four categories: the International Bill of Human Rights, six core treaties specific to the rights for various vulnerable groups, international humanitarian laws governing the rights of combatants and non-combatants in armed conflict and topic-specific treaties. (Source: adapted from Weissbrodt & de la Vega, 2007)

1. Human rights violations involve a wide range of perpetrators and victims

Despite the formal presence of various human rights instruments, various perpetrators routinely violate rights-of individuals or specific groups of individuals.

These actors can range from representatives of the state like the military and law enforcement agencies to non-state actors, such as armed groups, corporations, citizenry and organized crime groups. **Table 2** illustrates a typology of typical violations.

Typology of human rights violations

PERPETRATORS	TYPICAL VICTIMS				
	Workers	**General citizenry**	**Minorities and marginalized communities**	**Women**	**Combatants**
Military, paramilitary & non-state armed groups	Forced labor	• Human shields • Use of banned weapons	• 'Ethnic cleansing' • Forcing children into war	• Rape as a weapon of war • Sexual slavery	• Torture • Extrajudicial killing • Denial of POW rights
Law enforcement agencies	Forced labor	Denial of due process	Denial of due process	Harrassment of victims of sexual violence	N/A
Businesses	• Explotative conditions or wages • Child labor	Environmental destruction	Appropriation of land and other resources	Exposure to dangerous conditions	N/A
Citizenry	Abuse of domestic workers	Inter-community violence	Inter-community violence	Rape based on ethnicity or religion	N/A
Organized crime	Human trafficking	• Human trafficking • Terrorizing civilian population	N/A	Sex trafficking	N/A

Table 2: An indicative typology of the types of human rights violations that may occur at the hands of different types of perpetrators. (Source: ITT analysis)

Military or paramilitary forces and non-state armed groups

Armed state or non-state groups are often accused of using excessive force and violence on civilian populations, sexual violence in conflict settings and performing extrajudicial executions. For example, after a pro-independence referendum in 1999, pro-Indonesia militia allegedly attacked East Timor (occupied by Indonesia since 1975), killed more than 1,400 civilians and displaced 90 percent of the population.

Beginning the mid-nineties, the Democratic Republic of Congo witnessed heavy conflict involving state militia and rebel groups, with thousands of casualties and reports of widespread sexual violence (Human Rights Watch, 1999). In Colombia, both the FARC rebels and right-wing paramilitaries have been accused of large-scale violence and killings (Human Rights Watch, 2013).

Similarly, armed forces representing Israel have been accused of causing excessive civilian casualties in Lebanon in 2006 (Human Rights Watch, 2007), as have Indian armed forces in Kashmir since the 1990s (Amnesty International, 1995). In many conflicts, rape has been used as a weapon of war (UN Human Rights, 2014).

In Syria, the race to gain territory and secure power has led to grave violation of human rights. More than 40,000 have died since 2011, with 5 million people seeking refuge and more than 6 million displaced internally. More than half a million people are still living in besieged areas.

The Syrian regime uses arbitrary detention, torture and enforced disappearances as a method of compliance. As of 2017, more than 4000 individuals remain under forced arrest and more than 80,000 are reported missing. These individuals include notable activists and civilians protesting against the government.

Non-state armed groups like Hay'et Tahrir Al Sham (HTS), ISIS and Kurdish Party have been responsible for car bombings, civilian shootouts and political opposition, all leading to mass fatalities (Human Rights Watch, 2018a).

Law enforcement actors

Representatives of the police, judiciary and other law enforcement agencies can commit violations against citizens through arbitrary detention, torture, denial of justice and extrajudicial killings. Prominent examples of police brutality include the long-standing record of the Egyptian police, which eventually led to the 2011 popular uprisings (The Economist, 2013), and the Georgian police, where a majority of the force was fired after reforms were enacted in wake of the 2003 Rose Revolution (World Bank, 2012).

Such allegations are not restricted to developing countries. Several human rights groups have accused the United States, the United Kingdom and other OECD countries of gross violations through acts of extraordinary rendition and indefinite detention in prisons like the one in Guantanamo Bay in the aftermath of 9/11 (Human Rights Watch, 2014a).

Private businesses

Large international and national corporations are regularly accused of exploiting workers, subjecting employees to hazardous working conditions, displacing local populations, polluting the environment and using child labor.

Prominent examples of allegations include the forced displacement of the Ogoni people (as well as complicity in the execution of Ken Saro-Wiwa, the noted human rights activist) by the Shell oil company in Nigeria in collusion with the Nigerian military regime (New York Times, 2009), heavy pollution of the rainforest in Ecuador by Chevron (New York Times, 2014a) and use of 'sweatshop' labor by textiles, fashion and apparel (TFA) companies, such as Nike, Reebok, Adidas, Gap and Disney (Harrison & Scorse, 2010).

Such violations can be committed by multinational companies, local suppliers (including sub-contractors), private security firms they hire, or other value chain partners. Four industries—extractives, retail and consumer goods, pharmaceuticals and chemicals and infrastructure and utilities—account for the vast majority of documented violations by businesses (Wright, 2008).

Citizenry

Members of the citizenry can commit violations against their fellow citizens for a number of reasons. Traditional practices in many cultures around the world often discriminate against women and girls, through practices like child marriage, dowry-related abuse, female genital mutilation and even honor killings (WHO, 2013; Human Rights Watch, 2018b).

In ethnically-driven or religious conflicts communities can turn on each other, as seen in the Rwandan genocide in 1994 (UN Human Rights Council, 2014), the wars in the former Yugoslavia from 1992 to 1995 (International Criminal Tribunal for the former Yugoslavia, 2014) and the 2002 riots in Gujarat, India (Jaffrelot, 2003).

Organized crime groups

Groups such as the Juarez drug cartel in Mexico (Congressional Research Service, 2007) and the many gangs arising from the breakdown of law and order in Russia (Stoecker, 2000) have reportedly been responsible for widespread trafficking of illicit drugs, humans and weapons and terrorizing populations.

Gangs cause an estimated two-thirds of violent deaths worldwide (Small Arms Survey, 2013; Lind & Mitchell, 2013).

2. The only metrics for assessing any country's human rights record are subjective

While one measure of the rights of citizens is the number and types of international instruments their government has adopted, there is often a limited correlation between a country's formal laws and the reality of their enforcement.

Given the intrinsic subjectivity involved in characterizing the nature and severity of human rights violations, it is very difficult to objectively measure the strength of human rights protections in a country.

However, there are some indicators which attempt to quantify subjective analyses, the most well-known being the World Bank's Governance Indicator and the Freedom in the World Score by Freedom House.

The World Bank Governance Indicator (World Bank, 2018) uses aggregated surveys of citizens, institutions and experts to score the quality of governance of countries along six dimensions: voice and accountability, political stability and absence of violence, government effectiveness, regulatory quality, rule of law and control of corruption.

This index measures issues beyond human rights; at the same time, it does not fully address human rights with the necessary level of specificity.

Based on this indicator, the worst ranked countries include Uzbekistan, Equatorial Guinea, Saudi Arabia, China and Iran, and the best-ranked countries include Norway, Sweden, Denmark, Switzerland, New Zealand and Costa Rica. Senegal, India, Indonesia and Mexico are in the middle of the rankings.

On the other hand, the Freedom in the World score (Freedom House, 2018) on political and civil liberties is based on expert analysis (from academic institutions, think tanks and human rights organizations) based on news report, academic publications and NGO reports, etc.

According to Freedom House, the political rights score evaluates the "electoral process, political pluralism and participation, and functioning of government"; the civil liberties score assesses "freedom of expression and belief, associational and organizational rights, rule of law, and personal autonomy and individual rights."

Interestingly, the scores according to this assessment roughly align with the World Bank Governance Indicator rankings.

3. There is a strong link between a country's level of development and its protection of citizen rights

Human rights violations are not exclusive to low income countries. Governments, militaries and corporations from high income countries are routinely implicated in major human rights abuses, usually against citizens of lower income countries without the wherewithal or national-level regulatory protection to prevent the abuses, or find recourse.

There is also ample evidence that religious and ethnic minorities even in wealthy countries suffer systematic violations of their rights (Human Rights Watch, 2014a).

Still, it is natural that human rights protections accorded to citizens of a country are a function of the strength of the rule of law in that country.

Exhibit 1 shows the World Bank Governance Indicators and the Freedom House scores for countries grouped into quintiles along the United Nation's Human Development Index, or HDI (UNDP, 2018), a composite index combining health, economic capacity and education.

According to this analysis, the lower the HDI score of a country, the worse its human rights indices tend to be.

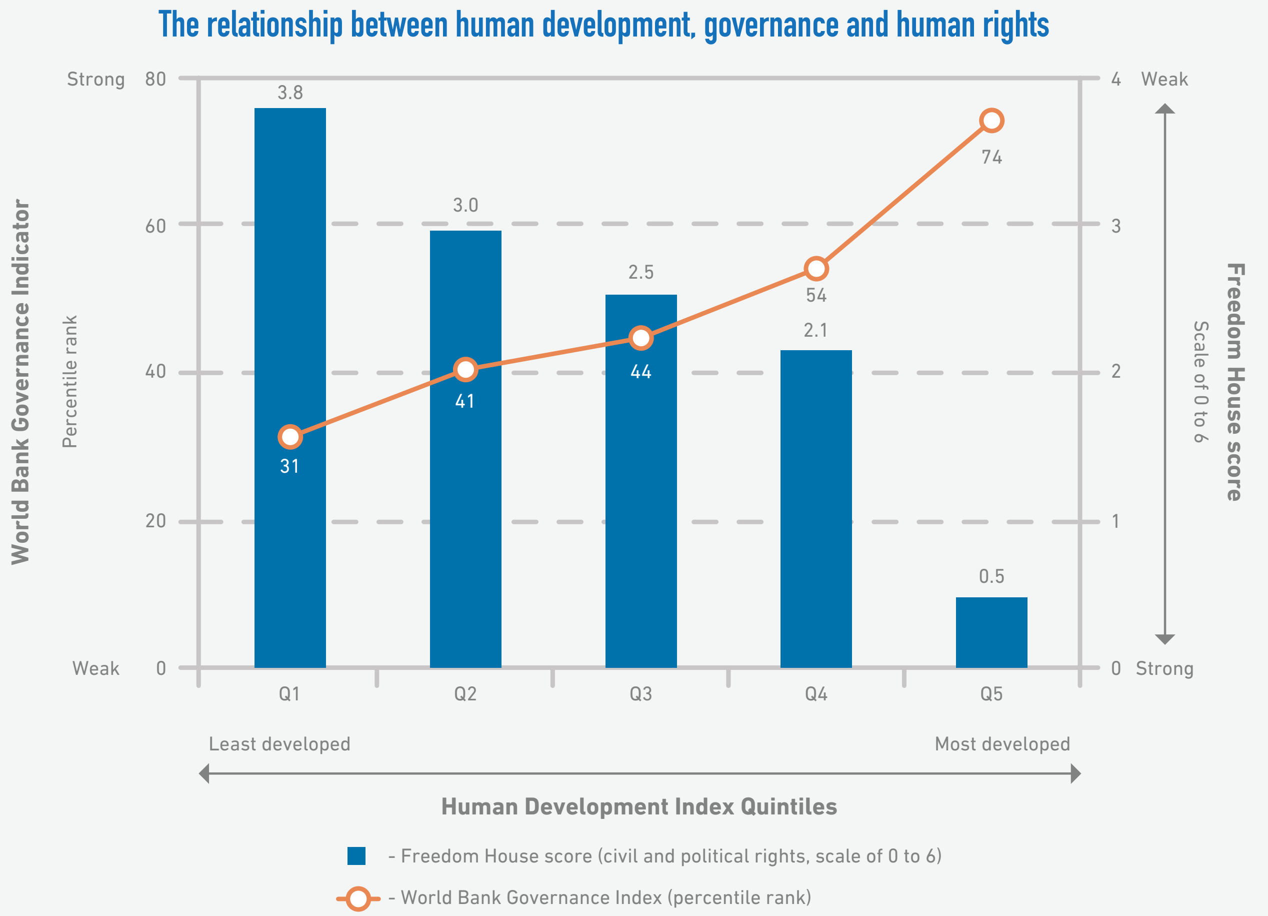


Exhibit 1: With some notable exceptions, the human rights protections given to citizens of a country tend to be a function of the level of human development in the country. This exhibit groups countries based on their Human Development Index score and plots the average scores or ranks according to the World Bank Governance Indicator (left axis) and the Freedom House index of civil and political rights (right axis; in which a lower score indicates better protection of human rights). (Source: ITT analysis based on World Bank, 2018; Freedom House, 2018; UNDP, 2018)

4. The number of refugees and other displaced people—groups particularly vulnerable to human rights abuses—is growing

Globally, the number of people forcibly displaced reached a record high to 68.5 million individuals by the end of 2017 (UNHCR, 2017). The population of displaced individuals has increased substantially over the last five years (**Exhibit 2**).

The total number of displaced persons includes 40 million internally displaced persons, 25 million refugees (who have fled across a national border) and 3 million individuals whose asylum applications had not yet been adjudicated. The primary reasons for displacement continue to be large scale persecutions, generalized violence and civil conflicts. Significant recent displacement occurred from DR Congo, Myanmar and Syria. Currently, one out of every 110 people in the world is displaced, compared to one in 157 individuals a decade ago.

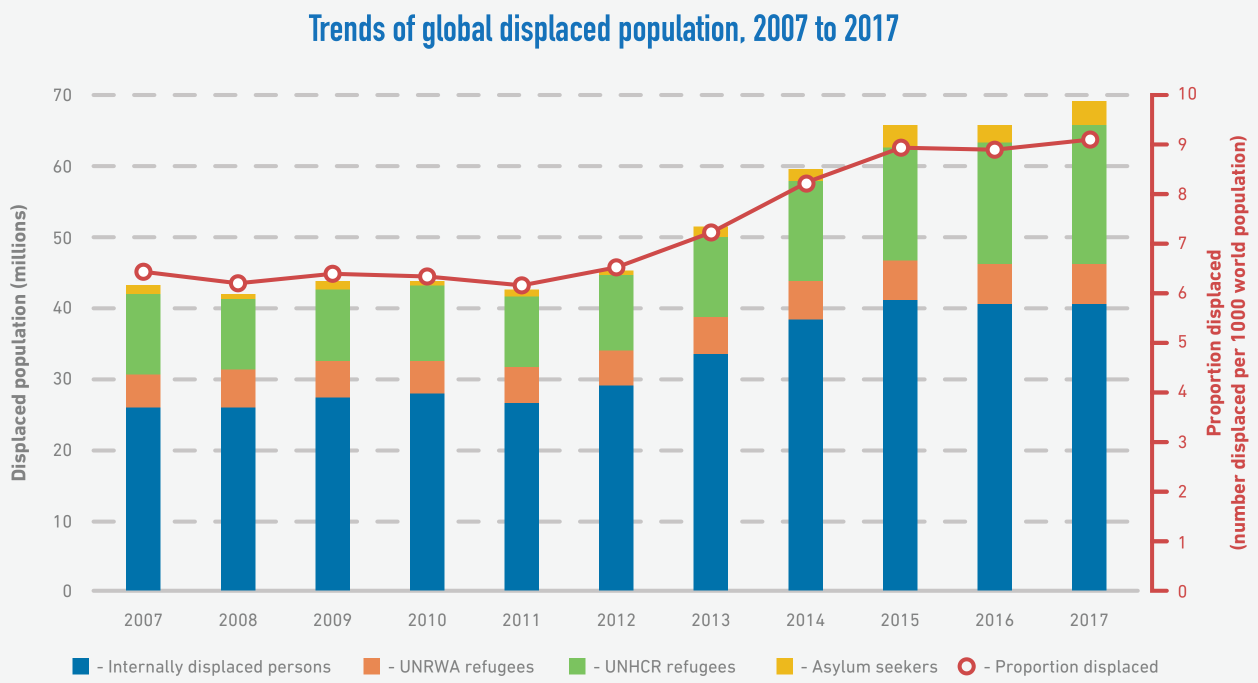


Exhibit 1: The global displaced population has increased by more than 50 percent over the last 10 years. Currently about 68.5 million people are displaced, including refugees, internally displaced persons and asylum seekers. (Source: UNHCR, 2017)

Of the 25 million refugees globally, about five million are Palestine refugees that are aided by UNRWA (United Nations Relief and Works Agency for Palestine Refugees in the Near East). The remaining 20 million refugees are assisted by UNHCR (United Nations High Commissioner for Refugees).

Syria is the largest source country of refugees, and more than 6.3 million people had fled Syria by end of 2017. Other countries with large numbers of refugee origin are Afghanistan (2.6 million), South Sudan (2.4 million) and Myanmar (1.2 million) (**Exhibit 3**).

Countries that experienced the largest increase in refugee origin between 2016 and 2017 were Syria (14 percent), Afghanistan (5 percent), South Sudan (71 percent) and Myanmar (100 percent).

Developing countries continue to host the majority of the world's refugees. About 85 percent of refugees flee to developing countries, which comprise nine of the 10 largest refugee-hosting countries. Many of these countries are already dealing with substantial barriers to sustainable development, making it particularly challenging for them to mobilize sufficient resources to respond to large refugee influxes (UNHCR, 2017).

Major source countries of refugees

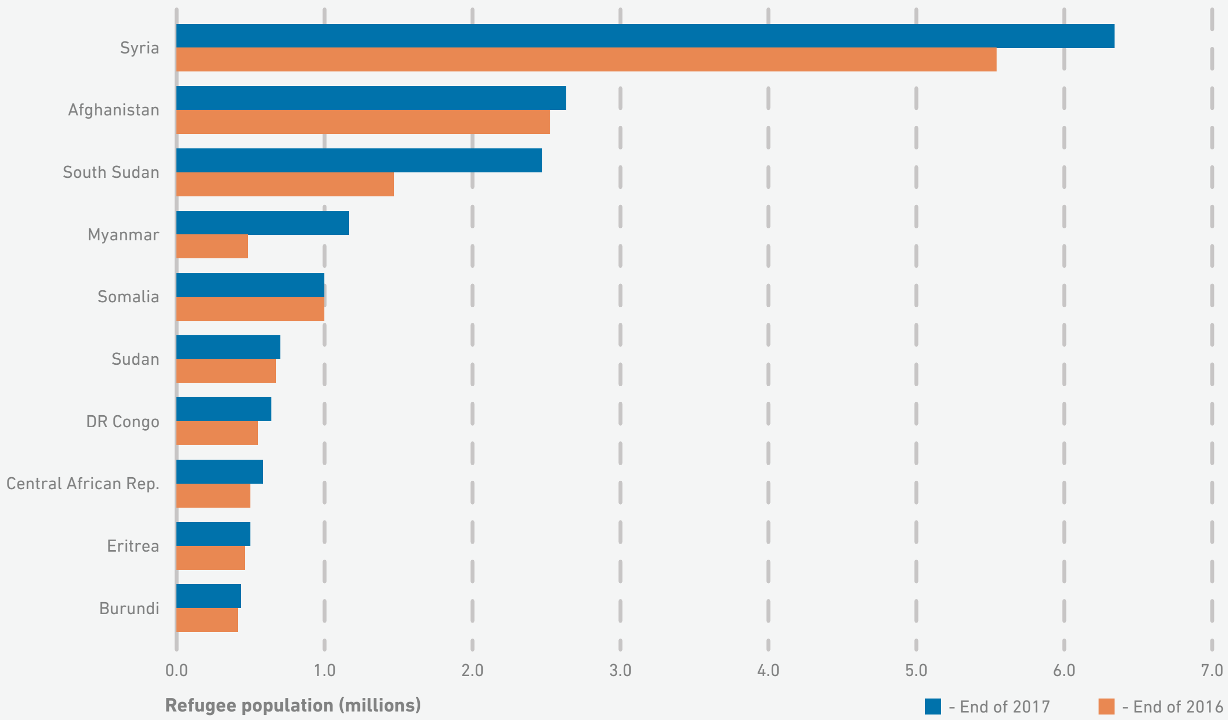


Exhibit 3: Syria is the largest source country of refugees. Other major source countries of refugees include Afghanistan, South Sudan and Myanmar. Five million Palestine refugees are not included in the figure. (Source: UNHCR, 2017)

5. Human rights interventions fall into five broad categories

Advocacy campaigns are aimed at changing policies or legislation at the national or international level in order to protect vulnerable groups, or for engendering formal responses to violations. They can be overtly public or entirely behind-the-scenes and completely out of the public eye.

High-profile examples of advocacy campaigns include the global multilateral effort to secure bans on the use of landmines and cluster bombs (UN, 1997; UNODA, 2014), the #BringBackOurGirls social media campaign to urge the Nigerian government to rescue the more than 270 schoolgirls kidnapped by the Boko Haram militia group (The New York times, 2014b) as well as the campaign to legalize same-sex marriage in the United States (Becker, 2014).

Name-and-shame campaigns are the most common type of human rights intervention, involving public embarrassment of alleged violators, or actors who can influence them but seemingly are turning a blind eye, with the intention of provoking corrective action.

These typically take the form of accusatory reports in popular or influential media, public protests, email chains or online petitions aimed at customers or constituents, or other forms of media campaigns to the same effect.

One of the earliest and best-known examples of name-and-shame campaigns is the one that led to the widespread boycott of Nestle's food products because of the company's aggressive push for its breast milk substitutes in low income countries and the alleged link to death and disease among affected babies (Muller, 1974). Arguably, name-and-shame campaigns can be considered a form of advocacy.

Criminal prosecution is usually the preferred mechanism for ex-post accountability, from the point of view of the victims. Given the broad range of violations, it is likely that most of the prosecuted cases are handled in routine criminal courts. In some cases, special local courts or other forums are created, like the Gacaca system for the Rwandan genocide (UN Outreach Programme on the Rwanda Genocide, 2007).

In cases when it appears unlikely that the accused will be tried fairly in the home country, prosecutions are conducted at the ICC,[1] or at other special international tribunals, such as the one for the former Yugoslavia (International Criminal Tribunal for the former Yugoslavia, 2014).

Civil litigation, especially against large companies, is a more recent phenomenon in which victims or their families seek financial compensation from the accused company. For example, companies like Chevron and Shell have been sued in the United States courts under the auspices of the Alien Tort Claims Act,[2] for their alleged violations in Ecuador and Nigeria, respectively (The New York Times, 2014a; The New York Times, 2009).

Standardization and certification of business practices, with compliance monitoring, has contributed to improvements in corporate responsibility in recent years. Examples include fair-trade certification of food and other farm-based products (Fair Trade USA, 2012), the Voluntary Principles on Security and Human

Rights for the extractive and energy industries (developed by a coalition of governments, NGOs and corporations) and the Kimberley Process Certification Scheme to monitor extraction and flow of diamonds across international borders to control the flow of conflict diamonds. Such mechanisms, to date, have been largely voluntary and are too recent to have yet made a long-term impact.

[1] Note that only citizens of countries which have adopted the Rome Statute of the International Criminal Court can be prosecuted at the ICC. The United States, Israel, China, India and number of other countries have not adopted the statute. In addition, controversies have led many members of the African Union to oppose the ICC's policies (Hickey 2013).
[2] Also known as the Alien Tort Statute, and since 1980, has been used to allow foreign citizens to seek remedies in the United States courts for human rights violations committed by American entities (or entities with a United States presence} outside the US.

6. In recent years, new communication tools and social media platforms have significantly improved transparency

The recent proliferation of information and communications technologies (ICT) like camera-enabled mobile phones and social content sharing platforms has dramatically increased the ability of affected communities to document and disseminate information about, and evidence of, violations, as well as create global awareness of events and issues that may have otherwise gone largely unnoticed.

One prominent example is Ushahidi from Kenya (MIT, 2014), a crowd-sourced, SMS-based reporting tool which tracked incidents of violence in the aftermath of the 2007 elections in the country. Since then, it has been used in South Africa, Haiti, The Democratic Republic of Congo and Gaza. Similarly, platforms like Twitter and Facebook are widely credited with having enabled the popular uprisings that together comprised the Arab Spring (Howard, et al., 2011).

Other examples include CGnet Swara, a mobile enabled network, which has helped tribal communities in India document police violence (International Center for Journalists, 2012), and HarassMap, a platform for crowd-sourcing and documenting cases of sexual harassment and abuse in Egypt (Chalabi, 2013).

More recently, the #MeToo social media campaign that has drawn attention to the problems of sexual harassment that women face, but has thus far had limited meaningfully impact on the lives of women in developing countries. This example is discussed in more detail in the Gender Equity chapter.

In addition to increasing transparency, such ICT technologies have had a disintermediating effect; vulnerable communities and groups can now make their voices heard globally, without relying on international NGOs or formal media channels as was necessary at the turn of the century. The broader manifestations and benefits of ICT are discussed in the Digital Inclusion chapter.

KEY CHALLENGES

Human rights violations occur, remain overlooked or go unpunished for a host of reasons. Perhaps the most demoralizing and daunting of these is the willingness of people and communities to accept-and even inflict-abuse on individuals and communities who they perceive as different from them.

There are a number of challenges that prevent universal protection of human rights from being a reality.

1. Lower income countries tend to have weaker legal frameworks and enforcement mechanisms

As shown in **Exhibit 1**, lower income countries tend have weaker laws and policy frameworks to protect and promote human rights.

In some cases, the laws are deliberately exclusionary or even outright discriminatory. Even if appropriate laws are on the books, many lower income countries lack the law enforcement and judicial capacity to enforce them. Corruption and a lack of incentives exacerbate capacity gaps, and cultural practices-especially when it comes to women and minorities-make matters worse.

Examples include the spate of anti-gay laws in a number of African countries (Amnesty International, 2014a) and in Russia (Amnesty International, 2014b), the new polygamy law in Kenya (Africa Review, 2014), anti-blasphemy laws in Islamic countries like Pakistan (Chowdhry, 2013) and the Armed Forces Special Powers Act in India, which has been used to impose long-term military or paramilitary presence in areas with religious, ethnic and separatist conflicts (Asian Human Rights Commission, 2014).

2. Perpetrators in positions of power often feel real or perceived impunity

When laws or enforcement mechanisms are weak, individuals and corporations in positions of power feel a certain degree of immunity from prosecution. The same can apply to countries with powerful militaries and political alliances: the many American invasions of weaker countries (Human Rights Watch, 2006),

Israel's actions in Lebanon and the Occupied Palestinian Territories (Human Rights Watch, 2014b) and Russia's interventions in Georgia and Ukraine (Human Rights Watch, 2014c) have all been documented by human rights organizations as examples of such aggression.

3. During ongoing conflicts, early-warning signs about imminent atrocities are difficult to effectively act on

In the past three decades, there have been several major human rights atrocities against people ostensibly under the protection of UN Peacekeepers or other forces. In the case of the Rwandan Genocide of 1994, there is now clear evidence that the UN peacekeepers knew about the imminent threat to the Tutsi community.

According to most accounts, however, the genocide went on partly because of political paralysis among institutions in a position to intervene (Dallaire, 2003). Similarly, the UN Protection Force for the former Yugoslavia (UNPROFOR) was seemingly aware of the impending massacre of civilians in Srebrenica in 1995, but for reasons similar to those in Rwanda did not prevent the incident (Human Rights Watch, 1995).

On the other hand, in the 2010 mass rapes in Luvungi in the Eastern Congo there are conflicting reports on how much the local UN Peacekeeping troops knew about the imminent threat of large-scale sexual violence (Heaton, 2013).

In the Darfur genocide that began in 2003, many atrocities, especially during the early years, occurred when there was no legitimate protection force around. A UN Peacekeeping mission (UNAMID) was not authorized and deployed until 2007; even since then, UNAMID has been limited in its ability to fully prevent atrocities in Darfur (UN Security Council, 2014).

As these examples show, war-related atrocities occur because there is no military protection of civilian populations, the legitimately appointed protection force does not have advance warning of an impending atrocity, or the ability of the force to intervene is frequently undermined by political or other considerations.

4. Often, there is lack of verifiable evidence to prosecute perpetrators

Timely, credible evidence is a prerequisite for holding violators legally accountable. Evidence can come in various forms: victim or witness accounts, photographs, video, aerial imagery and biological or chemical residue. Obtaining and preserving verifiable evidence is, however, challenging.

Digital cameras, while increasingly ubiquitous, can be confiscated by violators who can destroy critical data.

The proliferation of phone-based digital cameras has led to a dramatic increase in the ability of victims and witnesses to document violations, especially in conjunction with social networking tools. The obvious challenge is that perpetrators will attempt to confiscate all the cameras they can find. Even if imagery is presented in a court of law, its veracity (e.g., time and location of the photographed scenes) can be challenged.

Importantly, there is no broadly available platform for preserving footage and imagery related to human rights on public or restricted archives. Mass commercial platforms can be unreliable with respect to security, validation and digital chains-of-custody. Furthermore, the lack of reliable internet or phone network access in many conflict areas means that important data and recordings can be lost or destroyed before they can be saved or transmitted.

Aerial imagery is still expensive, and relatively low resolution

For some types of violations (e.g., large-scale destruction of entire villages, or tracking the movement of militia and vehicles, exodus of populations and creation of mass burial sites), aerial imagery—rather than ground level photographs or video—is more useful. This type of imagery can be collected via satellites, aircraft or drones. For example, satellite imagery was used to document the Sri Lankan military attack on the Tamil population in 2009, where civilians were trapped in no-fire zones. Similarly, in 2010 Amnesty International's Remote Sensing for Human Rights Program used satellite imagery to detect mass destruction of civilian housing in Kyrgyzstan (Amnesty International, 2014c).

For civilians, available satellite imagery comes with challenges, such as relatively low image resolution and limitation to outdoor settings visible from a cloud-free sky.

Satellites are traditionally expensive, although low cost options are being developed by some organizations. For example, Planet Labs lowered the cost of satellite imagery by building mini-satellites with off-the-shelf sensors and inexpensive smartphone components. Small satellites were launched at a development cost of $7,000.

The company's current fleet of 200 satellites captures around 1.4 million images of the Earth per day, covering an expansive (though not universal) area (Planet Labs, 2018). Governments and private companies can access the data for various uses, such as monitoring the health of crops and creating risk models for flood zones. The scalability and efficacy of such surveillance systems in context of capturing human rights violations remains to be tested and proved.

While high-resolution aircraft-based aerial imaging is available (for example, through unmanned aerial vehicles, or UAVs), it is restricted to military use and very expensive for civil society to commission. Lower cost drones can only be deployed locally and for a limited amount of time and must be flown to the point of observation from a nearby location, making it risky for users (Digital Globe, 2013; Gertler, 2012; Astrium, 2012).

Technologies that analyze biological (DNA) evidence are still nascent, especially in developing countries

Recent advances in DNA-based technologies have led to significant improvements in the ability of law enforcement agencies to conduct accurate forensic investigations. In the United States, this has contributed to a number of exonerations of individuals wrongly convicted of serious crimes (The Innocence Project, 2014).

The technology has also been used to develop rape kits to preserve the perpetrator's tissue samples for prosecution. These kits, however, require a trained medical examiner and gathered evidence needs to be processed in a lab with sophisticated equipment—each system costs more than $100,000.

Moreover, biological samples can degrade quickly or be tampered with, rendering them inadmissible in a court of law. While some preservation mechanisms exist, they may not be feasible at the location where samples are collected (RAINN, 2014; Engadget, 2012).

SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

The human rights of individuals and communities, especially those without power or voice, will only be adequately protected if attitudes about fairness and justice change and strong institutions capable of protecting the rule of law are developed.

Even as those fundamental improvements are achieved, a small number of technological breakthroughs can improve evidence collection, increase transparency and thereby enhance the prospects for accountability.

Breakthroughs:

1	2	3	4	5	6	7	8	9	10
11	12	13	14	15	16	17	18	19	20
21	22	23	24	25	26	27	28	29	30
31	32	33	34	35	36	37	38	39	40
41	42	43	44	45	46	47	48	49	50

20 A simple point-of-use, low-cost DNA-based rape kit capable of delivering rapid results

Sexual violence occurs for a whole host of reasons, including gender discrimination, societal and interpersonal power dynamics and impunity that comes from the lack of accountability.

A major challenge is that even if a person overcomes the stigma associated with being a victim of sexual violence and lodges a formal complaint, there is limited evidence to make a robust legal case. Rape kits to preserve semen and other degradable biological tissue and conduct DNA analysis to match against potential perpetrators are becoming increasingly common in higher income countries.

However, these require skilled technicians and a sophisticated, expensive laboratory to analyze the samples. To be useful in low resource or conflict settings, a rape kit would have to be very low cost (less than $10 per test, with the processing equipment not more than a few hundred dollars), usable off-grid and not require much clinical training to use. In addition, the analysis should be rapid, with the ability to digitize and transmit relevant data for secure (presumably cloud-based) storage.

Similar low-cost DNA-based technologies being prescribed and developed for medical diagnostics, are approximately three to five years from becoming available on the market. In principle, a DNA-based rape kit should not take more than five years beyond that.

Current State

Development Stage: R&D

Time to market (years)

<3 4-6 7-10 10+

Deployment: Extremely Challenging

Associated 50BT Chapters

Human Rights

Gender Equity

SDG Alignment

Impact

Health Improved (# of People)

<1M 10M+ 100M+ 1B+

Improved Quality of Life (# of People)

<1M 10M+ 100M+ 1B+

Commercial Attractiveness

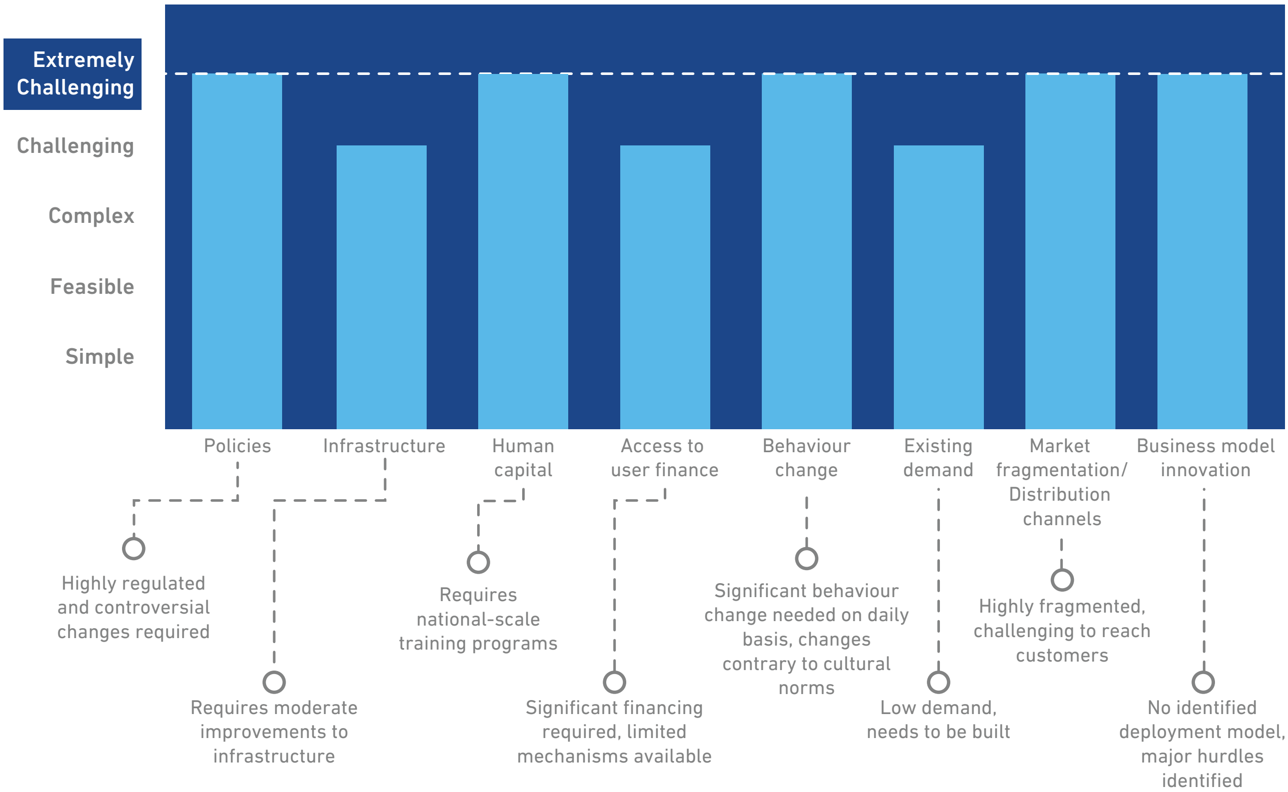
- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- Emerging markets potential; requires derisking (sustainable)
- **Non-commercial (unprofitable)**

However, once developed the technology will face significant challenges in deployment along virtually every dimension. Enough facilities (such as health clinics) will need to have the device at hand, those administering the test will require some level of training, and financing will be necessary to cover the costs involved.

Without financing it will also be very difficult for health facilities to ensure a steady supply of the kits and maintain the processing equipment. Moreover, policy changes will be necessary to determine how the judicial systems of different countries can best use such evidence in their legal proceedings.

Furthermore, rape kits can be administered only if a victim seeks help immediately after the incident while the biological evidence is still intact. For these reasons, deploying such a technology will be EXTREMELY CHALLENGING.

Breakthrough 20: Difficulty of deployment



21 Low cost (less than $50) wearable, or otherwise easily concealable, cameras with automatic geocoding and timestamps, capable of SOS data preservation (such as via satellite)

The proliferation of mobile-phone based digital cameras and cloud-based social media platforms has allowed citizens to make impromptu recordings of events of interest and post them online. This ability to instantly shoot-and-upload has led to an unprecedented level of citizen journalism and activism, and in turn, documentation of human rights violations.

While this steady march towards miniaturization of computing devices and sensors is eroding long-held notions of individual privacy, it has given an increasingly powerful tool to victims and witnesses of human rights violations to document incidents and push for accountability.

Crucially, any data stored in devices like mobile phones is dependent on phone networks and the internet for uploads or wider sharing. During emergencies and conflict situations, access to these is unreliable. Moreover, anyone with the intention of committing a violation will attempt to confiscate all phones and any other visible recording device, before data can be shared.

A particularly valuable feature for a wearable miniature camera would be the capability to preserve data (for example, via one-time SOS satellite uplink), especially in a situation where the data may otherwise be destroyed. If such a device comes equipped with geocoding and timestamps, the imagery captured will be even more powerful with respect to legal admissibility.

In recent years, wearable cameras like Google Glass have begun appearing on the market. However, they are still quite conspicuous and far too expensive (well in excess of $1,000), even for the average consumer in developed countries.

Still, given the speed with which these technologies are developing, it is quite likely that inconspicuous wearable cameras will become affordable enough for low-income populations within the next three years.

Current State

Development Stage: Engineering

Time to market (years)

<3 4-6 7-10 10+

Deployment: Complex

Associated 50BT Chapters

Human Rights Gender Equity

SDG Alignment

5 GENDER EQUALITY

16 PEACE, JUSTICE AND STRONG INSTITUTIONS

Impact

Lives Saved (# of People/Year)

<1M 10M+ 100M+ 1B+

Improved Quality of Life (# of People)

<1M 10M+ 100M+ 1B+

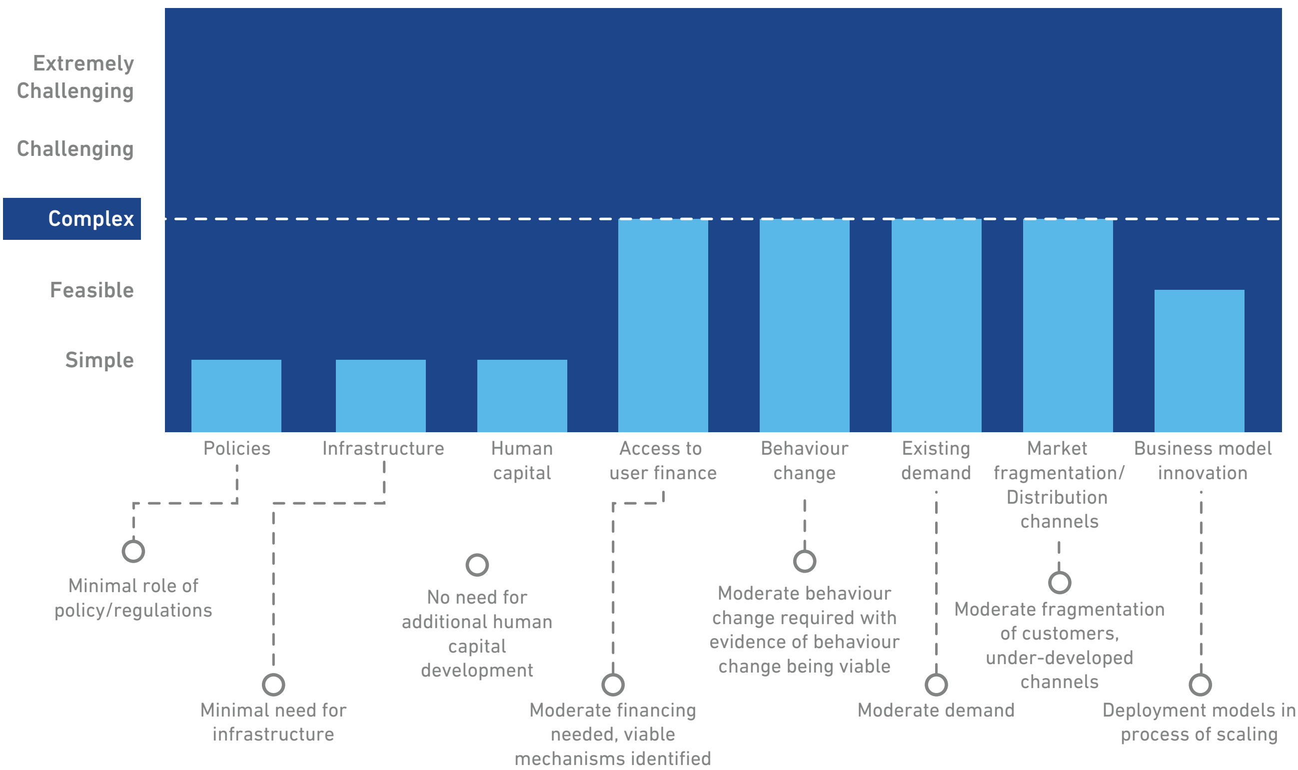
Commercial Attractiveness

- **Attractive for industrialized markets (high profits)**
- Attractive for emerging markets (lower profits)
- Emerging markets potential; requires derisking (sustainable)
- Non-commercial (unprofitable)

Once they are available on the market at the right price point, there is reason to believe that adoption will not be difficult, especially judging by the example of mobile phone-based cameras. It is important to note, however, that much of citizen journalism today happens because people carry their mobile phones everywhere.

It is not clear if consumers will find enough reason to carry a separate wearable device a routine basis, or if there will be a demand for such devices, except in higher income consumer segments (especially since mobile phones already have cameras). As such, we believe that the difficulty of deployment will be COMPLEX.

Breakthrough 21: Difficulty of deployment



22 Low-cost aerial vehicles to capture high-resolution imagery for use by civil society groups, to document large-scale human rights violations

Aerial images (via satellites or UAVs) can provide crucial evidence for tracking movements of large groups of people, such as combatant units. The ideal mechanism to capture aerial imagery for protecting human rights will have the following characteristics:

- The images are of high enough resolution to identify distinguishing features of vehicles or even individuals.
- The aerial vehicle should be deployable (in the case of UAVs) or usable (in the case of already deployed satellites) on demand and capture images for sufficiently long periods in diverse weather conditions and at sufficiently safe heights.
- Be affordable for human rights organizations to own, or use as a service.
- Have contingency transmission mechanisms, so that images are not lost due to disruptions in flight.

Over the past several years, low cost UAVs or drones have become increasingly available to the public. They can be deployed on-demand for capturing high resolution images, with in-flight transmission. However, the affordable drones (such as ones that cost less than $500) can only be used for relatively short periods of time (one hour or less), and are vulnerable to bad weather.

Also, a small number of companies (like Planet Labs) are building low-cost, low-orbit mini-satellites with off-the-shelf sensors and inexpensive smartphone components. The company's current fleet of 200 satellites captures around 1.4 million images of the Earth per day, covering a large (though not universal) area at a resolution of three to five meters.

Current State

Development Stage: In-Market Small Scale

Deployment: Challenging

Associated 50BT Chapters

Human Rights

SDG Alignment

Impact

Lives Saved (# of People/Year): <1M | 10M+ | 100M+ | 1B+

Improved Quality of Life (# of People): <1M | 10M+ | 100M+ | 1B+

Commercial Attractiveness

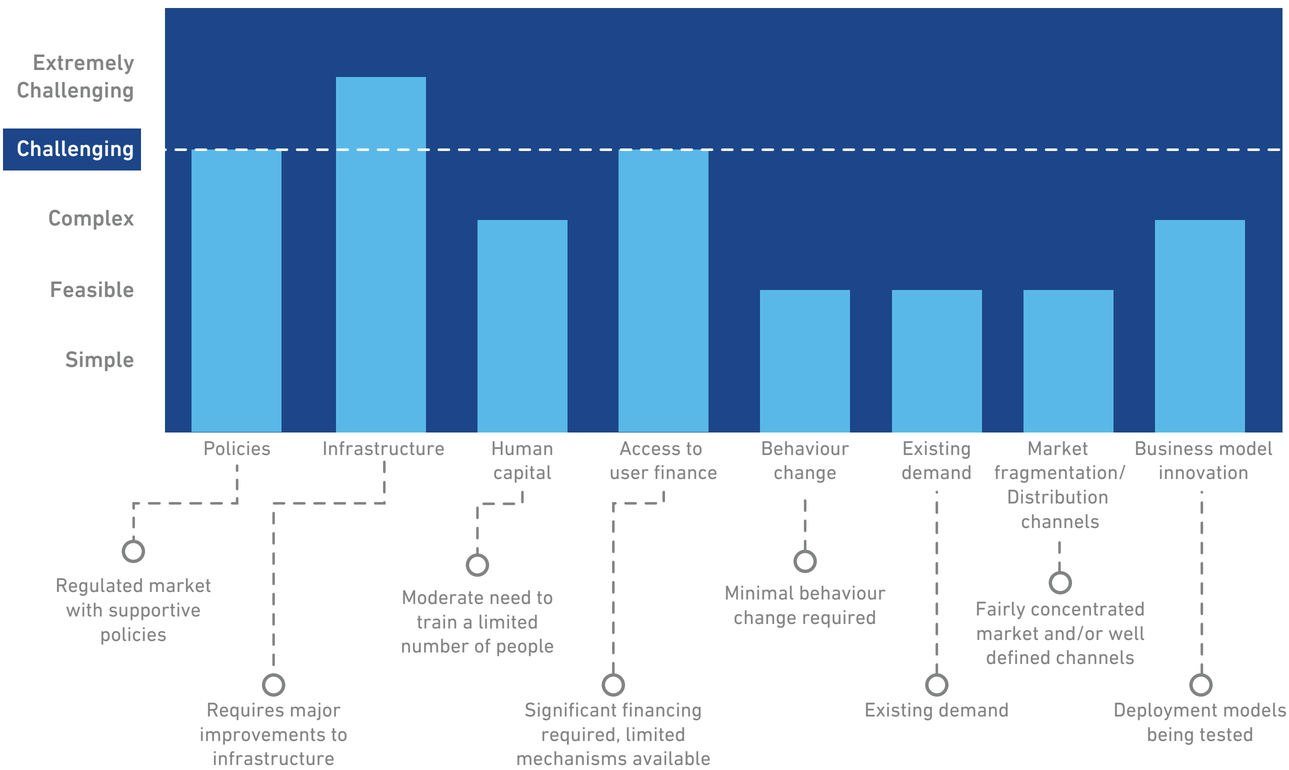
- **Attractive for industrialized markets (high profits)**
- Attractive for emerging markets (lower profits)
- Emerging markets potential; requires derisking (sustainable)
- Non-commercial (unprofitable)

These technologies are evolving rapidly and are already being used in a wide range of applications. Initial offerings providing an adequate combination of capabilities required for documenting human rights violations are market ready.

Drones, in particular, will likely be increasingly regulated, and governments (and other actors) committing human rights abuses may attempt to deter their use. However, these hurdles will not be insurmountable given the difficulty of enforcing regulatory restrictions. As such, usability and deployment is expected to increase dramatically over the next few years.

The existing market, in the shape of human rights organizations and media outlets, is niche. Given these factors, we believe the difficulty of deployment is CHALLENGING.

Breakthrough 22: Difficulty of deployment



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GLOBAL HEALTH

OVERVIEW

More than any other aspect of human development, health has benefited from scientific and technological breakthroughs.

Unfortunately, many of these breakthroughs have not reached the people most in need at the scale and form that are required. People living in tropical countries—particularly in South Asia and sub-Saharan Africa—are exposed to a far greater array of health hazards than those living in other regions. By implication, these populations need access to the most powerful solutions. Yet, they have the least access to such solutions.

The focus of this chapter is global health, which aims to ensure adequate health care for underserved populations. While overall health outcomes in low- and middle- income countries (LMICs) have improved over the past three decades, they lag the rest of the world in virtually every single health outcome metric (**Exhibit 1**).

Life expectancy in sub-Saharan Africa is now 60 years, substantially lower than the global average of 72 years (World Bank, 2016). Life expectancy in South Asia is 69 years, and in high-income countries is 80 years.

The maternal mortality ratio in sub-Saharan Africa is 547 (out of every 100,000 women giving birth), compared with 182 in South Asia, 13 in high-income countries and a global average of 216 (World Bank, 2015). Mortality of children under 5 in sub-Saharan Africa is 76 (out of every 1,000 children born live), compared to 45 in South Asia, 5 in high-income countries and 39 around the world (World Bank, 2017).

In sub-Saharan Africa and South Asia, 34.1 percent and 35.0 percent of children, respectively, suffer from stunting, compared with 22.2 percent globally and a negligible number in high-income countries (World Bank, 2017).

Importantly, non-communicable diseases (NCDs) like diabetes, cardiovascular disease and cancer, are on the rise in LMICs. In fact, these diseases already disproportionately affect people living in LMICs, compared with high-income countries. According to the WHO, 75 percent of the global deaths from non-communicable diseases today occur in LMICs.

These countries not only have the fastest increase in diabetes prevalence, but are also where more than 75 percent of all deaths from cardiovascular disease occur. NCDs are projected to cause an even higher disease burden in low- and middle- income countries within the next decade.

Health statistics in developing regions compared to global benchmarks

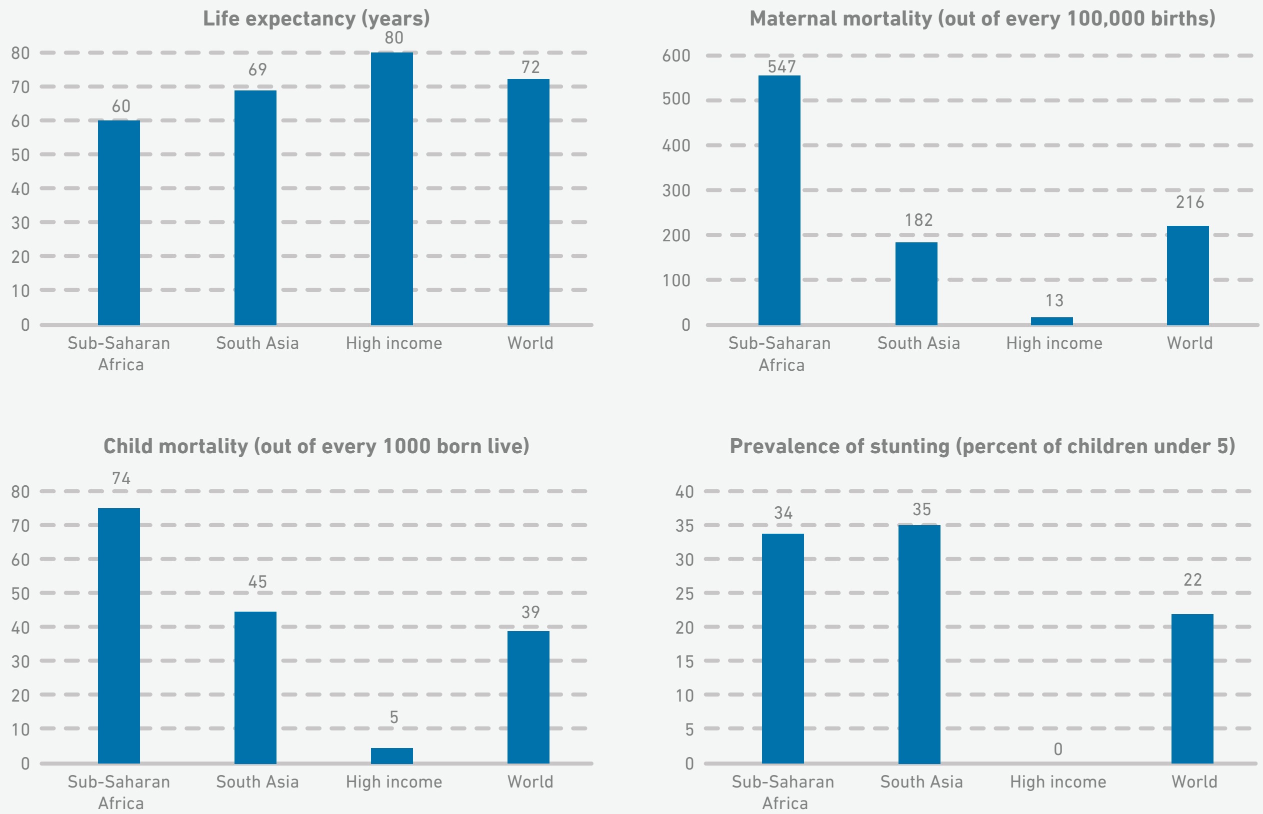

Exhibit 1: Countries in South Asia and sub-Saharan Africa have significantly worse health outcomes than their more industrialized counterparts and also fare poorly when compared with global averages. (Source: World Bank data for years 2015, 2016 and 2017)

Even as the causes of mortality vary by population segment and geography, a handful of conditions account for the majority of fatalities. As **Exhibit 2** shows, the leading causes of childhood mortality in sub-Saharan Africa are a host of neonatal conditions, malaria, diarrheal disease, and lower respiratory infections like pneumonia (IHME GBD, 2017).

In South Asia, malaria is not as significant a driver of childhood mortality; in percentage terms, neonatal conditions alone account for nearly as many deaths in South Asia as neonatal conditions and malaria deaths put together in sub-Saharan Africa.

For adult women in sub-Saharan Africa, the leading causes of mortality are HIV/AIDS, cardiovascular disease, lower respiratory infections and malaria, but in South Asia, HIV/AIDS and malaria are not as significant, instead NCDs are now the leading causes of death at an increasing rate.

Leading causes of mortality for key population segments in Sub-Saharan Africa and South Asia

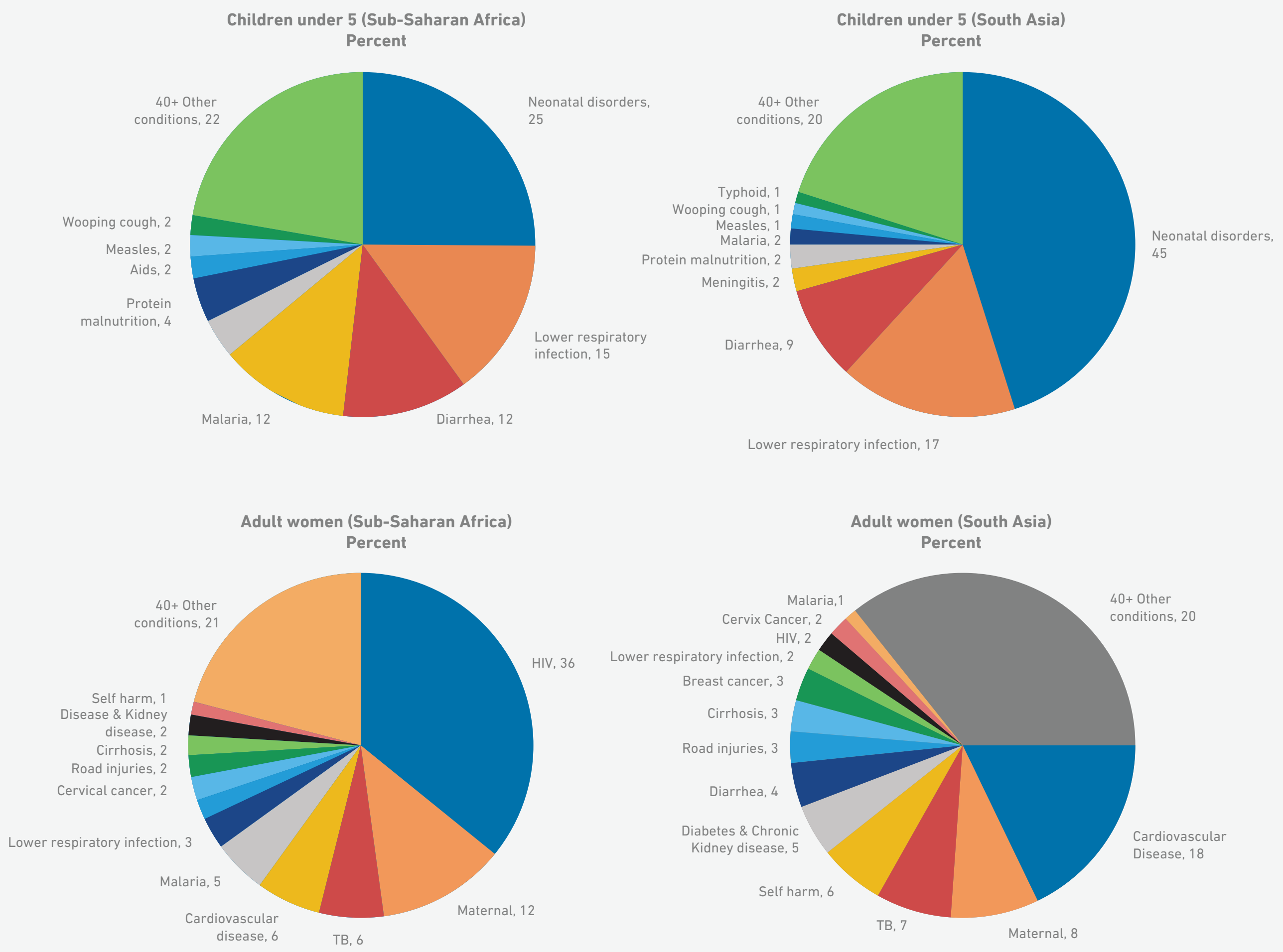

Exhibit 2: The leading causes of mortality are different for each population segment (for example, children versus women), with some differences between sub-Saharan Africa and South Asia. (Source: IHME GBD, 2017)

In addition to life expectancy and mortality, morbidity (the burden of disease on productivity and quality of life) is another valuable metric for understanding the state of health of national populations. Morbidity is measured in terms of disability-adjusted life-years (DALYs) lost.

A look at the leading causes of DALYs lost in South Asia and sub-Saharan Africa reveals that the indicators for children are not significantly different between deaths and DALYs, but the statistics for adult women show some meaningful differences.

This is primarily due to non-fatal conditions like mental/behavioral and musculoskeletal disorders, which cause a high disease burden (**Exhibit 3**).

Leading causes of DALYs lost in Sub-Saharan Africa and South Asia

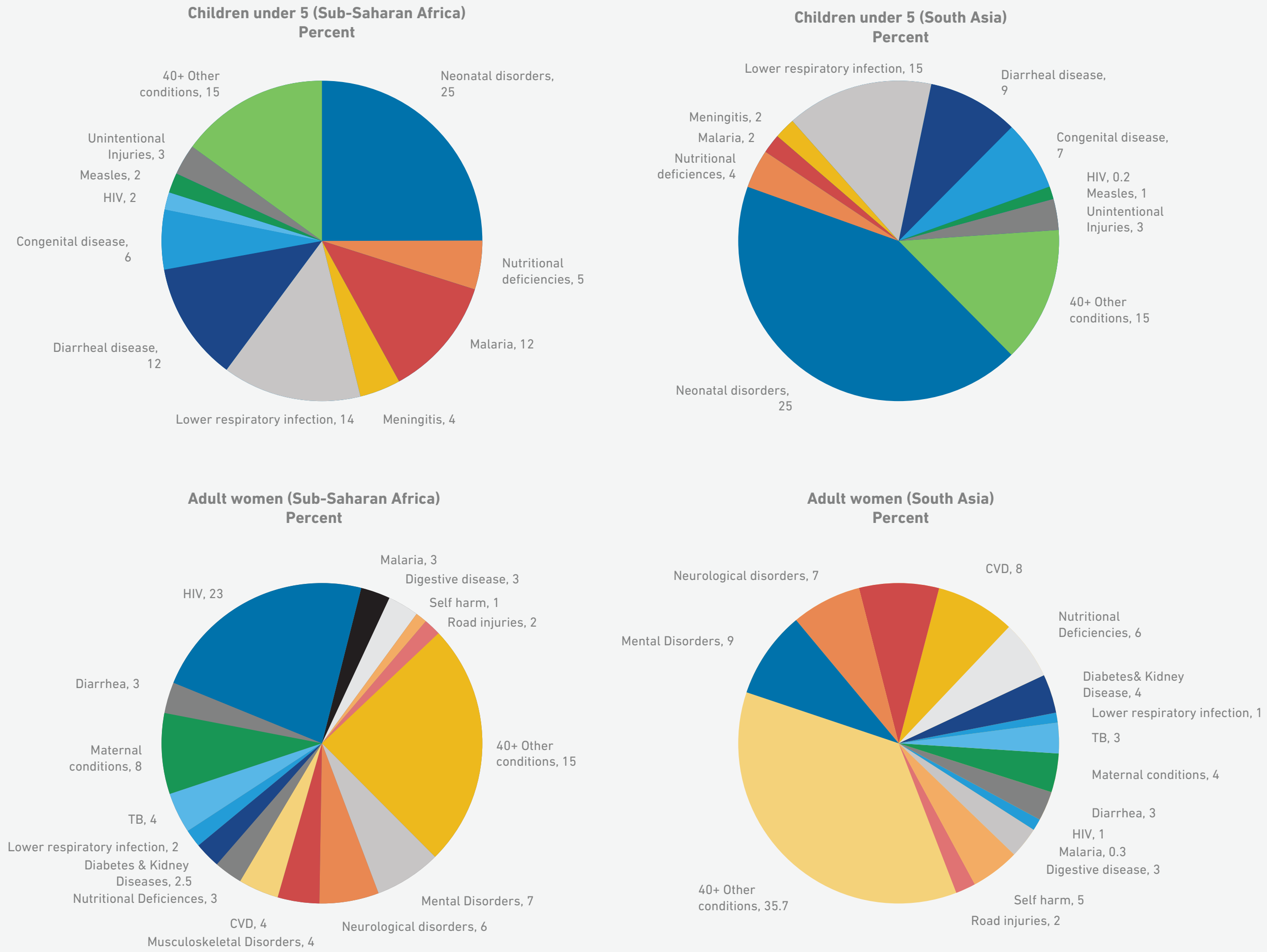

Exhibit 3: Analysis of disability-adjusted life-years (DALYs) shows that conditions like mental/behavioral and musculoskeletal disorders—while not leading to fatalities—cause a heavy disability burden among women. Among children, DALY statistics are similar to those for mortality. (Source: IHME GBD, 2017)

With these outcomes in mind, it is no surprise that indicators measuring the strength of health systems in sub-Saharan Africa and South Asia also lag behind substantially. **Exhibit 4** shows some of these indicators in South Asia and sub-Saharan Africa compared with high-income OECD countries and global averages.

Annual health expenditure per capita is $85 in sub-Saharan Africa and $58 in South Asia, compared with $4,875 in high-income countries, and an average of $1,002 globally (World Bank, 2014). As a combination of both public and private expenditure, this is a reflection how little public healthcare infrastructure there is in LMICs.

Crucially, households in LMICs—despite being considerably poorer than their high-income country counterparts—incur significantly higher per capita out-of-pocket healthcare expenditures; 36.3 percent of total healthcare expenditure in sub-Saharan Africa and 64.9 percent in South Asia is out- of-pocket, compared with less than 14 percent in high-income countries and 18.1 percent around the world.

Other signs of the sheer absence of adequate and dependable health systems is the lack of physical infrastructure and trained human resource. Across sub-Saharan Africa and South Asia, there are fewer than 0.2 physicians per 1,000 people in sub-Saharan Africa and 0.75 in South Asia. High-income countries have 2.8 physicians for every 1,000 people, and the global average is 1.5. Similarly, there are 1.1 nurses and midwives per 1,000 people in sub-Saharan Africa, 1.7 in South Asia, 7.4 in high income countries and 3.1 around the world (World Bank, 2014).

Statistics on health systems in sub-Saharan Africa and South Asia

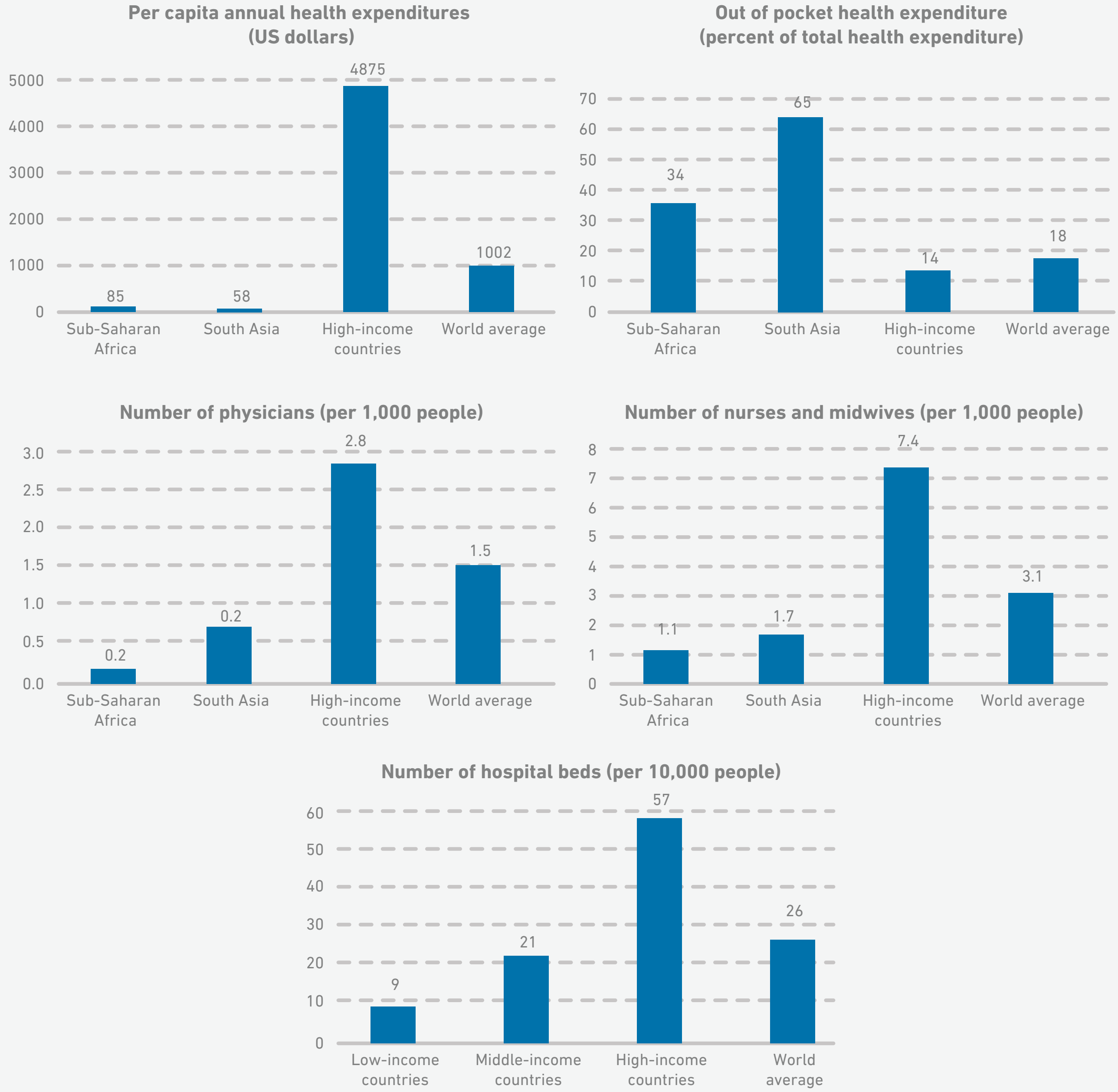

Exhibit 4: Healthcare systems in sub-Saharan Africa and South Asia, measured in terms of expenditure, human capital and access to care, lag significantly behind high income OECD countries and global averages. The challenges, deep-rooted and structural, are discussed in detail in our section on Healthcare Delivery. (Source: World Bank, 2014)

RECENT TRENDS IN GLOBAL HEALTH

As we analyze the role of technology in improving healthcare for low-income populations, the following six trends are important to consider.

Advances in diagnostic technology, Internet of Things (IoT) and data analytics are now redefining healthcare delivery systems in low-resource settings

Traditionally, healthcare delivery systems have been highly dependent on infrastructure and human resources. The past decade has seen the emergence of a new generation of low-cost medical devices which are more durable, less dependent on infrastructure, require less training to operate and are much less energy intensive.

As such, they are more appropriate for low-resource settings. Beyond diagnostics, sensors are being used to monitor cold chain supply networks to monitor and track the temperature at which vaccines are stored. Mobile-based thermal sensors record the temperatures in real time and a warning is issued to the responsible person if the temperatures exceed a threshold level.

IoT technologies are also being used to address immediate challenges in humanitarian response, such as the Ebola outbreak in West Africa. The United States Agency for International Development (USAID) has supported and employed IoT solutions via connected wearable technologies.

Sensor Technology and Analytics to Monitor, Predict and Protect Ebola Patients (or STAMP2) has been tested on Ebola patients in the United States and is being scaled up to meet the needs of government agencies, such as USAID for its Ebola treatment strategy in Liberia (ITU, 2016).

Combined with deep mobile network penetration and increasingly sophisticated data analytics, these new medical devices are laying the groundwork for effective task shifting of care delivery by local providers and for health systems to become much more decentralized. More information on other emerging technologies and their role in healthcare is in the Emerging Technologies chapter.

A number of gaps still exist in the understanding of the causes of major diseases

In recent years, science has made important advances in the understanding of diseases, particularly pertaining to issues such as the etiology of diarrheal diseases and pneumonia, the complex drivers of malnutrition and the long-term health impact of repeated exposure to diarrheal pathogens (beyond simply causing diarrheal disease).

Despite these advances, major gaps exist in the global health community's understanding of individual diseases, as well as the interaction effects of these diseases in the context of poverty. The knowledge gaps exist at a higher, epidemiological level (for example, the relative importance of various pathways to infection for diarrheal disease in rural versus urban areas), as well as at more fundamentally scientific level (such as the specific ways in which nutrition affects immunity from TB and other diseases).

Notwithstanding the gaps, these new findings already have significant implications on future research and development (like pathogen-specific vaccines for diarrheal diseases) and interventions designed to tackle major diseases, both at country and global levels.

A double burden of non-communicable (NCDs) and infectious diseases

In many LMICs, recent economic growth and the strengthening of healthcare systems have led to a reduction in the overall burden of infectious diseases. Higher life expectancy, along with demographic shifts like increasing urbanization, unhealthy diets and less physical activity, are leading to a surge in the incidence of non-communicable, chronic conditions like obesity, diabetes and cardiovascular disease. In India, for example, cardiovascular disease, followed by respiratory diseases, is now the leading killer of both men and women.

In most LMICs, healthcare systems were primarily focused on controlling infectious diseases and not NCDs. This double burden of disease (and in some countries, a changing burden of disease) seriously impacts their ability to combat the growing menace of these non-communicable diseases. In Sub-Saharan Africa, for example, for many types of cancer, the risk of getting cancer and the risk of dying from it are nearly the same, due to late stage diagnosis and lack of treatment (The Cancer Atlas, 2012).

Rising levels of antimicrobial resistance (AMR)

Antimicrobial resistance (AMR) is reaching dangerously high levels in all parts of the world, with some of the most common infections becoming difficult to treat (WHO, 2018). AMR occurs when germs, such as bacteria and fungi, develop the ability to defeat the drugs that are designed to kill them, making the drugs ineffective.

The term antibiotic resistance applies only to bacteria becoming resistant to antibiotics, while AMR is a broader term that encompasses resistance to drugs that treat infections caused by other microbes including parasites (such as malaria or helminths), viruses (such as HIV) and fungi (such as *Candida*). AMR does not mean the body becomes resistant to antimicrobials; instead, it means that microbes have become resistant to the drugs designed to kill them.

AMR is a serious and growing problem. At least 700,000 people die every year from drug-resistant strains of common bacterial infections, HIV, TB and malaria (O'Neill, et al., 2016). This number is projected to increase to 10 million lives each year by 2050 unless effective action is taken. Important examples of AMR include:

- Multidrug-resistant tuberculosis (MDR-TB) is a form of TB that is resistant to the two most powerful anti-TB drugs, and extensively drug-resistant tuberculosis (XDR-TB) is resistant to at least four of the core anti-TB drugs (see the Pulmonary Tuberculosis section for more details).
- The bacteria *E. coli* is gaining resistance to fluoroquinolone antibiotics, which are widely used to treat urinary tract infections.
- The common intestinal bacteria *Klebsiella pneumoniae* is becoming resistant to a last resort treatment, carbapenem antibiotics, in all regions of the world.
- The *P. falciparum* malaria parasite is gaining resistance to the first-line artemisinin-based combination therapies in Southeast Asia.
- Drug-resistant HIV is emerging with resistance to antiretroviral therapy (ART) in some developing countries.
- In at least 10 countries, gonorrhea is becoming resistant to the last resort medicine, third generation cephalosporin antibiotics.
- Resistance of *Staphlylococcus aureus* to first-line drugs is widespread, causing growing numbers of deaths due to MRSA (methicillin-resistant *Staphylococcus aureus*).

Emergence of AMR in microorganisms is a natural phenomenon, but has been greatly accelerated by the misuse and overuse of antimicrobials in health care and agriculture (Holmes, et al., 2016). For example, antibiotics are often taken by people with viral infections like colds and flu, for which they have no beneficial effect. Antimicrobials are one of the most commonly prescribed drugs used in human medicine, but up to half of all antimicrobials prescribed to people are considered unnecessary (CDC, 2013).

Factors contributing to AMR in low-income countries include over-the-counter availability with insufficient dosages, the use of counterfeit drugs and other less potent antibacterial agents, lack of diagnostic laboratories and poor level of sanitation, which all facilitate the spread of resistant organisms (Roca, et al., 2015).

AMR is a complex problem that is driven by many interconnected factors, and coordinated effort is required to minimize the emergence and spread of AMR. Without urgent and effective action, we risk returning to an era in which common infections and minor injuries can once again kill. A global action plan on AMR was endorsed in 2015 to ensure prevention and treatment of infectious diseases with safe and effective medicines (WHO, 2015).

The plan has five strategic objectives: improve awareness and understanding of AMR, strengthen surveillance and research, reduce the incidence of infection, optimize the use of antimicrobial medicines and ensure sustainable investment in countering AMR.

It is necessary to improve global awareness of AMR so that patients and farmers do not demand, and clinicians and veterinarians do not prescribe, antibiotics that are not needed (O'Neill, et al., 2016). It is also important to improve hygiene and sanitation conditions, because the fewer people that get infected, the less they will need to use antimicrobials and the less drug resistance will arise.

Another important step is the promotion of new, rapid diagnostics to reduce unnecessary prescription of antimicrobials and to optimize treatments. The development and use of vaccines should also be promoted, as they can prevent infections and therefore lower the need for therapeutic treatments, thus reducing the use of antimicrobials and the rise of drug resistance.

While there are some new antimicrobials in development, none of them are expected to be effective against the most dangerous forms of resistant germs. There is a need for better incentives to promote investment in new drugs, because the commercial return on R&D investment in new antibiotics is currently unattractive. Although the total market for antibiotics is relatively large, with annual sales of about $40 billion, only about $4.7 billion of this is from sales of patented antibiotics (O'Neill, et al., 2016). Between 2003 and 2013, less than 5 percent of venture capital investment in pharmaceutical R&D was for development of antimicrobials.

A greater focus on health system strengthening and affordability

Universal Health Coverage (UHC), a concept that aims to ensure that individuals and communities receive the health services they need without suffering financial hardship, is receiving more serious attention since it was adopted as a SDG in 2015. The scope goes beyond financing and includes all components essential to a well-functioning health system. Investing in improving in the delivery of primary care is essential in achieving UHC (SDG, 2015).

The focus on primary care provides a major opportunity to address many conditions like pneumonia, maternal, reproductive health, nutrition and diarrhea that are still major burdens on low and middle-income countries. But to achieve the broad goals of UHC is ambitious. Health systems need to overcome several key challenges, including attaining sustainable financing, ensuring true universalism so that poor and vulnerable are not left behind, and improving the quality and efficiency of health service delivery.

The increasing number of technology breakthroughs, if fully leveraged, will contribute greatly to improving the capabilities of providers and administrators, and better serve the needs of patients. Mobile and digital technologies, in particular, will play a key role by improving the methods and quality of data collection and turning that data into actionable information.

Disaggregated data that in an integrated system can improve the delivery of health services and products, provide timely, decision making, resource planning and increase accountability. Beyond the power of data, digital tools are also starting to play a role in the financing of healthcare, building engaging relationships between payers and beneficiaries.

Healthcare technologies are part of a complex ecosystem involving policy, behavior and economic factors

More than most other topics covered in this study, new technologies for health depend heavily on a range of required trials and approvals, policy and system reforms, behavior change on the part of users, improvement in the level of technical skills of care providers and their integration into mainstream healthcare service delivery. In this context, first it is important to remember that without an adequate number of trained healthcare workers and clinicians, as well as fundamental changes in how healthcare is sought and administered, there is a significant risk that many of these technologies will simply not have a market.

Second, conditions like diarrheal disease, pneumonia and TB, can benefit from individual technological breakthroughs. However, the underlying risk factors involved—particularly in densely populated urban settings—can only be alleviated through structural changes in how people live, especially those at the lower end of the income spectrum.

As long as the poor continue to live in squalid conditions, most medical technologies will only serve as a means to provide reactive interventions. For interventions to be proactively preventive, it is important to think beyond individual technologies and move towards a more integrated and long-term solution.

Third, not all health conditions can be battled through breakthrough technologies. This is particularly true of the rapidly escalating threat of non-communicable diseases—obesity, diabetes, cardiovascular diseases and, increasingly, cancer.

While technology can play a role in effective detection, diagnosis and treatment, incidence is primarily due to lifestyle and behavioral choices. Managing this burgeoning health challenge relies primarily on raising awareness and behavior change interventions.

In this chapter, we look at the major health conditions contributing to highest mortality and DALYs in developing countries, their clinical underpinnings, and the key challenges to overcoming them. These conditions, each a dedicated section, include:

- HIV/AIDS
- Pulmonary tuberculosis
- Malaria
- Maternal and neonatal health
- Pneumonia and lower respiratory infections
- Diarrheal diseases
- Non-communicable diseases
- Nutritional deficiencies

In addition, we examine two important systemic issues:

- Diagnostics
- Healthcare delivery

Note: In this chapter, childhood health (and related conditions) typically refers to children under 5. 'Resource-poor settings' refers to contexts in which low-income populations do not have access to clinics with basic amenities (such as reliable electricity, running water and functioning medical devices) or to adequately trained healthcare providers; this could be in rural or urban settings. 'Remote settings' usually refers to rural areas that are difficult to access due to the absence of reliable roads and/or transport. 'Peripheral clinics' refers to barely functioning healthcare facilities that serve populations in resource-poor or remote settings. Finally, 'point-of-care' describes services that are provided at or near where the patients are, rather than at laboratories or healthcare facilities which are far away from where the patients live and work.

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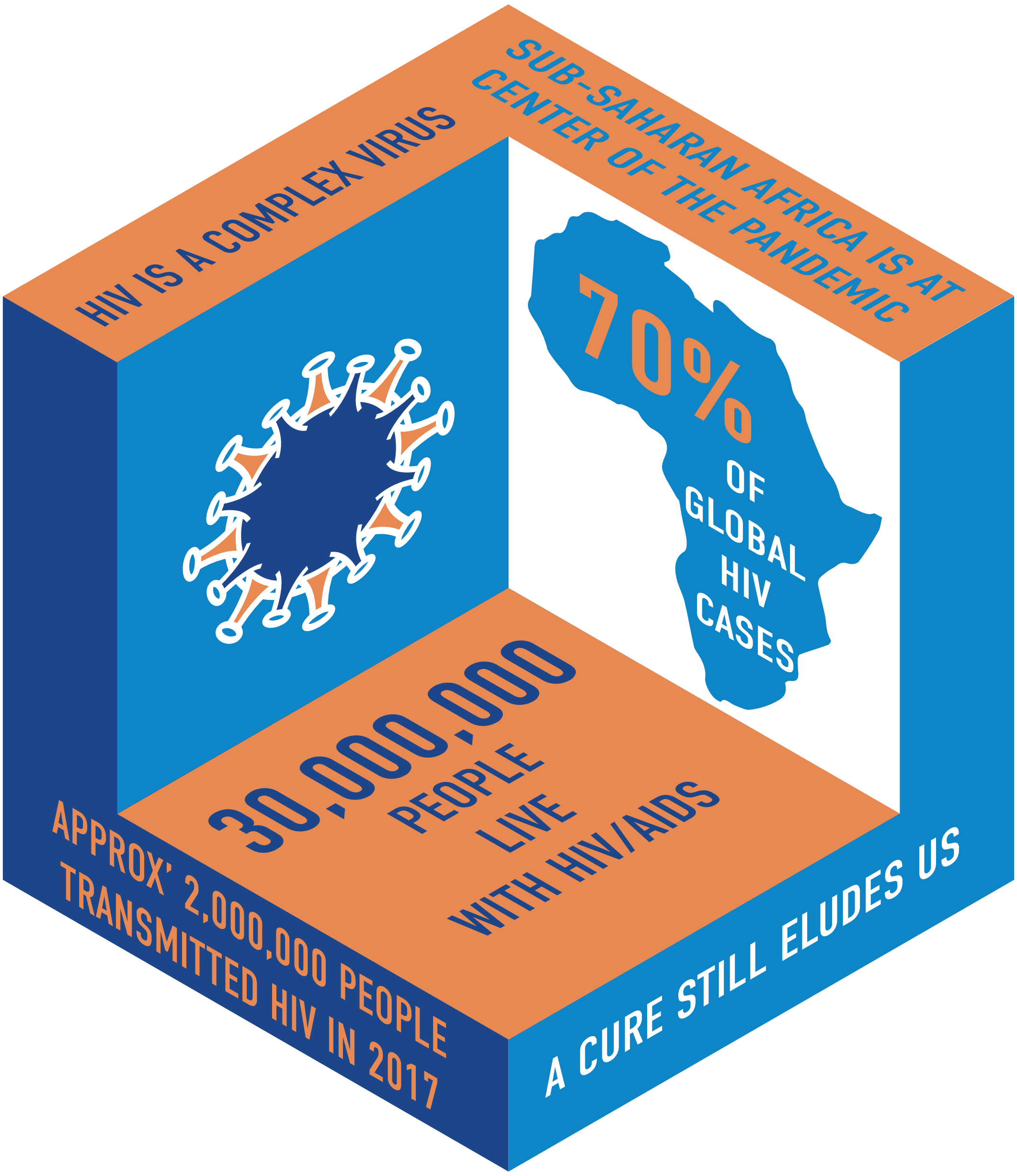

HIV IS A COMPLEX VIRUS
SUB-SAHARAN AFRICA IS AT CENTER OF THE PANDEMIC
70% OF GLOBAL HIV CASES
30,000,000 PEOPLE LIVE WITH HIV/AIDS
APPROX' 2,000,000 PEOPLE TRANSMITTED HIV IN 2017
A CURE STILL ELUDES US

HIV/AIDS

INTRODUCTION

Human immunodeficiency virus (HIV) is a retrovirus that causes acquired immune deficiency syndrome (AIDS), a disease that leads to the progressive deterioration of the immune system.

Left untreated, the disease leads to death. Though it is no longer a top 10 killer globally, HIV/AIDS continues to represent a serious global pandemic in low-income countries as the fourth largest cause of mortality.

Concerted global efforts to curb transmission and the development and distribution of antiretroviral drugs have substantially reduced mortality and gradually converted HIV into a chronic disease. While the overall number of new HIV infections has fallen from 3.2 million in 2000 to 1.8 million in 2017, the pandemic is far from over. In 2017, 36.9 million people around the world were living with HIV/AIDS; about 70 percent of whom are in sub-Saharan Africa. Globally, some 940,000 people died due to AIDS-related causes in 2017 (UNAIDS, 2018).

HIV is primarily transmitted through unprotected sexual contact, contaminated needles, and from infected mother to child—in utero, at birth or through breastfeeding. There is neither a vaccine to prevent HIV infection, nor a cure for it. Consequently, targeting risk-reducing behaviors is important for preventing HIV infection and controlling the spread of the disease.

Antiretroviral treatments (ARVs) are widely available. While they do not cure the disease, they control disease progression and are able to dramatically reduce transmission. However, enabling early diagnosis and widespread access to ARVs is a significant challenge, especially in developing regions. Treatment is lifelong and very costly, and preventing patient drop off during treatment is difficult.

Given the above challenges, there are four technologies that can help reduce the burden of HIV/AIDS in developing countries.

- Breakthrough 23. Vaccines that can effectively control and eventually help eradicate the major infectious diseases of our time—HIV/AIDS, malaria, tuberculosis and pneumococcus
- Breakthrough 24. Microbicides to provide a method of protection for those who are otherwise vulnerable to HIV/AIDS infection by their partner
- Breakthrough 25. PrEP (pre-exposure prophylaxis) to reduce the risk of HIV infection
- Breakthrough 26. Improved, longer-lasting antiretroviral therapy (ART) formulations to control HIV viral replication and increase patient adherence

Though it is no longer a top 10 killer globally, HIV/AIDS continues to represent a serious global pandemic in low-income countries as the fourth largest cause of mortality. Concerted global efforts to curb transmission and the development and distribution of antiretroviral drugs have substantially reduced mortality and have gradually converted HIV into a chronic disease. While the number of deaths and new HIV infections have fallen, the pandemic is far from over. Globally each year, almost a million people die due to AIDS-related causes.

CORE FACTS AND ANALYSIS

Human immunodeficiency virus (HIV) is a retrovirus that causes Acquired Immunodeficiency Syndrome (AIDS), a disease characterized by progressive deterioration of the immune system. The diminished immune function of HIV/AIDS patients puts them at greater risk for a variety of infections, which without treatment leads to death.

In 2017, 1.8 million people contracted the virus and 940,000 people died of AIDS-related causes (UNAIDS, 2018). Particularly vulnerable, young women are twice as likely to be living with HIV than men (UNAIDS, 2018). Importantly, those living with HIV have a 20 to 37 times higher risk of developing TB (WHO, 2012).

The HIV/AIDS pandemic poses an enormous economic burden on countries with high incidence and prevalence rates, especially in light of higher prevalence in younger individuals. The resulting disability and death among workers and young parents has devastating effects on household income, and also decreases productivity and growth at the national level.

The care of children orphaned by the virus further adds to the economic burden of the worst-affected countries. Globally more than 13.4 million children are defined as AIDS orphans (UNICEF, 2016). Put together, these factors create downward spirals of poverty and social disruption in regions severely affected by HIV/AIDS.

1. Sub Saharan Africa is the center of the HIV/AIDS pandemic

Although HIV is prevalent across the world, sub-Saharan Africa is home to 25.7 million of the 36.9 million people living with HIV worldwide (UNAIDS, 2018). In sub-Saharan Africa, HIV/AIDS is the leading cause of death and third largest disease burden, representing 9.5 percent of all deaths and 8.2 percent of all DALYs (Global Burden of Disease, 2017).

It is also the single most important contributing factor in the overall disease burden among the adult population in Southern and Eastern Africa. **Table 1** illustrates the total number of people living with HIV and the number of new HIV infections and deaths in 2017 (UNAIDS, 2017)

Region	People living with HIV 2017	New HIV infections 2017			AIDS-related deaths 2017	People accessing treatment 2017
		Total	Aged 15+	Aged 0-14		
Eastern and Southern Africa	**19.6 million** (17.5 million-22.0 million)	**800 000** (650 000-1.0 million)	**710 000** (580 000-890 000)	**92 000** (61 000-130 000)	**380 000** (300 000-510 000)	**12.9 million (11.4 million-13.4 million)**
Asia and the Pacific	**5.2 million** (4.1 million-6.7 million)	**280 000** (210 000-390 000)	**280 000** (210 000-390 000)	**10 000** (7 4000-14 000)	**170 000** (110 000-280 000)	**2.7 million (2.4 million-2.9 million)**
Western and Central Africa	**6.1 million** (4.4 million-8.1 million)	**370 000** (220 000-570 000)	**310 000** (180 000-470 000)	**67 000** (36 000-100 000)	**280 000** (180 000-410 000)	**2.4 million (2.1 million-2.5 million)**
Latin America	**1.8 million** (1.5 million-2.3 million)	**100 000** (77 000-130 000)	**99 000** (75 000-130 000)	**2400** (1800-3600)	**37 000** (26 000-51 000)	**1.1 million (992 000-1.2 million)**
The Caribbean	**310 000** (260 000 420 000)	**15 000** (11 000-31 000)	**14 000** (10 000-24 000)	**1 100** (710-1 900)	**10 000** (7 100-17 000)	**181 000 (159 000-188 000)**
Middle East and North Africa	**220 000** (150 000-300 000)	**18 000** (10 000-31 000)	**17 000** (9 200-28 000)	**1 300** (780-1 900)	**9 800** (6 400-15 000)	**63 200 (55 600-65 700)**
Eastern Europe and Central Asia	**1.4 million** (1.9 million-2.4 million)	**130 000** (120 000-150 000)	**30 000** (120 000-150 000)	_*	**34 000** (25 000-41 000)	**520 000 (458 000-541 000)**
Western and Central Europe and North America	**2.2 million** (1.9 million-2.4 million)	**70 000** (57 000-84 000)	**69 000** (57 000-83 000)	_*	**13 000** (9 990-18 000)	**1.7 million (1.5 million-1.8 million)**
Global totals	**36.9 million** (31.1 million-43.9 million)	**1.8 million** (1.4 million-2.4 million)	**1.6 million** (1.3 million-2.1 million)	**180 000** (110 000-260 000)	**940 000** (670 000-1.3 million)	**21.7 million** (19.1 million-22.6 million)

Table 1: Global HIV/AIDS statistics show that the disease continues to be a major health problem, especially in Africa. (Source: UNAIDS, 2018)

In terms of prevalence, South and Southeast Asia are second to sub-Saharan Africa with a total of 1.9 million individuals living with HIV/AIDS (GDB 2017). However, in contrast to sub-Saharan Africa, HIV/AIDS is only the 17th largest cause of disease burden in South Asia, behind lower respiratory infections, preterm birth complications and diarrheal diseases, among others, and represents 0.54 percent of all DALYs (GDB, 2017).

2. HIV/AIDS attacks immune cells and is transmitted person to person

HIV is a member of the genus Lentivirus within the Retroviridae family. The virus infects immune cells, such as T cells, which bear the surface molecule CD4. HIV can also infect other immune cells, such as macrophages, which may serve as both a reservoir for the virus and a means of viral spread to other body tissues.

After entry into a permissive cell, a viral enzyme called reverse transcriptase converts the RNA genome into double stranded DNA. This DNA becomes integrated into the cellular genome by a second HIV enzyme, integrase.

Once integrated, the HIV provirus takes advantage of host cell enzymes to transcribe and translate its genetic material into the viral proteins, which together with its genetic copies, assemble into new viral particles and bud from the infected cell.

The body's defenses weaken when subsets of immune cells, such as T cells, are infected and destroyed. Once a patient develops AIDS, they are highly susceptible to a wide variety of opportunistic infections (BVGH, 2012).

HIV/AIDS transmission in some ways parallels the transmission patterns of other sexually transmitted diseases such as syphilis, gonorrhea and of diseases like Hepatitis B and C, which are also transmitted via blood transfusion or intravenous drug use.

HIV transmission requires unprotected and close contact with body fluids of other infected individuals, primarily through exposure to blood, semen, vaginal secretions and breast milk. As a result, the major routes of infection are through sexual contact, contaminated needles and from infected mother to child in utero, at birth or through breastfeeding.

3. Interventions have revolved around preventing transmission, and treatment with antiretroviral therapy (ART)

In addressing the HIV/AIDS pandemic, there are two key avenues for intervention: the prevention of transmission and diagnosing and treating the virus (WHO, 2013). Currently, there is neither a vaccine to prevent HIV infection nor a cure for it. Available antiretroviral drugs (ARVs) require lifelong treatment and only control viral replication and disease progression. While ARVs do dramatically reduce HIV transmission, targeting risk-reducing behaviors and preventing the spread of the disease are equally important.

In 2015, UNAIDs established the 90-90-90 targets: By 2020, 90 percent of all people living with HIV will know their HIV status; 90 percent of all people with diagnosed HIV infection will receive sustained antiretroviral therapy; and 90 percent of all people receiving antiretroviral therapy will have viral suppression. In 2017, the figures for the 90-90-90 initiative were 75 percent, 79 percent and 81 percent respectively (UNAIDS, 2018).

Interventions aimed at preventing transmission

Condoms and abstinence

Sexual transmission of HIV can be reduced by consistent and correct use of male and female condoms, limiting the number of sexual partners or abstaining from sexual activity all together. Consistent use of condoms reduces the risk of contracting or transmitting HIV by about 80 percent (Weller & Davis-Beaty, 2011).

Despite this, in 2013 only 41 percent of adults with multiple sexual partners report having used a condom during the last time they had sex. Condom use is particularly low among adolescent girls in Africa and among men who have sex with men (WHO, 2014). UNAIDS also estimated a large gap between condom availability of more than three billion condoms (UNAIDS, 2015).

Male circumcision

Medical male circumcision (the surgical removal of the penis foreskin) has been recognized since 2007 by the WHO, UNAIDS and other major health organizations as an effective component of the global strategy to end the HIV/AIDS pandemic. Clinical trials have demonstrated that male circumcision can reduce a man's risk of acquiring HIV from his female infected sexual partner by at least 60 percent (Wawer, et al., 2008).

Modeling studies show that this would also have vaccine-like efficacy, in that each man who is protected via circumcision would therefore not be capable of transmitting to a subsequent partner; thus women stand to derive some long-term benefit from circumcision due to lower probability of being exposed to, and infected by, HIV.

Voluntary male circumcision has been promoted in 14 priority countries in Africa since 2007, and by the end of 2017 nearly 18.6 million men had undergone the procedure, an almost five-fold increase from 2012. The service package now includes safer sex education, condo promotion and HIV testing as well. The number of annual circumcisions rose from 900,000 in 2011 to more than 1.7 million in 2012, and up to 4.04 million in 2017 (WHO, 2018).

Treatment as Prevention (TasP)

In 2011, an international study showed that ART can prevent the sexual transmission of HIV among heterosexual couples where one partner is HIV infected and the other is not. UNAIDS described the result as a "serious game changer" for HIV prevention (The Lancet, 2011). In 2011, a nine-country trial called HPTN 052 panning Africa, Asia and South America demonstrated that treating an HIV positive person with ART successfully decreases the amount of virus present in their bodies and reduces HIV transmission rates during sexual intercourse by 96 percent (WHO, 2012).

In 2014, the PARTNER study, in which more than 1,000 heterosexual and gay couples were enrolled, found no transmissions within mixed-status couples when the viral load of the positive partner was undetectable, and provided good evidence for the effectiveness of TasP. The WHO has embraced TasP as a key element of HIV prevention and as a major part of the solution to ending the HIV pandemic.

Pre-exposure prophylaxis (PrEP)

In November 2010, the results from a clinical trial showed promise for a new HIV prevention strategy called pre-exposure prophylaxis or PrEP. This involves the use of antiretroviral drugs by HIV negative people who are at a high risk of contracting HIV to reduce the risk of HIV infection. The trial, iPrex, demonstrated that daily use of a combination ART and Truvada (emtricitabine/tenofovir disoproxil fumarate) reduced the risk of HIV dramatically among men who have sex with men.

Since then, more than 10 clinical trials have demonstrated its effectiveness of PrEP in reducing HIV transmission among a range of populations. As of September 2015, WHO recommends that people at substantial risk of HIV infection, including HIV-negative women who are pregnant or breastfeeding, should be offered PrEP containing tenofovir as an additional prevention choice as part of comprehensive prevention (WHO, 2018).

Drug counseling, treatment and clean needles

Intravenous injection of illicit drugs is a high-risk behavior for HIV/AIDS transmission, as the virus can be passed on through contaminated needles. Prevention of drug use is targeted through counseling and treatment. Programs that have supplied drug users with clean needles have markedly reduced their risk of infection. In addition, post-exposure prophylactic treatment with ART can sometimes prevent infection if administered within 72 hours of potential exposure.

Preventing mother to child transmission of HIV/AIDS (PMTCT)

The risk of mother to child transmission (MTCT) of HIV is directly linked to maternal viral load[1]. ART use has led to the virtual elimination of perinatal HIV cases in the United States, and different regimens are being successfully used to decrease the risk of such transmission worldwide.

The 2013 WHO guidelines recommend starting all HIV-infected pregnant and breastfeeding women on lifelong ART, regardless of their CD4+ count (WHO, 2013). In 2017, 80 percent of the estimated 1.1 million pregnant women living with HIV globally received ARV treatments to prevent transmission to their children.

Substantial progress in PMTCT has been achieved in countries like Botswana where mother-to-child HIV transmission has come down from 20 to 40 percent in 2001 to less than 7 percent in 2007 (Botswana Ministry of Health, 2013). A few LMICs like Armenia, Belarus, Cuba and Thailand have eliminated MTCT as a public health problem. Such success is an indication that developed world paradigms for HIV control can be successfully implemented in developing countries.

Interventions aimed at controlling viral replication

Diagnosis of infected patients

Guidelines for HIV testing continue to evolve with changes in technology. Generally, diagnosis of infection occurs in two stages. First, a screening or first-line test is used for presumptive diagnosis. Such tests are generally immune-based enzyme-linked immunosorbent assays (ELISAs) that measure the presence of antibodies in blood or saliva.

The new generation of tests also incorporate HIV antigen detection to increase the sensitivity of the assay (WHO, 2018). As no one test can provide an absolute HIV-positive diagnosis, patients who receive a positive diagnosis from the first-line screening test then receive a higher specificity confirmatory test that verifies HIV infection and stage of disease.

Simplified, instrument-free and immune-based assays are available for rapid HIV screening in settings without access to laboratory facilities. These rapid tests have allowed many countries to implement and expand community-based and self-testing HIV diagnosis and increase HIV diagnosis.

A systematic review of studies on the reliability of self-testing showed that self-testers were able to interpret rapid test results as accurately as trained health workers (Figueroa et al., 2018). Confirmatory diagnosis can be performed using western blot, line immunoassays or for high prevalence areas by using a minimum of two to three different rapid assays. The choice of confirmatory test depends on HIV prevalence in the population, as well as by the cost and availability of laboratory services.

Treatment of infected patients

The WHO recommended treatment for HIV/AIDS is a combination of ART and management and treatment of opportunistic infections that may result from HIV-related immune suppression. The ART strategy most widely used is called Highly Active Antiretroviral Therapy (HAART) and consists of combination treatment with two nucleoside reverse transcriptase inhibitors (NRTIs), co-administered with a third drug with a different mechanism of action, such as a non-nucleoside reverse transcriptase inhibitor (NNRTI), a protease inhibitor or an integrase inhibitor.

There are currently 40 HIV products approved by the U.S. Food & Drug Administration (FDA) including individual drugs and fixed dose combinations (US FDA, 2018). The 2016 guidelines include new alternative ARV options with better tolerability, higher efficacy and lower rates of treatment discontinuation when compared with medicines being used currently: dolutegravir and low-dose efavirenz for first-line therapy and raltegravir and darunavir/ritonavir for second-line therapy.

[1]Also known as viral burden, viral titre or viral titer is a measure of the severity of a viral infection and can be calculated by estimating the amount of virus in an involve body fluid. For example, it can be given in RNA copies per milliliter of blood plasma.

Viral load testing to monitor treatment efficacy

Viral load testing is the most sensitive method to monitor patients for ART failure and determine the need to progress to second-line treatment regimens. The majority of tests today use nucleic acid amplification techniques to detect the presence of viral nucleic acid.

Treatment failure occurs when viral load either does not drop or repeatedly rises after having dropped previously, in what is called virologic failure. Though viral load monitoring capacity is being scaled up, it remains limited in low-income setting because it is cost-prohibitive and requires sophisticated laboratory equipment and highly trained personnel.

Challenges extend beyond access to the lab, from correct sampling methodologies to obtaining and transporting specimens and timely delivery of results to providers (El-Sadr et al., 2017).

Monitoring patient adherence

Treatment interruption leads to a large and quantifiable increase in viral load and dramatically increases chances of disease progression and transmission (Bangsberg, et al., 2001). Lack of treatment adherence is a leading predictor of HIV/AIDS mortality globally.

There are numerous reasons for patients falling out of treatment, described in detail further in this chapter, and include social stigma, cost of treatment and transportation constraints. Additionally, once patients begin treatment and start to feel better, they may become lax about their treatment. The support from friends and family, who have made it possible for a patient to make it to a clinic for starting treatment, may begin to wane.

Numerous approaches are being explored to increase patient adherence, including the development of long-lasting treatment formulations, mobile-health solutions, such as SMS reminders to patients to take their medicines (Siedner, et al., 2012), and real-time adherence monitoring devices that are linked to patient pill boxes and can transmit information back to a clinic about when patients have opened their medication boxes.

These approaches are superior to current adherence monitoring methods that either rely on structured patient interviews and pill counts or tracking pharmacy refill information; these methods operate on an intermittent basis and missed doses go undetected for several weeks or months. Realtime, wireless monitoring mechanisms may offer the opportunity to proactively prevent virologic rebound and treatment failure and prevent death (Haberer, et al., 2010; DeSilva, et al., 2013).

KEY CHALLENGES

While much has been done globally to tackle the HIV/AIDS pandemic, several scientific and social factors limit transmission control and finding a definite cure.

Highlighted below are some of the major challenges in the fight to reduce HIV/AIDS related mortality.

1. A highly complex virus, which makes developing vaccines difficult

HIV mutates rapidly and patients can be infected by numerous different strains of the virus. HIV is broadly classified as HIV-1 or HIV-2. The former is more virulent, causes majority of the infections and can be divided into several distinct groups; these groups are further divided into subtypes (clades) that display distinct geographic patterns of infection.

The acute diversity of HIV strains and the alacrity of the virus' spread and mutation within the human body are the principle impediments to the development of new biomedical prevention tools. Once inside the body, the virus mutates so fast that the immune system simply cannot keep pace. Indeed, it is the immune system itself that is the target of the virus.

After one week of infection, HIV is overwhelmingly found in the T cells of the gut—exactly the cells that have the capacity to defeat it. Because HIV is a retrovirus, it integrates into a person's DNA. The problem of rapid integration is particularly crucial for a vaccine. Once the virus integrates, it has the ability to hide from the immune system. Integration means that any vaccine must be able to act within the short interval between infection and before the integrated form of the virus takes over a substantial number of CD4 T cells.

An effective vaccine would be the single most transformational technology intervention to prevent HIV transmission, yet more than three decades of R&D led to scant success until 2009 and the 10 years since.

In December 2009, the first hopeful clinical trial results were published; the results of the RV144 vaccine trial in Thailand. In this study more than 16,000 HIV negative volunteers received a series of priming vaccinations with a canarypox-based viral vector vaccine (Sanofi-Pasteur), followed by boosters with a recombinant protein vaccine containing subunits of the HIV surface glycoprotein gp120 (AIDSVAX B/E, VaxGen/GSID).

The study showed approximately 31 percent protection against HIV infection as compared to the placebo control group, and the efficacy of this protective effect declined with time (Rerks-Ngarm, 2009). This study made clear that numerous basic science questions about the virus still remain unanswered.

The correlates of protection are unclear

In general, when developing a vaccine, an important input is an understanding of the natural history of a disease and the immune response it elicits. In the context of HIV, there are no examples of natural immunity in the human environment. While there are examples of a few individuals who are genetically resistant to infection and those who control the virus at low levels for a long time, there is no population of people that have actually overcome the infection.

This is a major obstacle to HIV vaccine development. The 2009 RV144 Phase III trial results gave the first supporting evidence of any vaccine being effective in lowering the risk of contracting HIV, but yielded additional questions about the immunological basis of protection in those people who received the vaccine.

In 2012, more research on this topic provided some additional but not conclusive data on correlates of protection, indicating that the immune response was antibody-based (Haynes, et al., 2012). In 2015, an experiment using 3BNC117, an antibody which blocks the first contact between the virus and the cell it is about to infect, to treat HIV-infected patients in passive immunotherapy showed that the antibody neutralized HIV and reduced the amount of virus circulating in the patients' bloodstreams. Since 3BNC117 is a type of antibody that would be generated by an ideal vaccine, the outcomes not only showed the potential of passive immunotherapy as a treatment, but also suggested that a vaccine which induced this type of antibodies would be widely protective (Caskey et al., 2015).

More research is needed to understand and elicit durable antibody response

One of the main challenges in vaccine development had been the difficulty in eliciting a timely and long-lasting immune response. During the RV 114 trial, researchers reported that vaccine efficacy seemed to peak early; cumulative vaccine efficacy was estimated to be 60.5 percent through the 12 months after initial vaccination, but declined to 31 percent after three years, a problem that is linked to waning antibody responses (Robb, et al., 2012). Much progress has been made since 2012 in developing new antigens and adjuvants capable of inducing longer-lasting antibody responses. There is also increasing understanding of factors that influence the body's immune response, such as the virus load, the diversity of the viruses, the duration of the infection, the ethnicity of the affected person and identification of special envelope proteins, etc. (University of Zurich, 2018).

2. Complex and inter-related drivers of transmission make disease control problematic

The number, complexity and interrelated nature of the drivers of HIV transmission pose enormous challenges for HIV control, and in particular, for pinpointing and implementing preventative behavioral interventions (**Exhibit 1**).

Drivers of HIV transmission

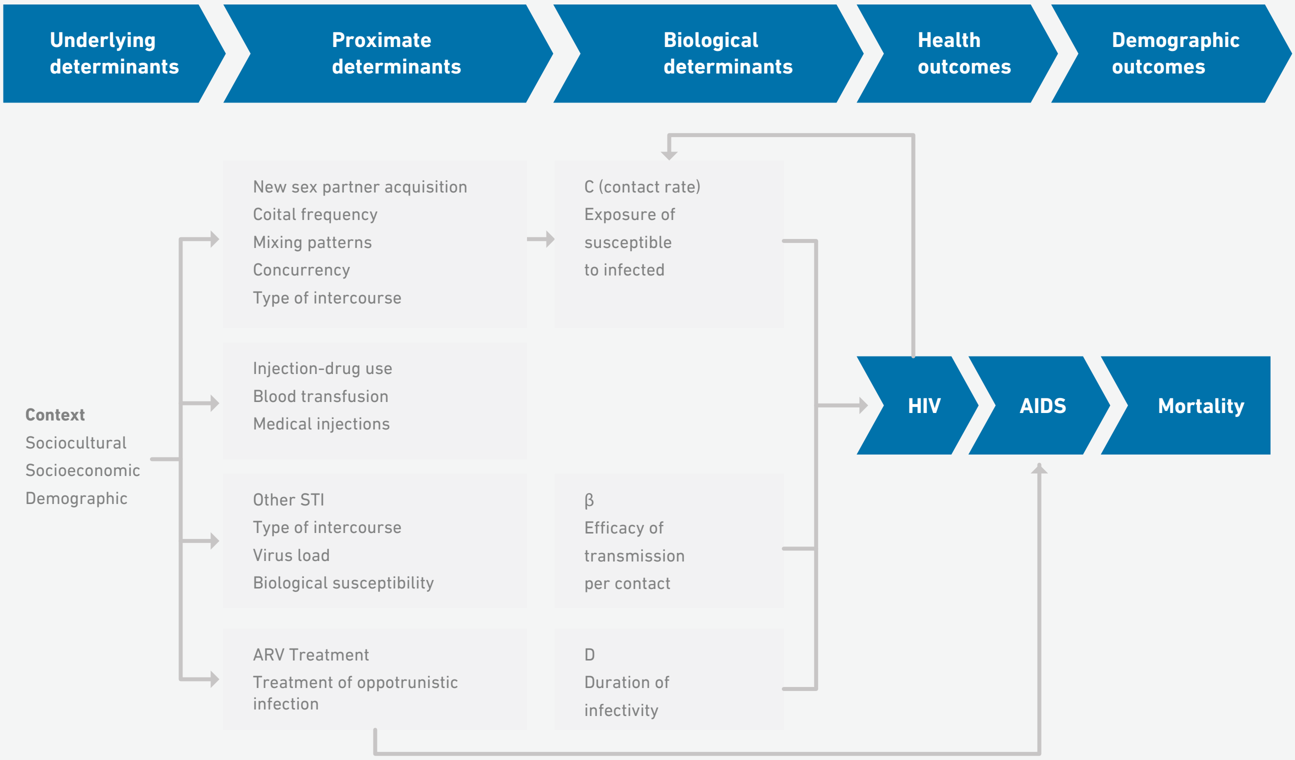


Exhibit 1: HIV/AIDS transmission is complex. The underlying sociocultural, socioeconomic and demographic determinants of HIV/AIDS transmission that drive sexual behaviors in turn shape the downstream proximate determinants of transmission. (Source: Boerma & Weire, 2005)

The key biological determinants that underlie HIV transmission include the contact rate (C), which describes the exposure of the susceptible to the infected, the efficacy of transmission per contact (B) and the duration of infectivity (D).

Those with HIV infect others in line with the contact rate, but the development of HIV into AIDS can be prevented by early detection and treatment with ART. Each of these biological determinants of infection is in turn impacted by proximate determinants (**Table 2**).

Biological and proximate determinants of HIV transmission

Biological driver	Proximate Determinants
Contact rate: Sexual Transmission	• New sex partner acquisition: the frequency of engagement in sexual activity with a new partner • Coital frequency: the frequency of sexual activity • Sexual partnership mixing patterns: the extent to which subpopulations with different prevalence of infection engage in sexual partnership mixing with others of different levels of education, involvement in illicit drug use, concurrent sex partners, and incarceration • Concurrency: the existence of more than one long-term sexual partner • Type of intercourse
Contact rate: Needle Transmission	• Use of injected drugs • Frequency of blood transfusions • Frequency of medical injections
Efficacy of transmission per contact (β)	• Prevalence of other sexually transmitted infections: STIs have been shown to increase the susceptibility of an individual to being infected, and also increase the virulence of the infection in an HIV infected person • Type of intercourse • Viral load of infected individual impacts efficacy of transmission • Biological susceptibility: individuals can have different basic levels of susceptibility to HIV infection
The duration of infectivity	• Treatment with ART. Duration of infectivity is life-long without antiretroviral therapy

Table 2: Several proximate determinants impact biological determinants of HIV transmission and infection.

The underlying sociocultural, socioeconomic and demographic determinants of HIV/AIDS transmission that drive sexual behaviors shape the downstream proximate determinants of transmission.

In recent years, increased understanding about human sexual behaviors and how they are shaped by social, economic and legal-political structures has made it indisputable that reducing HIV risk is embedded in structural change in economic opportunities, social norms, gender roles and legal freedoms (Parkhurst, 2013). HIV prevention efforts are particularly challenging in situations where power is skewed structurally along gender divisions.

Particular groups, such as commercial sex workers and women in polygamous marriages, become extremely vulnerable. Based on our current understanding of the structural determinants of HIV infection, commonly-identified high risk groups include: adolescents (in particular, underprivileged or street children), women (in particular, young women between the age of 15 and 24 years and commercial sex workers), men and transgender individuals who have sex with men, truck drivers, displaced populations and prisoners.

Such populations represent the majority of people affected by HIV outside Africa, and a significant share of new infections within Africa (WHO, 2014).

3. Difficulty of patient monitoring and adherence to treatment

The HIV/AIDS treatment cascade (**Exhibit 2**) is a way of showing the number of individuals living with HIV/AIDS who are actually receiving the full benefits of the medical care and treatment they need. Even in the United States only 1 in 4 HIV infected individuals receives the full care they need (Gardner, et al., 2011).

While little comprehensive data is available about the treatment cascade in sub-Saharan Africa and other developing countries, it is generally agreed there is a high level of drop-off that occurs between diagnosis to initiation of ART. One meta-analysis suggests a median completion rate of 17 percent for those who get from diagnosis to initiation of ART (Rosen & Fox, 2011). But gaps are closing with the most recent WHO Treat All guidelines.

United States treatment cascade

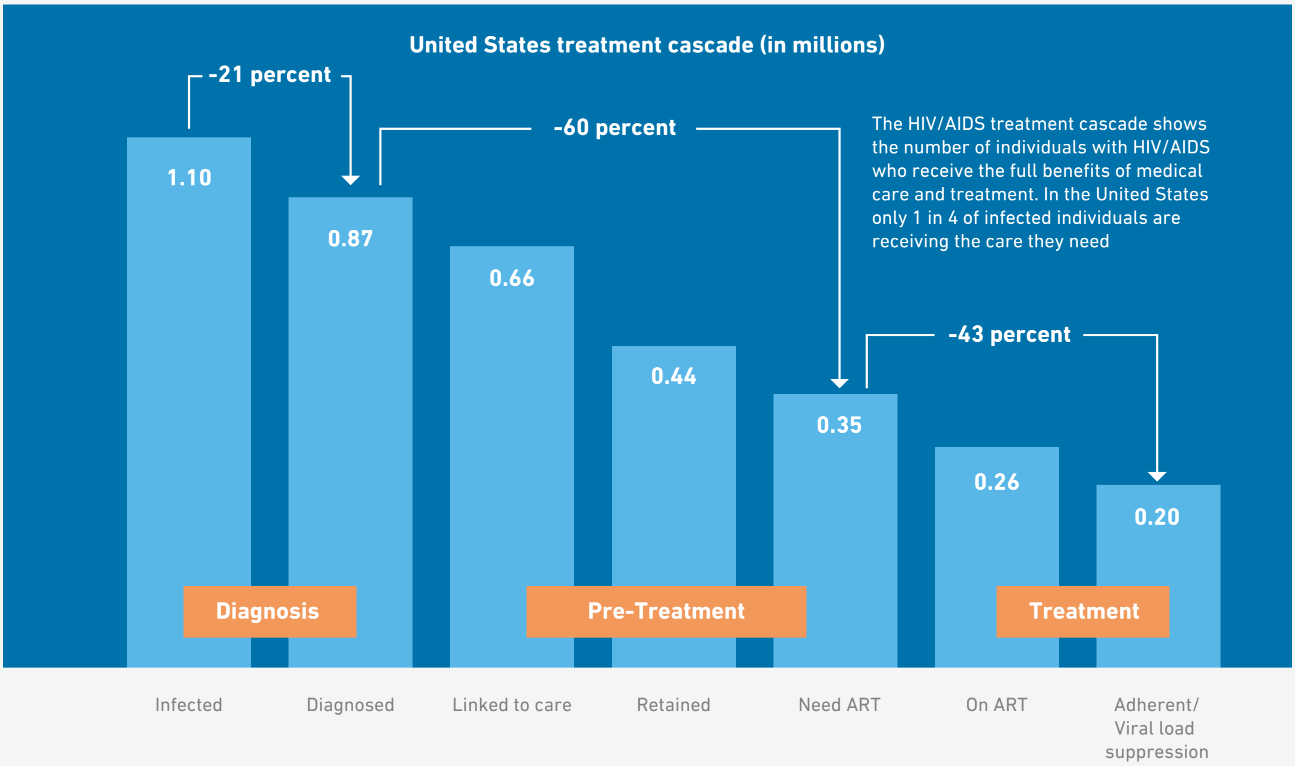


Exhibit 2: In the United States, only 1 in 4 HIV infected individuals receives the care they need. (Source: Gardner, et al., 2011)

There are a number of reasons for the rapid drop-off in the treatment cascade, as described below.

Difficulty of identifying infected individuals

Early identification of HIV infection is critical to treatment outcomes. However, HIV cannot be diagnosed through clinical symptoms. Two to four weeks after infection, patients may display flu-like symptoms accompanied by a rash and fever. Many patients are initially asymptomatic. This makes diagnosis difficult.

Although the incubation period between infection and onset of AIDS is often cited as seven to 10 years, disease course can be accelerated in LMICs due to environmental factors, co-morbidities and poor nutrition (BVGH, 2012).

Social stigma also prevents many individuals from even getting tested for HIV. HIV self-testing, as recommended in WHO's 2016 testing guidelines update, is becoming more widely available and an important new option for reaching greater numbers of people living with HIV who otherwise may not take an HIV test (WHO, 2016).

Moving from diagnosis to care and patient retention

There are now an increasing number of testing facilities offering immediate ART to those individuals they diagnose.

The CASCADE randomized control trial in 2016 and 2017 showed that offering same-day home-based ART initiation to individuals who tested positive during home-based HIV testing, compared with usual care and standard clinic referral, significantly increased linkage to care at three months and HIV viral suppression at 12 months (Labhardt et al., 2018).

Monitoring CD4+ counts generally requires expensive flow cytometry equipment and a highly trained laboratory workforce. Although simplified bench-top devices are available (for example, FACSCount, BD; Guava EasyCD4; Partec Cyflow; PointCare), most of these machines are expensive to purchase, repair and maintain and require regular electricity to operate, largely limiting their utility in developing countries to centralized laboratory facilities (WHO, 2007).

As a result, CD4+ testing means patients seeking care in one clinic may need to be referred to a separate location to provide a blood sample for diagnosis, and a follow-up visit is typically required to receive results.

Even after diagnosis and receiving care, regular monitoring to determine ART eligibility may not be perceived as medically beneficial by patients. This is especially true for those patients who do not feel sick, particularly when weighed against the out-of-pocket costs of missing work, transportation costs to access the nearest testing facility and the stigma of being identified as HIV positive within the community despite no outward symptoms.

These challenges are consistent with the results from a WHO survey of 127 member states that showed sufficient centralized laboratory capacity existed for at least four CD4+ cell count tests per HIV-infected person per year, but only 11 percent of the CD4+ testing capacity was utilized (Habiyambere et al., 2016).

There has been some recent progress towards simplifying diagnostic devices for monitoring CD4+counts, including approved and licensed devices that are inexpensive and do not require reliable power or technical prowess to operate.

Availability of ARVs and Drug Resistance

Between 2005 and 2017, the number of people who can access ARTs greatly increased from 2.1 million to 21.7 million (representing 59 percent of all persons living with HIV). Availability of ART drugs varies from country to country depending on the drug (composition, manufacturer and government approval among others), as well as health system resources.

Apart from the upfront cost of making ARTs available and accessible for everyone in need, high HIV incidence throughout sub-Saharan Africa has increased pressure on HIV clinics to rapidly expand accessibility to ART. As clinics are already overburdened and understaffed, many locations are experiencing long patient wait times and poor retention in care. As well, many countries are experiencing recurring stock outs[2] and there is increasing fear of mass drug resistance.

Patient adherence to treatment regimen

Side effects, constant necessity to be on medication (treatment is required for life) and costs involved, both medical and incidental costs to access medical care, can impact an individual's inclination and ability to stay on treatment.

Monitoring for treatment failure is extremely difficult in the low-income countries; currently prevalent diagnostics require expensive infrastructure and resources, making their widespread implementation in low resource settings very difficult. There is a particularly pressing need to develop strategies to improve adherence among young people aged 15 to 19 years, as they are more likely than adults to drop out (UNAIDS, 2018).

Adherence is generally improving with community-based or community-supported models of care (UNAIDS, 2018). Digital and mobile innovations are also found to be highly accepted and feasible and according to some evidence improving ART adherence and clinic attendance rates (Daher et al., 2017).

Pediatric challenges

The challenges outlined above are intensified for pediatric patients. Of all individuals living with HIV, children are the most vulnerable. Of the estimated 1.8 million children in need of ART in 2017, only 52 percent were receiving it (UNAIDS, 2018), lower than treatment coverage of adults.

Point-of-care early infant diagnosis (EID) reduces the waiting times for the return of test results from months to hours, improving access to early treatment for children living with HIV. However, bottlenecks remain as only half of infants who are exposed to HIV are tested before eight weeks of age. Mentor mothers are playing a big role in strengthening retention of mothers in HIV care, higher uptake of early infant diagnosis and initiation of ART for infants (USAID, 2018).

There are numerous barriers to appropriate treatment for children: Clinics are often far from home and treatment is difficult to administer, stigma prevents families from getting children diagnosed and there is a lack of training and support for families. For young children on liquid ART formulations, dosage is important.

Pediatric formulations are based on weight and the risk of measuring and administering an inadequate dose is more likely than for adults. In 2015, the United States Food and Drug Administration tentatively approved a new formulation of lopinavir/ritonavir (LPV/r), a pediatric antiretroviral for use in children 3 months or older (USAID AIDSFree).

More affordable medicines specifically adapted to the needs of children need to be developed. Nevertheless, pediatric patients are dependent on their caregivers to support adherence to treatment and for that it is essential that the caregiver is consistent and dependable.

[2] In 2017 and 2018, countries including Uganda, South Africa, DR Congo and Ghana reported worrisome ARVs stock outs.

SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

There is neither a vaccine to prevent HIV infection, nor a cure for it. As things stand, the only effective methods of combating the HIV/AIDS pandemic have been the prevention of transmission and diagnosing and treating those infected.

Drawing strength from a massive global effort, these interventions, despite the complexities involved, have shown results; since 2001, the total number of new infections has fallen substantially.

Sustaining and accelerating this decline is now crucial in the fight against the virus.

There are four scientific and technological breakthroughs that are capable of significantly advancing our fight against the HIV/AIDS pandemic.

Breakthroughs:

1	2	3	4	5	6	7	8	9	10
11	12	13	14	15	16	17	18	19	20
21	22	23	24	25	26	27	28	29	30
31	32	33	34	35	36	37	38	39	40
41	42	43	44	45	46	47	48	49	50

23 Vaccines that can effectively control and eventually help eradicate the major infectious diseases of our time—HIV/AIDS, malaria, tuberculosis and pneumococcus

Collectively, HIV/AIDS, malaria, tuberculosis and pneumonia kill more than five million people a year, and represent a significant disease burden for low income populations in sub-Saharan Africa and South Asia. Effective and affordable vaccines for these diseases do not exist yet due to the intrinsic complexity of the pathogens causing them, and a lack of understanding of the specific mechanisms through which our immune systems protect against these diseases. The process of vaccine development—basic research on disease etiology, vaccine construction, pre-clinical and clinical testing—is technically challenging, expensive and time consuming.

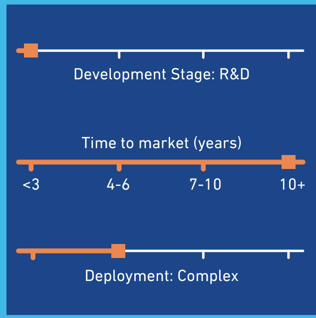
23a. A safe and efficacious HIV/AIDS vaccine

The extreme diversity of HIV strains, the rapid mutation of the virus inside the body and the fact that HIV is a retrovirus which integrates into an infected individual's DNA makes vaccine development for HIV particularly challenging. A vaccine must therefore act quickly in the short interval between infection and establishment of the integrated form in a substantial number of CD4 T cells.

After nearly three decades of HIV vaccine R&D, there are finally some promising candidates, building on some pivotal trials and better understanding of factors that influence immune responses. Current vaccine research is largely focused on understanding and developing specific or combinations of broadly neutralizing antibodies (bNABs) that have the ability to neutralize, or block, many strains of HIV and potentially prevent the virus from establishing a lasting infection. Around 1 per cent of patients have the ability to develop these bNABs that bind to structures on the surface of the pathogens. As these structures barely change and are identical among different strains, researchers are hopeful that these bNABs may help address one of the greatest challenges in HIV vaccine development—the virus's ability to mutate rapidly (AVAC, 2018).

As of 2018, there are two vaccines in large scale studies: 1) The HVTN 702 trial, also known as Uhambo, ongoing in South Africa, which is building on the RV144 trial, 2) The HVTN 705/HPX2008 trial, also known as Imbokodo, underway in multiple countries in southern Africa, which is a proof-of-concept study using a novel vaccine with mosaic immunogens. For both studies, results are expected in 2021.

Current State

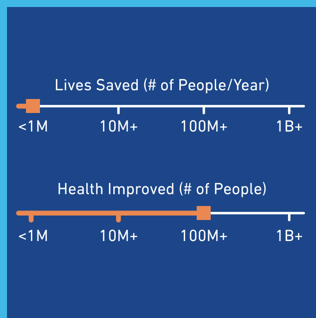


Associated 50BT Chapters

Global Health

SDG Alignment

Impact



Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

Other novel strategies entering human trials include protein antigens engineered to coax the immune system down a pathway that might lead to the production of broadly neutralizing antibodies (bNAbs), as well as several trials using passive immunization, investigating whether bNAbs can prevent HIV infection (Pipeline Report, 2018).

Another potential approach is gene therapy or transfer that involves identifying high-risk individuals and turning their cells into protein factories that can create and circulate antibodies that offer long-lasting protection.

Since 2009, 19 new bNABs have been isolated and characterized[4]. However, this is an area of very early research and a viable vaccine candidate is several years away. The ultimate vaccine is likely to rely on a multi-component, prime boost strategy and will have to elicit multiple bNABs, increasing the technical difficulty of the development process. The vaccine will also need to overcome the problem of antibody durability to provide long-lasting protection so that individuals do not require frequent re-immunization.

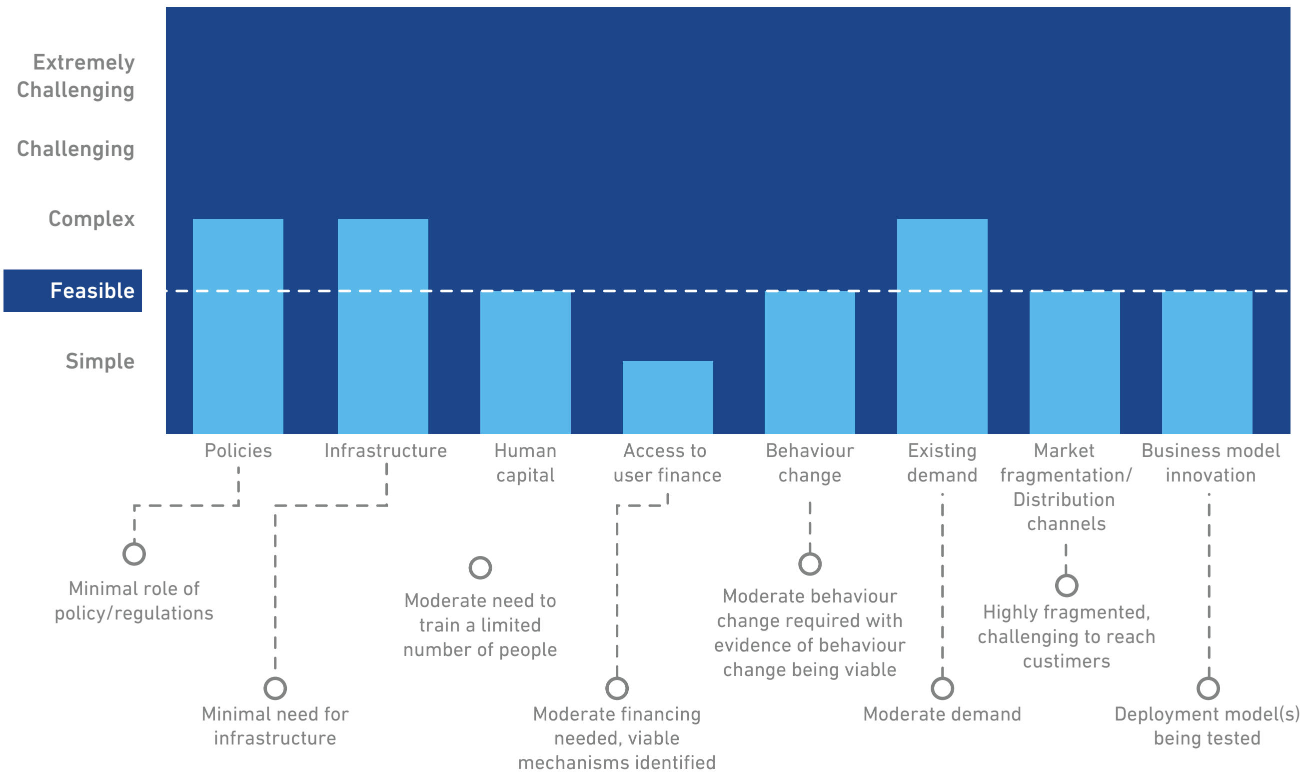
Deployment of new vaccines

Once any of these vaccines is developed, it can be deployed to children through existing, reasonably established, vaccine delivery channels. However, there are few mechanisms for delivering vaccines to adolescents and adults, and successful vaccination campaigns for these population segments would require significant government coordination, behavior change and financial investment.

Furthermore, even today vaccine delivery remains a challenge in many remote locations where supporting infrastructure like cold storage facilities are either few or non-existent. While vaccines are expected to be made available to patients at a low cost, financing for the vaccines by national governments or international donors would need to be secured in order to support widespread distribution. Policy changes would also need to support its introduction and distribution through public health systems.

Based on the above assessment, the projected time to market readiness is more than ten years, and the difficulty for deployment is FEASIBLE.

Breakthrough 23: Difficulty of deployment



[4] A large effort at research centers including International AIDS Vaccine Initiative (IAVI)'s Neutralizing Antibody Consortium (NAC), NIH's Vaccine Research Center (VRC) and Duke University's Center for HIV/AIDS Vaccine Immunology (CHAVI) have invested in this area. Since 2009, IAVI, the NAC, Theraclone and Monogram have collaborated to isolate and characterize 19 new broadly neutralizing antibodies from the Protocol G blood specimens.

24 Microbicides to provide a method of protection for those who are otherwise vulnerable to HIV/AIDS infection by their partner

Women, especially those living in societies and situations plagued by gender and income inequality, are often limited in their ability to ensure that their sexual partners use condoms. This risk is exacerbated in places with high rates of sexual violence and prevalence of polygamy. Specific high-risk populations, like sex workers and transgender people, also find themselves restricted in their ability to use protection during sexual contact.

Microbicides are currently under development as vaginal or rectal products designed to protect healthy men and women from HIV/AIDS infection. These products are being tested in multiple forms—vaginal and rectal gels that can be used at the time of sexual contact and vaginal film, tablets or rings that can slowly release the microbicide drug to provide preventative coverage for up to a month.

Unlike vaccines, an effective microbicide must be made into a commodity that individuals will want to and can safely use, on a regular basis. Ideally, microbicides would be discreet, easy to use, long-lasting and easy to distribute.

There are several different microbicide candidates currently being studied. Between 2012 and 2016, two Phase III trials were conducted on the dapivirine vaginal ring and showed that ring use reduced the rate of new HIV infections by 56 percent among the women who used it as instructed (AVAC, 2018). Regulatory decisions are expected by end of 2018.

A couple of other studies are looking into how young women use the ring. Even after regulatory approval, the ring will take a few years before it becomes available for use. It will also take time to work out the best formulation and dosage, find a suitable delivery method and identify appropriate distribution channels before the product can be made available to the public.

Current State

Development Stage: Engineering

Time to market (years): <3 | 4-6 | 7-10 | 10+

Deployment: Challenging

Associated 50BT Chapters

Global Health
Gender Equity

SDG Alignment

3 GOOD HEALTH AND WELL-BEING
5 GENDER EQUALITY

Impact

Lives Saved (# of People/Year): <1M | 10M+ | 100M+ | 1B+

Health Improved (# of People): <1M | 10M+ | 100M+ | 1B+

Commercial Attractiveness

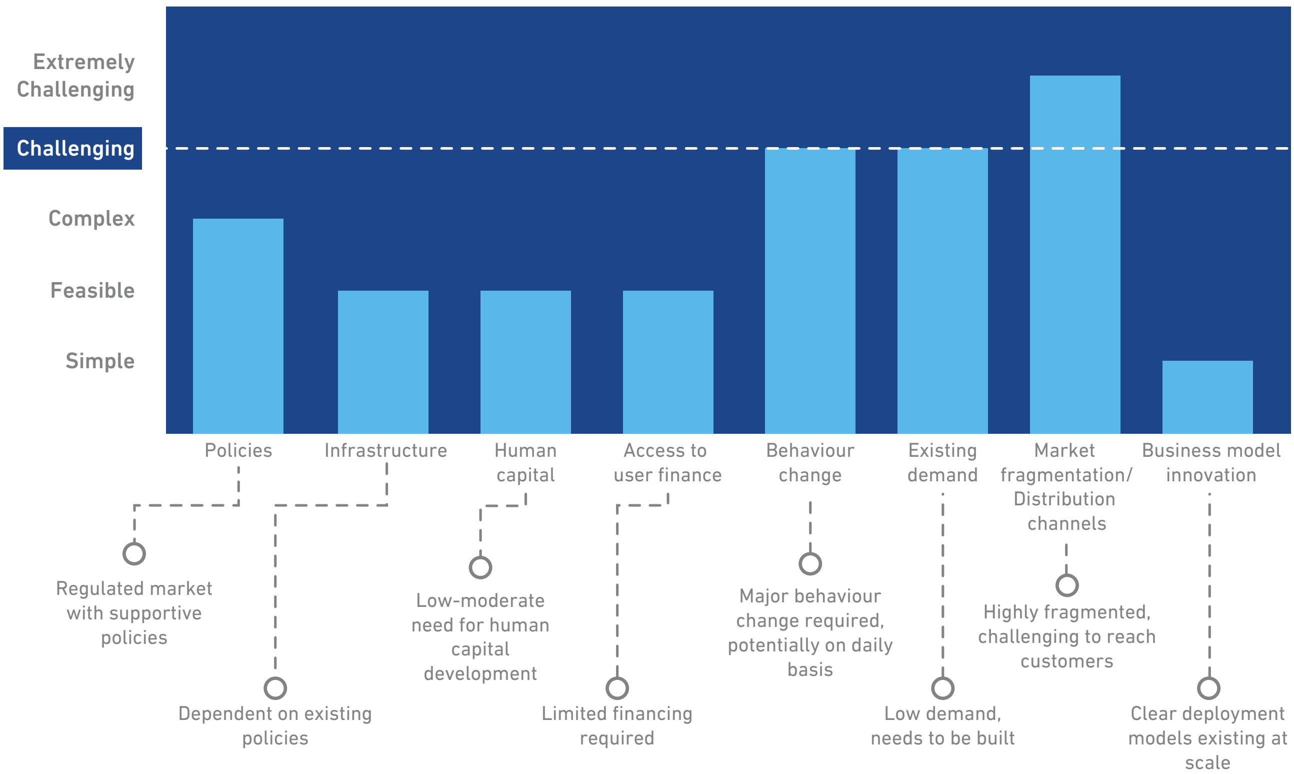
- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

Difficulty of deploying microbicides, once available, will depend on human factors, including how easy and convenient they are to use (microbicides require regular reapplication) and whether they are made available to consumers over the counter or by prescription only.

To ensure microbicides are widely available to people in LMICs, the price will have to be affordable, and this may mean that profit margins have to be kept low.

Based on the above assessment, the projected time to market readiness is one to five years and the level of difficulty for deployment is CHALLENGING.

Breakthrough 24: Difficulty of deployment



25 PrEP (pre-exposure prophylaxis) to reduce the risk of HIV infection

PrEP involves the use of antiretroviral therapy (ART) by those at a high risk for HIV infection to reduce the possibility of contracting the disease. It has already been included as a preventive strategy in WHO HIV prevention guidelines for high-risk populations.

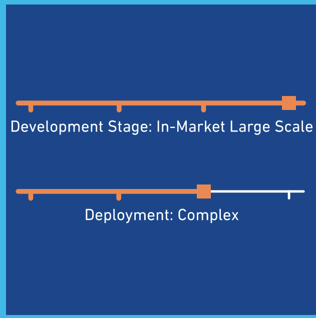
However, access to PrEP and ARVs in general is challenging, as is adherence for certain populations. Newer formulations and different delivery methods, such as a long-acting injectable PrEP or implants, can improve adherence. In addition to the currently available Truvada, a large number of ARV-based preventive products are now in the pipeline, mostly in the pre-clinical stage.

Next-generation strategies will use longer-acting drugs, focusing on delivery methods that are not widely used for HIV treatment. These include Cabotegravir, a long-acting injectable vaginal ring containing dapivirine that could be market-ready in 2019 (AVAC, 2018).

Despite these early encouraging signs, next-generation products will bring other challenges and much needs to be learned about how to enable large-scale adoption and use of PrEP, particularly among high risk populations. If the early results hold, the projected time to market readiness in developing countries is one to three years.

However, most countries facing the full impact of an HIV/AIDS epidemic do not have the infrastructure or economic resources to implement a PrEP strategy. Large scale implementation will be challenging.

Current State



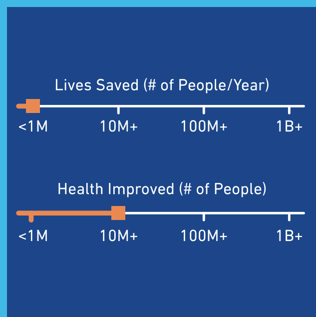
Associated 50BT Chapters

Global Health

SDG Alignment

3 GOOD HEALTH AND WELL-BEING

Impact

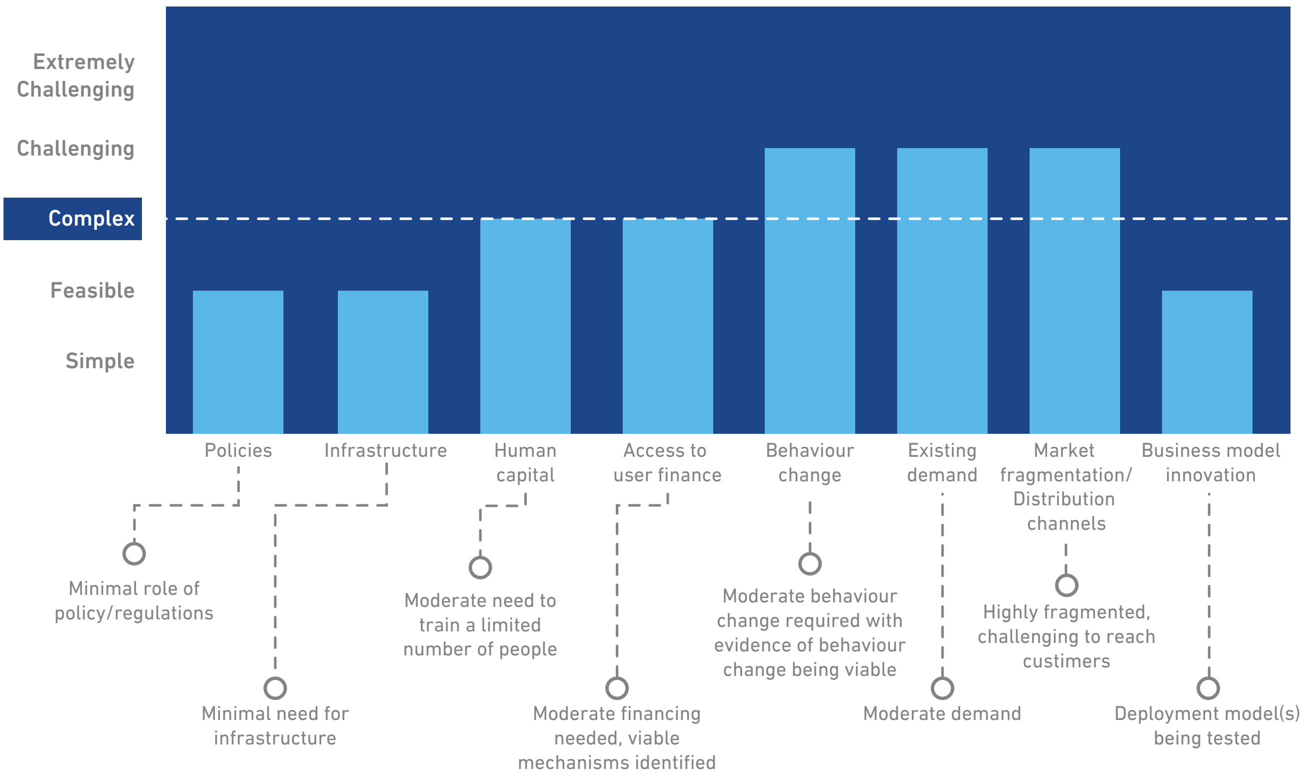


Commercial Attractiveness

- **Attractive for industrialized markets (high profits)**
- Attractive for emerging markets (lower profits)
- Emerging markets potential; requires derisking (sustainable)
- Non-commercial (unprofitable)

Based on the above assessment, the level of difficulty for deployment is COMPLEX.

Breakthrough 25: Difficulty of deployment



2.6 Improved, longer-lasting antiretroviral therapy (ART) formulations to control HIV viral replication and increase patient adherence

While globally access to ART is improving, children and those living in rural areas with poor infrastructure are still particularly disadvantaged due to the demands of the treatment and associated costs and constraints. Reformulation of current ART drugs can improve ease of use, and in turn access, especially for neglected populations.

Improved and more effective drugs with simplified treatment regimens (like single fixed-dose pill or easy to administer pediatric formulations) and reduced toxicity can help prevent treatment interruption and increase patient adherence. Long-acting ARTs can go a step further by helping reduce overall treatment costs.

These improved treatments should ideally be low cost, remain stable in high heat and humidity, require few supportive technologies to deliver the treatment and offer improved safety profiles to allow use with minimal medical supervision.

There are currently a handful of long-lasting injectable ARV drugs in development. In August 2018, the Phase III study showed a monthly injectable cabotegravir and rilpivirine had similar efficacy to a standard of care, daily, oral three-drug regimen at week 48 (Viiv Healthcare, 2018).

Some of these new formulations are also being tested to see if they have a preventative effect in HIV negative individuals.

Current State

Development Stage: R&D

Time to market (years)

<3 4-6 7-10 10+

Deployment: Feasible

Associated 50BT Chapters

Global Health

SDG Alignment

3 GOOD HEALTH AND WELL-BEING

Impact

Lives Saved (# of People/Year)

<1M 10M+ 100M+ 1B+

Health Improved (# of People)

<1M 10M+ 100M+ 1B+

Commercial Attractiveness

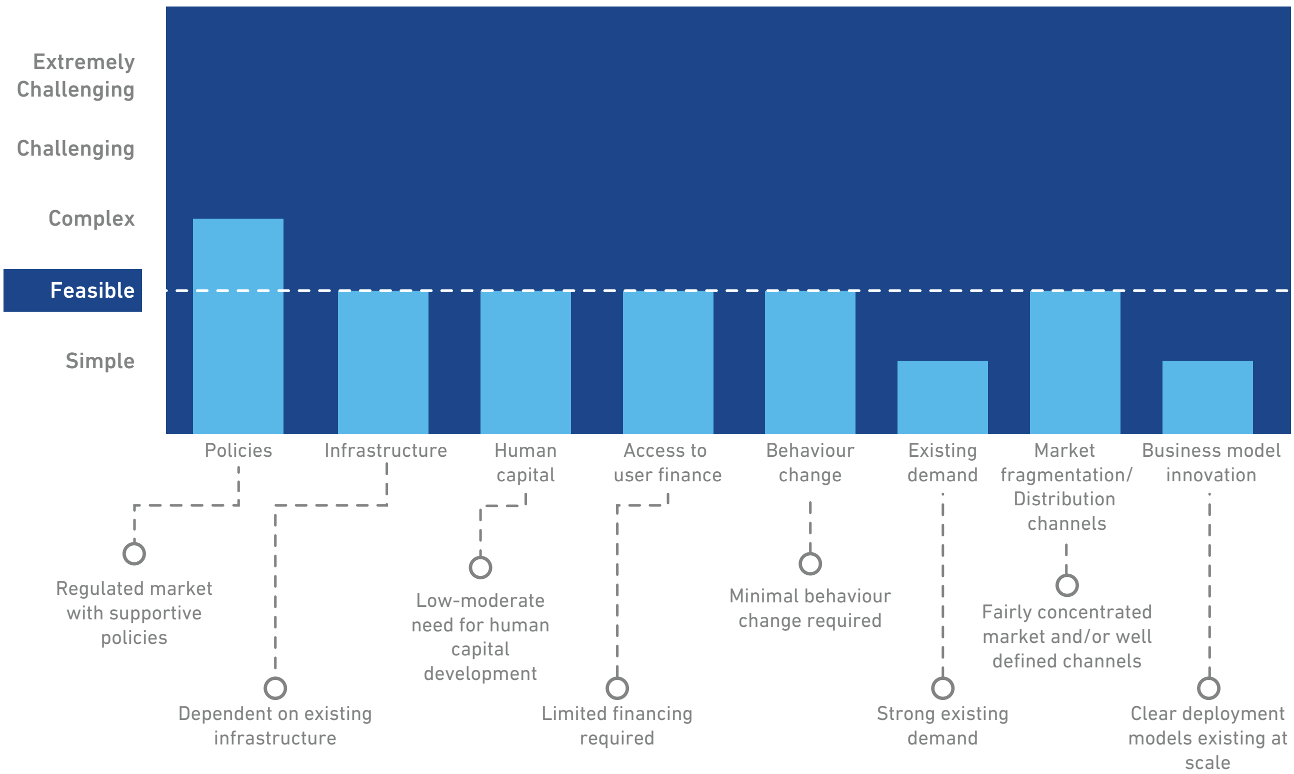
- **Attractive for industrialized markets (high profits)**
- Attractive for emerging markets (lower profits)
- Emerging markets potential; requires derisking (sustainable)
- Non-commercial (unprofitable)

Cost is the main barrier to widespread availability of new formulations and treatment. A 2010 study that modeled long-term funding needs for HIV/AIDS control in developing countries estimated that in the absence of an HIV/AIDS vaccine, global HIV control programs would cost between $400 and $700 billion for the period from 2009 to 2031 and approximately $22 billion to $24 billion annually by 2015, depending on policy choices adopted by governments and donors (Hecht, et al., 2010).

Today, in excess of $15 billion is spent on treating HIV positive people in the developing countries, and drug prices are believed to be near bottom.

The required investment to make improved therapies widely available is likely to be enormous. Based on the above assessment, the projected time to market readiness is seven to 10 years and the difficulty of deployment is FEASIBLE.

Breakthrough 26: Difficulty of deployment



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PULMONARY TUBERCULOSIS

INTRODUCTION

Pulmonary tuberculosis, commonly referred to as TB, is an airborne bacterial infection of the lungs. It is one of the most pervasive infectious diseases in the world.

In 2017, there were an estimated 10.4 million new cases and 1.2 million deaths (IHME GBD, 2017). As much as one quarter of the global population is estimated to be infected with latent TB, which occurs when someone is exposed to TB but their immune system keeps the bacteria sequestered in the body.

Most TB cases can be treated with first line antibiotics, however, a full course lasts six months, which makes compliance with treatment challenging.

Failure to complete full treatment has resulted in the emergence of TB that is resistant to first line drugs (referred to as multidrug-resistant TB or MDR-TB), which requires dramatically more expensive second line drugs taken over the course of 18 to 24 months. MDR-TB is becoming increasingly common and it is believed most cases of MDR-TB are now acquired directly, as opposed to being a result of failed treatment.

Diagnosis of TB is complex. There must be timely initial screening of patients who present with TB symptoms at the first point of care. For those patients screened as having TB, there must then be accurate diagnosis that can detect and distinguish between drug-sensitive TB and the various types of drug-resistant TB (DR-TB) including multiple drug-resistant (MDR-TB) and extensively drug-resistant TB (XDR-TB).

Current diagnostic methods possess low specificity and sensitivity and are unable to discriminate between drug-sensitive and DR-TB. The lack of a precise and accessible diagnostic for DR-TB is a critical challenge in stemming the disease's growth.

In light of the above challenges, five technologies can help reduce the burden of TB in developing countries.

- Breakthrough 23. Vaccines that can effectively control and eventually help eradicate the major infectious diseases of our time—HIV/AIDS, malaria, tuberculosis and pneumococcus
- Breakthrough 27. Shorter course treatments for both drug-sensitive TB and MDR-TB
- Breakthrough 28. New generation of antibiotics capable of treating fast-mutating bacteria like MTB and MRSA
- Breakthrough 35. Point-of-care nucleic acid test (NAT) that is simple, robust, and compatible with easily collected sample types
- Breakthrough 37. Affordable wearable technology with broader functionality for patient adherence and monitoring of health status

Pulmonary tuberculosis, also simply referred to as TB, is a bacterial infection caused by Mycobacterium tuberculosis (MTB). Affecting the lungs, it is one of the most pervasive infectious diseases in the world, with more than 10 million new cases every year and 1.2 million deaths annually.

CORE FACTS AND ANALYSIS

1. Tuberculosis is a contagious airborne disease that becomes problematic in immunocompromised people

TB is a highly contagious airborne disease that is most commonly transmitted through coughing and sneezing (WHO, 2018). It is one of the most pervasive infectious diseases in the world (**Table 1**), causing about 1.2 million deaths annually (IHME GBD, 2017).

Along with those suffering from active TB infections, an estimated one quarter of the world's population is infected with latent TB, which occurs when the MTB bacteria are sequestered by the body's immune system and remain alive but are neither an active infection or contagious. About five to 10 percent of individuals with latent TB will develop active TB in their lifetime, with the majority developing active TB within the first five years after infection (WHO, 2018).

TB Cases in 2017

Latent TB	1.9 billion total cases
Drug-sensitive TB	9.44 million new cases
Multiple drug-resistant TB (MDR-TB)	457,600 new cases
Extensively drug-resistant TB (XDR-TB)	38,900 new cases

Table 1: TB cases are often classified based on drug resistance or susceptibility. The WHO estimates that in 2017 some 9.44 million people fell ill with drug-sensitive TB that can be treated with a combination of first line drugs; 0.46 million fell ill with multidrug-resistant TB, of which 8.5 percent are considered to be extensively drug-resistant TB. (Source: WHO Global TB Report, 2018)[1]

When exposed to TB, people with healthy immune systems often only develop latent TB. However, individuals with compromised immune systems (due, for example, to malnutrition, aging or infections like HIV) are more likely to develop active TB upon initial exposure itself.

They are also more likely to develop active TB from latent TB infections. For instance, people infected with latent TB who are also HIV positive are 20 to 30 times more likely to develop active TB compared with those without HIV infection (WHO, 2018).

[1]Latent TB figures are calculated based on 25 percent of total world population of 7.6 billion in 2017.

In sub-Saharan Africa, HIV co-infection—found in 9 percent of new TB cases and 19 percent of TB-related deaths—is a major complication (WHO, 2018). Of all HIV-TB cases, 72 percent are found in the African region. Healthcare systems, especially for diagnosing and treating TB, are weaker in sub-Saharan Africa than in South Asia.

As a result, mortality rates, even for those without HIV co-infection, are higher in sub-Saharan Africa than in South Asia and Southeast Asia (WHO Global TB Report, 2018) (**Table 2**).

Regional prevalence of TB and HIV-TB co-infection

	Africa	Southeast Asia
New cases per year	2.48 million cases	4.44 million cases
Mortality (excluding TB-HIV)	413,000 deaths	638,000 deaths
Mortality rate	39 percent	26 percent
HIV prevalence in new cases	2.7 percent	3.5 percent
Percent new cases with MDR-TB	2.7 percent	2.7 percent
Percent TB re-infection cases with MDR-TB	14 percent	13 percent

Table 2: The underlying factors driving the spread of TB and the effectiveness of treatment are different in South-East Asia and Africa. (Source: WHO Global TB Report, 2018; MDR-TB includes rifampicin-resistant TB)

TB Testing, Photograph by CDC Global

KEY CHALLENGES

Although the epidemiology of TB is not fully understood, it is generally accepted that the spread of TB is facilitated by crowded, unhygienic conditions, both in homes and specific locations like public transport and hospitals. A critical role is also played by 'pump' populations, such as miners, prisoners and migrants (WHO, 2008; Stuckler, et al., 2010).

While coverage of TB services is high, in particular direct observed therapy (DOT), the slow decline in incidence rate, high number of missing TB cases, and growing concern for severe forms of drug resistant TB show that there is still a lot to be done to end the epidemic.

Most experts believe that it is feasible to end the TB epidemic, but lament that not enough funding and effort has been put into new tools to manage the disease.

In September 2018, world leaders convened for a historic UN high-level meeting on TB and endorsed a declaration to diagnose and successfully treat 40 million people with TB by end of 2022 and provide 30 million people with preventive treatment by 2022.

Member states committed to nearly doubling global levels of TB funding ($13 billion per year, with $2 billion for R&D by 2022). Nevertheless, it remains to be seen how accountability of the declaration will be ensured (Stop TB Partnership, 2018).

The most significant hurdles in the path to TB control are outlined below.

1. There is no effective vaccine for TB

The only available TB vaccine, Bacille Calmette-Guerin (BCG), was developed in the 1920s. It has so far proved effective only for preventing TB meningitis in children and severe Miliary TB, a form of the disease which tends to spread throughout the human body and cause small lesions.

The vaccine has variable efficacy in preventing pulmonary TB infections and the precise duration of the protection it affords is unknown. There is currently no TB vaccine specifically for adults. While a TB vaccine blueprint was published in 2012 by the TB vaccine community, the pace of new candidates entering pre-clinical stage and those already in the pipeline have moved slowly (Voss et al., 2018).

As well, up until 2018, there was no consensus within the community on product criteria for advancing vaccine candidates. WHO has since published two sets of preferred product characteristics (PPCs) for research and development efforts for vaccines for adults and adolescents and for improving upon BCG vaccination for infants (WHO, 2018).

The 2018 Global Report on TB Vaccines estimated that $1.25 million investment is needed to fund development of a TB vaccine (GTBVP, 2018).

2. Drug resistant TB is a growing problem

Standard treatment of active TB consists of combination treatment with four drugs (isoniazid, rifampicin, pyrazinamide, and ethambutol) daily for two months followed by two drugs (isoniazid and rifampicin) for four months.

All four drugs are generally available and relatively inexpensive. In many countries, complete treatment incurs a direct patient cost of $0 to $20, with a provider cost of $100 to $500. Costs, however, vary widely based on country and its healthcare system. Failing to complete this treatment regimen can lead to drug resistance in patients.

WHO-mandated DOTS protocol (directly observed treatment, short-course) has a patient monitoring component that ensures that patients complete the full treatment regimen.

However, 36 percent of TB patients in 2017 were not diagnosed (WHO, 2018), which can cause resistance to first line drugs, leading to multidrug-resistant TB (MDR-TB). From a negligible number in 2000, MDR-TB cases rose sharply to an estimated 558,000 total cases in 2017 (WHO, 2018).

On average, about 3.5 percent of new cases (**Exhibit 1**) and 18 percent of retreatment TB cases are now estimated to be MDR-TB. Some experts believe—although there is no supporting data—that this increase in incidence reflects an improved ability of health systems to diagnose MDR-TB, which has been widespread, and that perhaps the growth has not been as explosive as it seems.

Percentage of new TB cases that are drug-resistant

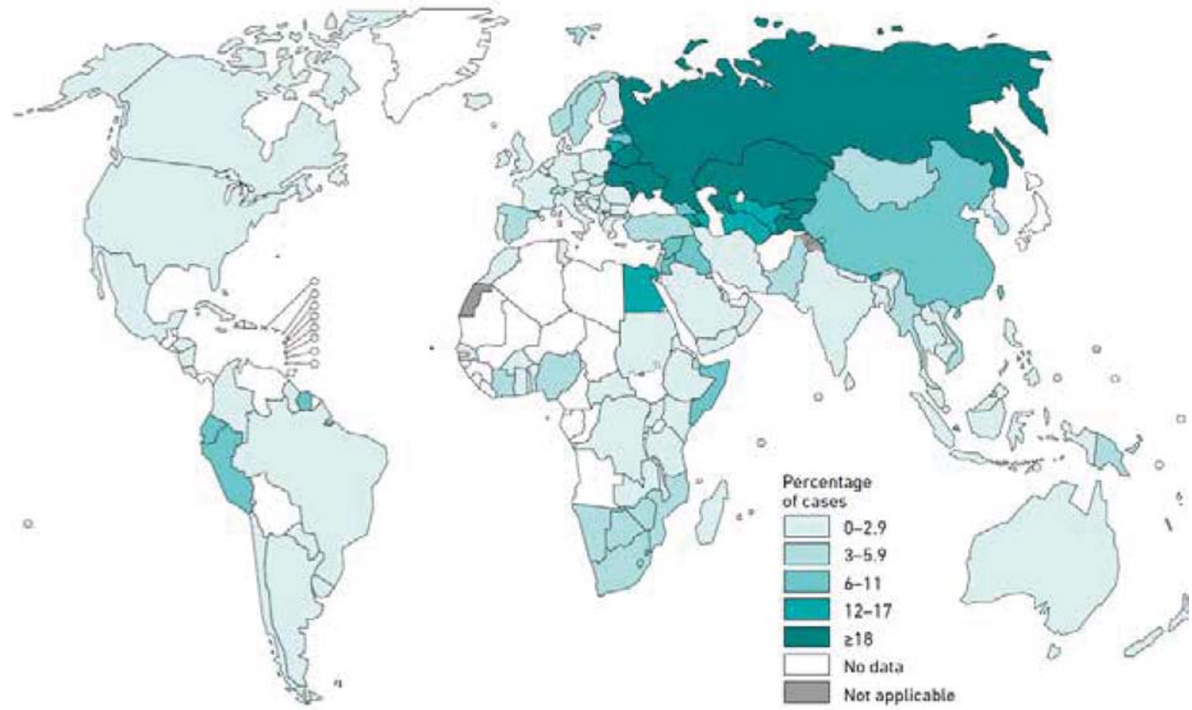


Exhibit 1: There is wide variety between countries in the percentage of new TB cases that are multidrug- or rifampicin-resistant TB (MDR/RR-TB). Countries in Eastern Europe and Central Asia have the highest rates of drug resistance, with more than 25 percent of new TB cases being MDR/RR-TB. (Source: WHO, 2018)

MDR-TB is significantly harder to treat. It requires an array of second line drugs, at a total cost of $2,600 to $4,700 to the provider, over a period of 18 to 24 months. Resistance to certain second line drugs is called extensively drug-resistant TB (XDR-TB).

This type of TB has also sharply increased in recent years, with 127 countries reporting cases of XDR-TB in 2017 (WHO, 2018). Combining these reported incidents of XDR-TB, the WHO has estimated that the proportion of MDR-TB cases that are extensively drug resistant is 8.5 percent (WHO, 2018).

Worryingly, MDR-TB appears to have transitioned from being primarily a developed condition in patients, stemming from not completing a full course of treatment, to a community-acquired disease where individuals are catching MDR-TB directly. It is believed that most cases of MDR-TB are now acquired, rather than developed due to lapses in treatment.

3. Current diagnostics are insufficient for both drug-sensitive and drug-resistant TB

Despite a variety of methods available for diagnosing TB, actual diagnosis remains suboptimal. Diagnostic challenges are further intensified in cases of HIV co-infection where existing diagnostic technologies are rendered largely ineffective.

While progress has been made in developing and introducing new diagnostic tools, such as rapid screening tests, point-of-care molecular diagnostics and next-generation sequencing for detecting drug-resistant TB, most are not only expensive but require highly trained personnel to operate.

Furthermore, there are challenges in the supply management of consumables, data storage, reporting and actionable use of diagnostic data to ensure appropriate treatments are provided.

Challenges with specific types of tests are highlighted below.

Sputum-Smear Microscopy (SSM)

The WHO DOTS protocol for TB diagnosis calls for the use of SSM where specially stained sputum is examined through a microscope for the presence of acid-fast bacilli (AFB). The protocol emphasizes the detection and treatment of sputum-smear positive cases of pulmonary TB (the most infectious cases).

However, it is now widely recognized that this approach alone is insufficient for diagnosis because:

- SSM requires extensive training for those administering the test, and delivers low-throughput results.
- SSM is not highly sensitive—roughly 70 percent sensitive in TB patients and less than 50 percent sensitive in patients with HIV co-infection.
- SSM does not identify people who have smear negative forms of TB; smear-negative pulmonary TB is especially common among people who are HIV-positive.
- SSM cannot be used to discriminate between drug-sensitive and drug-resistant forms of TB.
- SSM cannot be used to detect extra-pulmonary TB.

Bacterial Culture

To diagnose smear-negative and MDR-TB cases, sputum specimens can be cultured (grown) in laboratories, after which it is possible to diagnose or rule-out TB.

However, culture grown on solid media takes three to four weeks if not months to yield a result. This method also lacks accuracy and reproducibility. More recently, the use of liquid culture and molecular technologies has been recommended to reduce diagnostic delays (Stop TB Partnership, 2013).

Rapid Serological Tests

There are numerous rapid TB tests available on the market in developing regions. In July 2011, however, the WHO recommended against the use of these rapid serological tests for active TB, calling them "inconsistent and imprecise" and potentially leading to "misdiagnosis, mistreatment, and potential harm to public health." (WHO, 2011).

Nucleic Acid Amplification

The state-of-the-art method for TB diagnosis, recommended by the WHO since 2013, is highly precise and based on nucleic acid amplification technology (NAT), which identifies the presence of the bacterium at the DNA level.

The leading product in this space, Xpert MTB/RIF®[2], is capable of identifying rifampicin-resistant infections without bacterial culture, allowing it to accurately discriminate between drug-sensitive TB and MDR-TB. The technology is expensive. In 2015, each single-test disposable cartridge cost about $10 with concessional pricing, and the back-end reader cost approximately $17,000.

These prices, however, are changing rapidly. A number of less expensive, point of care NATs are now, or will soon be, on the market.

[2]Developed by FIND, Cepheid, Inc., and the University of Medicine and Dentistry of New Jersey with funding from NIH, and the Bill & Melinda Gates Foundation.

Next-Generation Sequencing

One of the greatest threats to global TB care and prevention efforts is the persistence of drug-resistant TB (DR-TB). Next-generation sequencing (NGS) presents an attractive option for DR-TB detection and characterization, and many NGS platform options now exist for DR-TB diagnosis (WHO & FIND, 2018).

NGS assays can provide detailed sequence information for multiple gene regions or whole genomes of interest, and assess the occurrence of rare mutations and other genomic data that molecular assays may not detect. The uptake of these technologies has been slow, due to the high cost, need for very specialized training and lack of easily actionable data outputs.

Simple rapid diagnostic tools that can replace SSM at the lower levels of healthcare systems where patient first present for care are urgently needed. These diagnostics should be effective in peripheral level health systems in diagnosing active pulmonary TB, including sputum-smear negative TB and detecting drug resistance (Stop TB Partnership, 2013)

4. Major challenges exist in the effective treatment of TB depending on whether an individual has drug-sensitive TB, MDR-TB or TB-HIV co-infection

Treatment for TB is lengthy and physically demanding. Drug-sensitive TB treatment lasts at least six months and the medication can cause significant side effects. MDR-TB treatment lasts 18 to 24 months and requires even more physically demanding medication. The length and difficulty of treatment is one of the key underlying factors influencing TB mortality and its importance as a global health issue.

Within this context, there are several important break points in the treatment process that lead to mortality.

The importance of each breakpoint varies by clinical scenario (such as whether a patient has drug-sensitive TB, MDR-TB or TB with HIV co-infection) and is outlined below.

Drug-sensitive TB

The largest drivers of mortality are patients who die in treatment and patients who are treated outside of DOTS protocol[3], as shown in **Exhibit 2** (WHO, 2013). These drivers are listed below.

- Of known TB deaths, the majority are patients who die in treatment. This reflects the fact that most individuals who develop TB do ultimately end up seeking care, but many patients do not receive treatment until the disease has become too advanced.

  This is caused by patient delays in seeking care, provider-caused delays in treatment, natural rates of treatment failure and also the effects of HIV co-infection. Delays in seeking care are driven by a lack of awareness of early TB symptoms, considerable community stigma and insufficient access to healthcare. Provider-caused delays often arise in diagnostics and referrals. TB is often diagnosed clinically or with methods that produce false negatives.

  Furthermore, diagnostics can be slow to produce results, which means some patients fall off before receiving their results and subsequently treatment, especially in rural sub-Saharan Africa where patient follow-up is particularly challenging. Patients visit an average of three clinics before receiving a positive diagnosis and care referral, creating a delay of 16 to 85 days (Nogueira et al., 2018; Virenfeldt et al., 2014). There is also a natural rate of failure with current drugs due to their interactions with the body and the disease, although most experts believe that this is a far less significant cause of mortality relative to delays in treatment.

[3]ITT analysis, based on expert interviews and literature cited throughout this report.

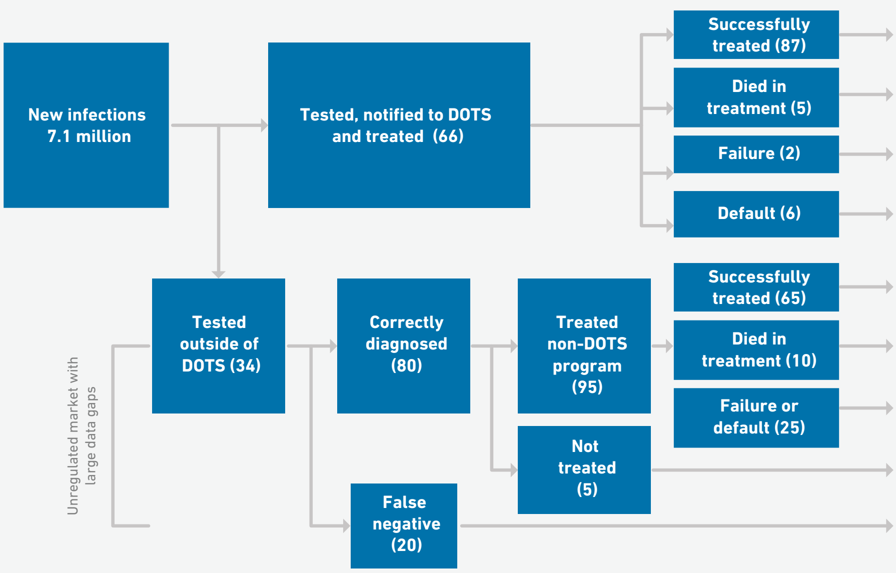
Finally, the number of patients who die in treatment is influenced by patients with TB-HIV co-infection, and while this analysis looks specifically at the 7.1 million TB patients who do not have HIV, the percentages applied in the analysis are global figures and include TB patients with HIV who have greater case fatality rates in treatment.

- Roughly a third of patients do not receive DOTS-compliant treatment because they go to private practitioners or traditional healers. These patients receive non-WHO approved treatments, which produce lower success rates.

- The latest treatment outcome data show success rates of 82 percent for TB (2016 cohort), 77 percent for HIV-associated TB (2016 cohort), 55 percent for MDR/RR-TB (2015 cohort) and 34 percent for extensively drug-resistant TB (XDR-TB) (2015 cohort) (WHO, 2018).

  Six percent of patients under DOTS coverage and 25 percent of patients outside of DOTS default due to the long treatment cycle, even if they are receiving treatment through DOTS-compliant facilities, because of insufficient compliance monitoring systems. This is a key contributor in the growth of MDR-TB, which is now driven primarily by transmission (WHO, 2013).

Drug-sensitive TB mortality drivers



People (rounded)	Mortality rate (percent)	People (rounded)
4,077,000	0	0
234,000	100	234,000
94,000	30	28,000
281,000	30	84,000
1,193,000	0	0
183,000	100	183,000
458,000	30	138,000
97,000	30	29,000
483,000	30	145,000
7.1 M	**N/A**	**841,000**

Exhibit 2: A breakpoint analysis for drug-sensitive TB. The largest breakpoints involve mortality during treatment due to delays in seeking care, provider-caused delays in treatment, and non-WHO approved treatment by private health practitioners.[4]

[4]See "Data Sources for Analysis of Mortality from Drug-Sensitive TB and MDR-TB" at the end of this section for full explanation of data and sources.

MDR-TB

- The major challenge in treating MDR-TB (**Exhibit 3**) is that it is typically misdiagnosed as drug-sensitive TB. Even if it is appropriately diagnosed, the antibiotics required for treatment are neither available nor affordable for most patients. Additionally, treatment is non-curative in almost half the patients. As a result, overall mortality rate for MDR-TB is 41.2 percent (WHO, 2018).

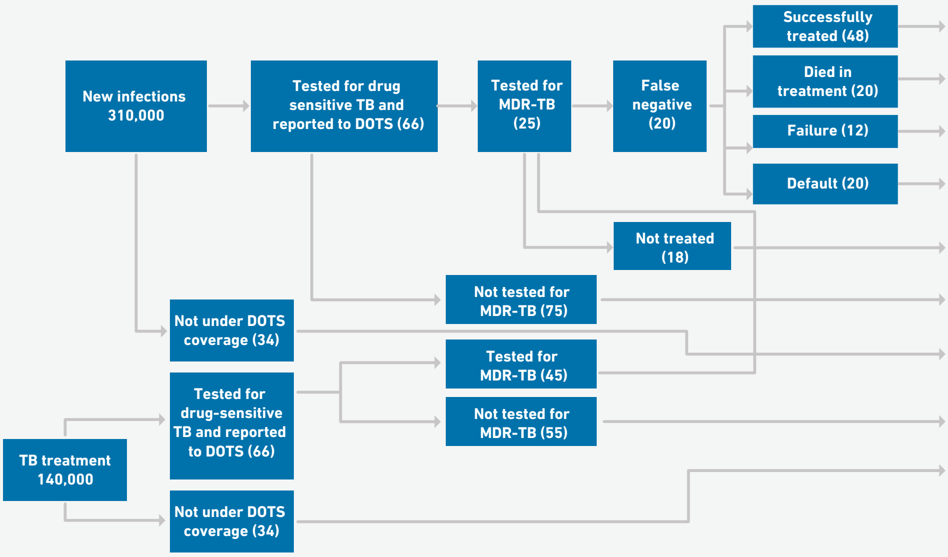
- The most significant driver of mortality from MDR-TB is a lack of positive diagnosis of MDR-TB, which in turn is driven by lack of diagnostics that can discriminate between MDR-TB and drug-sensitive TB. Only 24 percent of new TB cases and 70 percent of relapse cases are tested for MDR-TB, and undiagnosed cases account for over 90 percent of deaths from MDR-TB (WHO Global TB Report, 2018).

  It is worth noting that in our analysis we used calculated MDR-TB case detection rates that are much higher than global estimates. In order to reconcile global infection and mortality figures, and given the case notification rate through DOTS, and known outcomes of treatment, we calculated that 25 percent of new MDR-TB infections and 45 percent of retreatment MDR-TB cases were accurately diagnosed. These are much higher than global estimates and reflect the lack of high-quality data in MDR-TB global surveillance.

- Only 87 percent of all MDR-TB patients notified of their TB condition receive appropriate treatment (WHO, 2018). This is primarily due to low number of treatment facilities capable of administering MDR-TB and the high cost of second line drugs. Only 9 percent of TB management units have MDR-TB treatment services, while necessary drugs can cost 130 times as much as the first line drugs (Pooran, 2013). The length and technical complexity of administering proper treatment for MDR-TB is a key reason for low coverage.

- MDR-TB treatment is non-curative in more than half of patients. MDR-TB treatment has higher failure, default and death while in treatment rates than drug-sensitive TB. This is due to a number of factors including that MDR-TB patients often receive appropriate treatment at a more advanced stage of disease (after a previous round of TB treatment, or after a series of misdiagnoses for drug-sensitive TB), and longer and more physically demanding treatment regimes (WHO, 2018).

MDR-TB mortality drivers



People (rounded)	Mortality rate (percent)	People (rounded)
36,000	0	0
15,000	100	15,000
9,000	40	4,000
15,000	40	6,000
17,000	40	7,000
153,000	40	61,000
105,000	40	42,000
51,000	40	20,000
48,000	40	19,000
449,000	**N/A**	**175,000**

Exhibit 3: A breakpoint analysis of mortality due to MDR-TB shows that misdiagnosis of MDR-TB as drug-sensitive TB is the most significant problem. A second major concern is that even with accurate diagnosis, treatment is non-curative in more than 50 percent of patients.[5]

HIV co-infection

Nine hundred thousand people (13 percent) around the world with active TB have HIV co-infection. Of these cases, 72 percent are in Africa, where 27 percent of the 2.48 million new TB cases in 2017 had HIV co-infection (WHO Global TB Report, 2018). In most regions it is not standard practice to test for HIV when an individual is being tested for TB and vice versa.

Moreover, if an individual has HIV, diagnosing a TB co-infection using a standard sputum smear test is even harder given the high false negative rate of the test. Further complicating the challenge is that HIV-TB co-infection is often extra-pulmonary and does not show up at all in SSM tests.

For those who do receive an accurate diagnosis, drug compatibility poses a challenge. Many TB treatments are incompatible with ARVs for HIV. Rifampicin, in particular, can cause some ARVs to be metabolized too quickly, reducing their effectiveness.

[5]See "Data Sources for Analysis of Mortality from Drug-Sensitive TB and MDR-TB" at the end of this section for full explanation of data and sources.

SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

Many interventions have proven effective in reducing the spread and burden of TB and warrant continued attention and expansion, for example, the DOTS protocol. Additional non-technology interventions include bringing down the cost of second line drugs through market coordination interventions, similar to those used for first line drugs, and interventions to reduce care seeking and provider-caused delays. As the spread of the disease is poorly understood, there are significant opportunities in better understanding the epidemiology and transmission of the disease to design effective public health interventions.

These interventions would likely be focused on high transmission settings such as hospitals, public transportation and potentially households in urban slums. There is also a need to scale available innovations, as widespread access has still not been achieved with existing technologies and many people with TB still struggle to access an adequate initial diagnosis.

In addition to these interventions, there are five major scientific and technological opportunities to reduce TB mortality.

Breakthroughs:

1	2	3	4	5	6	7	8	9	10
11	12	13	14	15	16	17	18	19	20
21	22	23	24	25	26	27	28	29	30
31	32	33	34	35	36	37	38	39	40
41	42	43	44	45	46	47	48	49	50

23 Vaccines that can effectively control and eventually help eradicate the major infectious diseases of our time—HIV/ AIDS, malaria, tuberculosis and pneumococcus

Collectively, HIV/AIDS, malaria, tuberculosis and pneumonia kill more than five million people a year, and represent a significant disease burden for low income populations in sub-Saharan Africa and South Asia. Effective and affordable vaccines for these diseases do not exist yet due to the intrinsic complexity of the pathogens causing them, and a lack of understanding of the specific mechanisms through which our immune systems protect against these diseases. The process of vaccine development—basic research on disease etiology, vaccine construction, pre-clinical and clinical testing—is technically challenging, expensive and time consuming.

23c. A vaccine for pulmonary TB

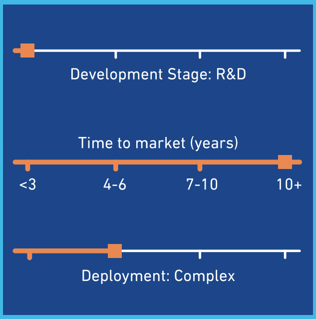
There is currently no vaccine for pulmonary TB. If available, it could be one of the most effective ways to prevent the spread of the disease. Most experts agree that without a vaccine, the ambitious SDG and End TB goals will not be met by 2035.

There are multiple potential vaccination strategies including pre-exposure vaccination to create immunity to TB, post-exposure vaccination to delay development of latent TB to active TB—particularly for HIV positive patients—or therapeutic vaccination to kill TB bacteria. The current focus is on pre-exposure vaccines for adults and adolescents as opposed to children. This is due to the higher projected impact of strategies targeting adolescents and adults over children, as well as the more advanced state of research on pre-exposure vaccines relative to post-exposure vaccines. Strategies include a pipeline of vaccine candidates that includes whole cell, adjuvanted proteins and vectored subunit vaccines.

The lack of a basic scientific understanding of protection against TB is one of the major challenges in development of a vaccine. Specifically, the correlates of protection for TB had not been well understood. However, since 2012 new information has been generated from the many preclinical and clinical test results from vaccine candidates regarding the molecular mechanisms of disease-producing activity of Mtb, immune response to a vaccine that correlate with protection from Mtb infection and basic pathogenesis of TB disease in humans and animal models.

There are now tools to manipulate the vaccine induced immune response with choice of vaccine technology, antigen and adjuvant. However, the mechanism with which the quality of immune response is affected by these choices has not been well explored (Voss, et al., 2018; GTBVC, 2018).

Current State

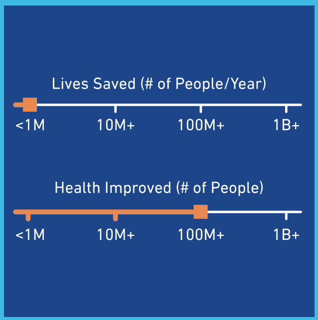


Associated 50BT Chapters

Global Health

SDG Alignment

Impact



Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

As of 2018, 14 different TB vaccines are undergoing clinical trials, compared with seven in 2014 when the first edition of this report was published. All of these are either in Phase I or Phase II, with one candidate that has entered in Phase III. Seven more pre-clinical candidates also exist, with 20 novel strategies in discovery phase (GTBVC, 2018).

Two studies in particular are showing promise after a decades long quest to develop a more effective vaccine against TB.

In July 2018, a Phase II trial showed that re-vaccinating adolescents with BCG who received the vaccine as infants was 45 percent effective in preventing sustained TB infection (Nemes, et al., 2018). A Phase IIb trial conducted in September 2018 is showing promise of a vaccine candidate, M72/AS01E (GSK).

The results illustrate that the vaccine candidate was 54 percent effective at preventing active pulmonary TB disease from developing in adults with latent TB infection (Van Der Meeren, et al., 2018).

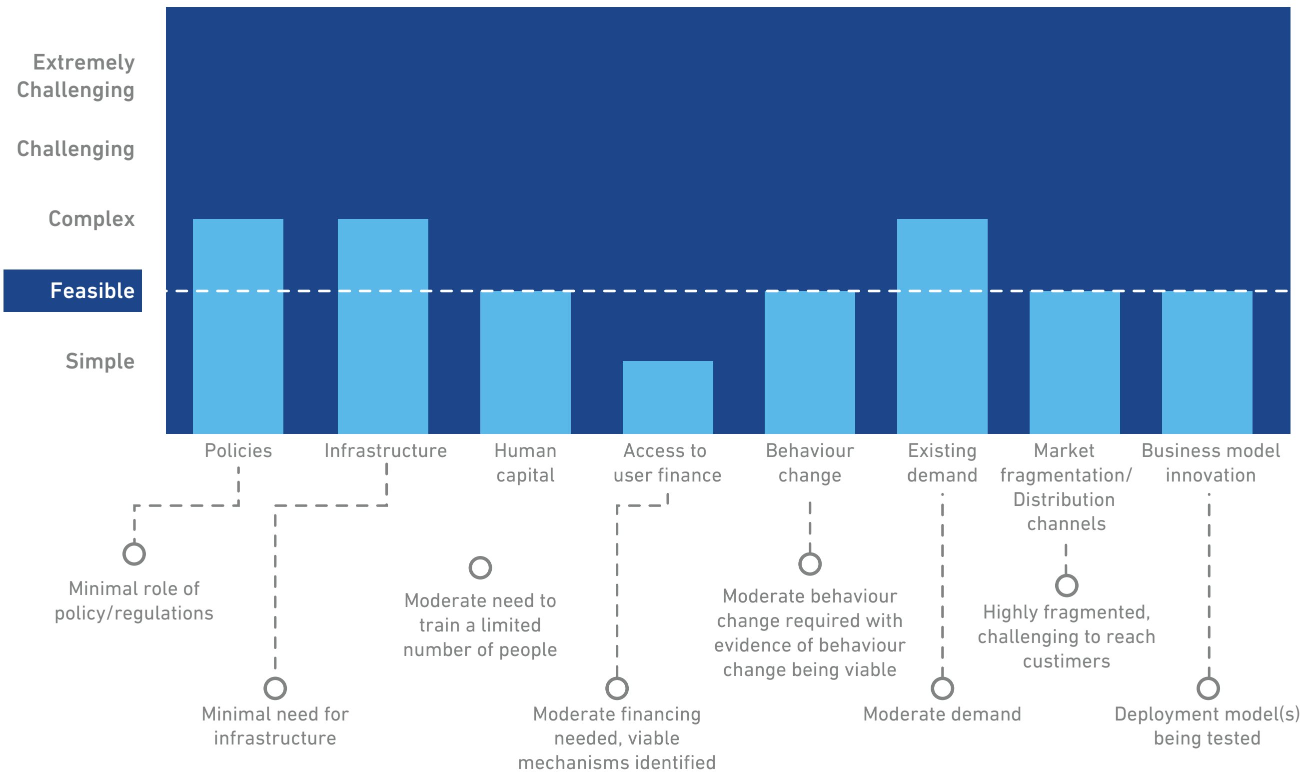
Deployment of new vaccines

Once any of these vaccines is developed, it can be deployed to children through existing, reasonably established, vaccine delivery channels. However, there are few mechanisms for delivering vaccines to adolescents and adults, and successful vaccination campaigns for these population segments would require significant government coordination, behavior change and financial investment.

Furthermore, even today vaccine delivery remains a challenge in many remote locations where supporting infrastructure like cold storage facilities are either few or non-existent. While vaccines are expected to be made available to patients at a low cost, financing for the vaccines by national governments or international donors would need to be secured in order to support widespread distribution. Policy changes would also need to support its introduction and distribution through public health systems.

Based on the above assessment, the projected time to market readiness is more than ten years, and the difficulty for deployment is FEASIBLE.

Breakthrough 23: Difficulty of deployment



27 Shorter course treatments for both drug-sensitive TB and MDR-TB

Many challenges related to controlling TB are a function of long and demanding treatment regimens. Even though treatment duration of drug-sensitive TB has been brought from nine to 12 months down to six to nine months, this long time frame still creates major challenges. Second line drug regimens for MDR-TB take 18 to 24 months and are able to cure only about 50 percent of the cases. Treatment for drug-resistant TB sometimes exceeds two years. In addition, some current drugs are not easily co-administered with antiretrovirals (ARVs) for patients with TB-HIV co-infection.

These drug challenges lead to high rates of non-compliance, expensive delivery systems to provide treatment responsibly, and the growth of drug-resistant TB. New drugs that can treat drug-sensitive TB over the course of weeks as opposed to months, will dramatically alleviate many of the challenges of controlling TB. Shorter treatment for latent TB infection is already available.

The TB Alliance highlights several drugs at various stages of clinical testing for both drug-sensitive and drug-resistant TB. Three drug regimens in Phase III trials for drug-sensitive TB could be available within a few years, reducing treatment time from six to three or four months.

Current State

Development Stage: R&D

Time to market (years)

<3 4-6 7-10 10+

Deployment: Feasible

Associated 50BT Chapters

Global Health

SDG Alignment

3 GOOD HEALTH AND WELL-BEING

Impact

Lives Saved (# of People/Year)

<1M 10M+ 100M+ 1B+

Health Improved (# of People)

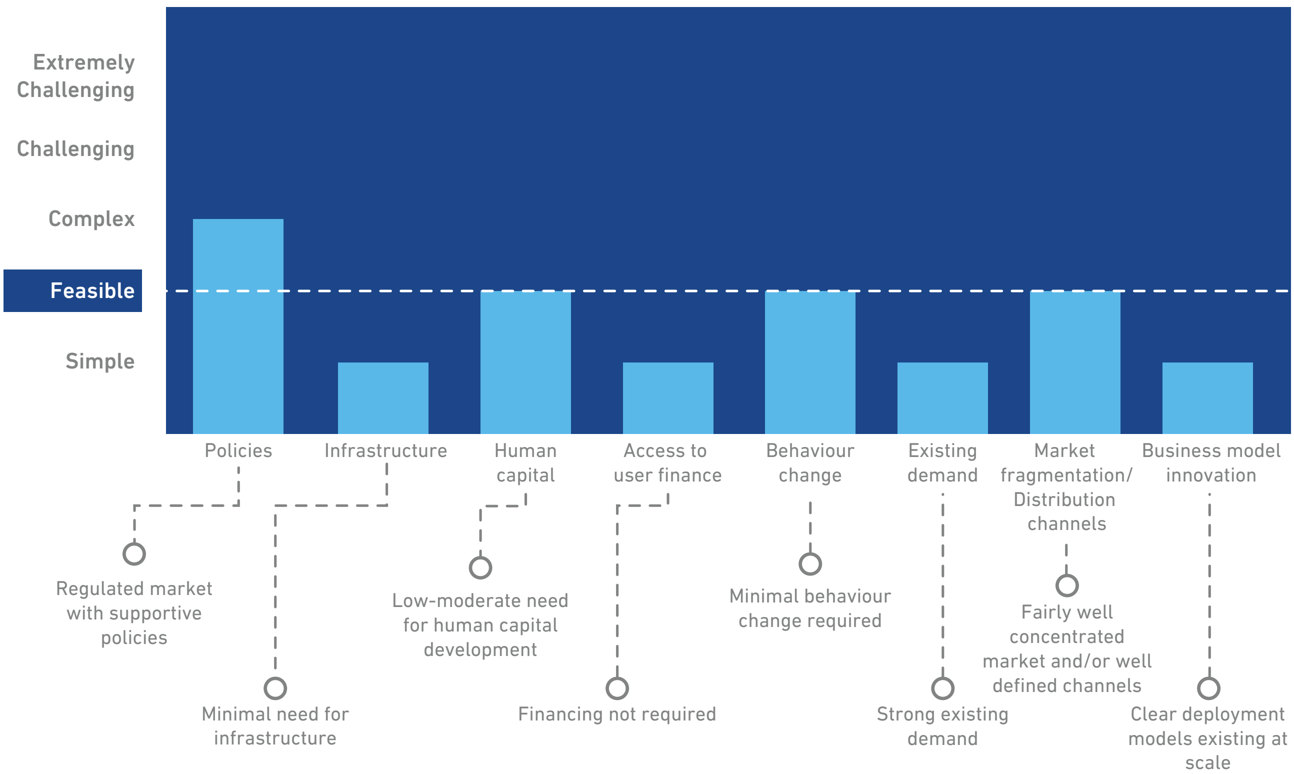
<1M 10M+ 100M+ 1B+

Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

The projected time to market readiness—depending on the drug—is two to four years and difficulty of deployment is FEASIBLE.

Breakthrough 27: Difficulty of deployment



28 New generation of antibiotics capable of treating fast-mutating bacteria like MTB and MRSA

Antibiotic resistance is reaching dangerously high levels in all parts of the world, with some of the most common infections becoming difficult to treat. This occurs when bacteria develop the ability to defeat the drugs that are designed to kill them, making the drugs ineffective. Antibiotic resistance does not mean the body becomes resistant to antibiotics; instead, it means that bacteria have become resistant to the drugs designed to kill them. Each year, hundreds of thousands of people die from drug-resistant strains of common bacterial infections, and the number is increasing steadily. Important examples of resistant bacteria include:

- Multidrug-resistant tuberculosis (MDR-TB), a form of TB that is resistant to the two most powerful anti-TB drugs, and extensively drug-resistant tuberculosis (XDR-TB) that is resistant to at least four of the core anti-TB drugs.
- The bacteria *E. coli*, which is gaining resistance to fluoroquinolone antibiotics that are widely used to treat urinary tract infections.
- The common intestinal bacteria *Klebsiella pneumoniae*, which is becoming resistant to a last resort treatment, carbapenem antibiotics, in all regions of the world.
- The bacteria *Staphlylococcus aureus*, which has widespread resistance to first-line drugs, causing growing numbers of deaths due to MRSA (methicillin-resistant *Staphylococcus aureus*).
- The bacteria *Neisseria gonorrhoeae*, responsible for the sexually-transmitted disease gonorrhea, is gaining resistance to the last resort medicine, third generation cephalosporin antibiotics, in at least 10 countries.

Antibiotic resistance is a complex problem that is driven by many interconnected factors, and coordinated effort is required to minimize its emergence and spread. Without urgent and effective action, there is a risk of returning to an era in which common infections and minor injuries can cause death.

Action on several fronts is needed, including improving awareness and understanding of antibiotic resistance, strengthening surveillance and research, reducing the incidence of infection through improved hygiene and sanitation, improving diagnostics to reduce unnecessary prescription of antibiotics, and optimizing the use of existing antibiotic medicines. Critically, there is also a need for a new generation of antibiotics that are effective against the bacteria that are resistant to current drugs.

Current State

Development Stage: R&D

Time to market (years)

<3 4-6 7-10 10+

Deployment: Feasible

Associated 50BT Chapters

Global Health

SDG Alignment

3 GOOD HEALTH AND WELL-BEING

Impact

Lives Saved (# of People/Year)

<1M 10M+ 100M+ 1B+

Health Improved (# of People)

<1M 10M+ 100M+ 1B+

Commercial Attractiveness

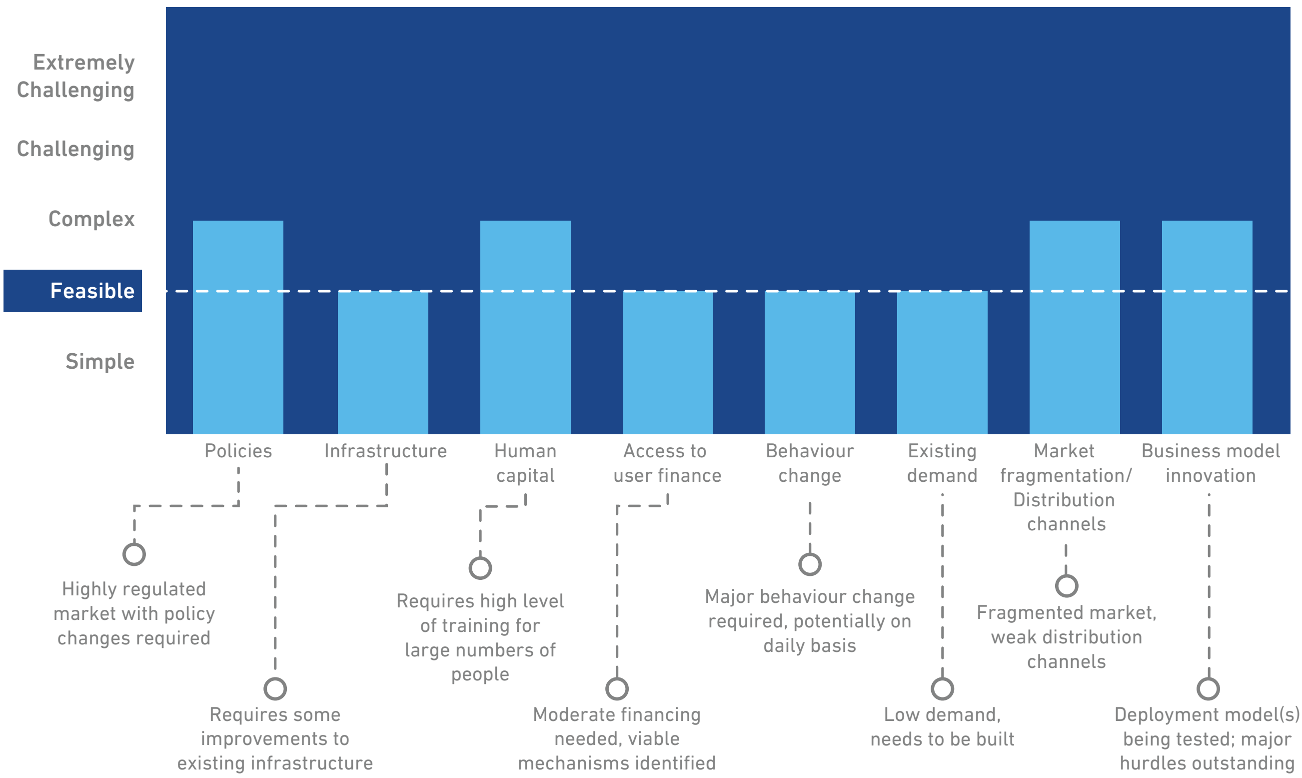
- **Attractive for industrialized markets (high profits)**
- Attractive for emerging markets (lower profits)
- Emerging markets potential; requires derisking (sustainable)
- Non-commercial (unprofitable)

While there are some new antibiotics in development, none of them are expected to be effective against the most dangerous forms of resistant bacteria. There is a need for better incentives to promote investment in new drugs, because the commercial return on R&D investment in new antibiotics is currently unattractive.

Although the total market for antibiotics is relatively large, with annual sales of about $40 billion, only about $4.7 billion of this is from sales of patented antibiotics. Between 2003 and 2013, less than 5 percent of venture capital investment in pharmaceutical R&D was for development of antimicrobials.

Even with adequate funding, the development of improved antibiotics is scientifically challenging, and we expect it will take up to 10 years for new drugs to be market ready. Once developed, the deployment of new antibiotics can use existing supply chains and is expected to be FEASIBLE.

Breakthrough 28: Difficulty of deployment



35 Point-of-care nucleic acid test (NAT) that is simple, robust, and compatible with easily collected sample types

A key breakthrough in disease detection is the development of point-of-care nucleic acid tests (NATs) applicable to a wide range of disease conditions. These tests should be compatible with simple sample types (such as whole blood), portable, rapid, robust despite high ambient heat and humidity, capable of being used by minimally trained technicians, and non-reliant on refrigeration, running water, and stable electricity. In addition, the technology should have a low price point to make it appropriate for use in peripheral healthcare facilities. Developing such a test poses significant technical challenges; it requires modular, instrument-free technologies for each of the NAT steps: sample processing, signal amplification and detection.

Sample preparation technologies

The manual, time-consuming and infrastructure-intensive sample collection, processing and purification associated with preparing an optimal sample for NAT must be integrated and automated so that minimally trained healthcare workers can perform testing. Non-invasive sampling technologies, simplified extraction techniques, sample concentration technologies and purification-free chemistries can help advance this goal.

Signal amplification technologies

The thermocycler, electricity and temperature control required for polymerase chain reaction (PCR) make NAT unsuitable for point-of-care adoption in low-resource settings. New technologies that are less sensitive to sample contaminants, have simpler thermal profile mechanisms that reduce sample processing requirements, and are not dependent on grid electricity, appear to be the way forward. Also critical is reduced reliance on cold chains and refrigeration. This will come from improvements in packaging, the ability to monitor temperature history, and the use of more stable substitutes in place of heat-sensitive reagents. Additionally, NATs that do not have to rely on stable grid power may depend on improved battery technology, solar chargers or generators, or any other new technology breakthroughs that provide instrument-free heat sources.

Detection technologies

Optical detection poses a challenge because of its potential dependence on extensive equipment. There are new detection technologies that do not rely on optical detection, including measurements of mass, magnetic properties, diffraction, or electrical potential that may enable development of more robust detection systems.

Current State

Development Stage: Engineering

Time to market (years)

<3 4-6 7-10 10+

Deployment: Extremely Challenging

Associated 50BT Chapters

Global Health

SDG Alignment

3 GOOD HEALTH AND WELL-BEING

Impact

Lives Saved (# of People/Year)

<1M 10M+ 100M+ 1B+

Health Improved (# of People)

<1M 10M+ 100M+ 1B+

Commercial Attractiveness

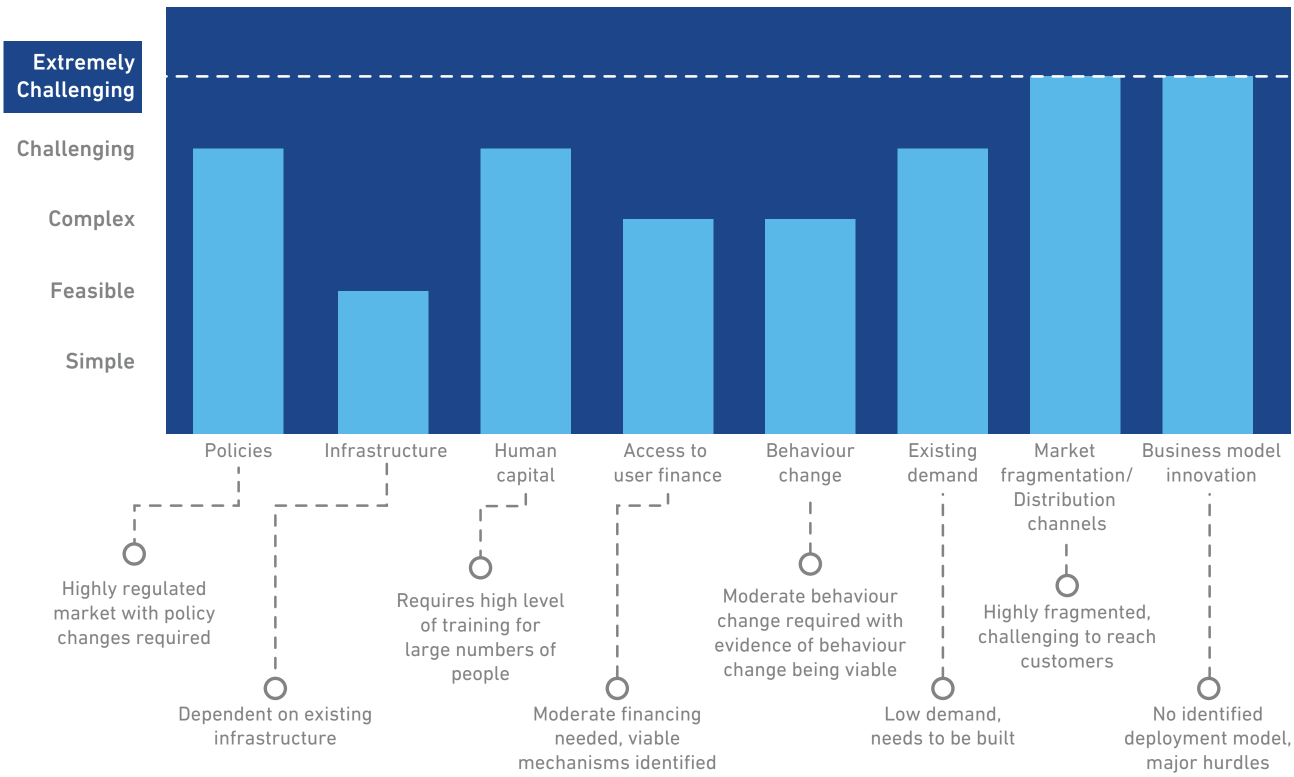
- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

Developing a point-of-care NAT will further depend on advancements in micro-fabrication and the ability to miniaturize test components that allow for multiplexing, reductions in sample size, and reduced reagent costs. Microfluidic platforms may yield a possible path forward for NATs as well, as demonstrated by the GeneXpert test for TB.

Deployment challenges include regulatory processes and WHO endorsement, as well as the large capital expenditure required of countries that may look towards adopting new diagnostics on a large scale. Regardless of how pressing a need for a new diagnostic may be, two important factors that will impact the end adoption are the costs and resources required to adequately train healthcare workers to use the new tests, and patients' willingness to pay for them.

Based on the above assessment, the projected time to market readiness is seven to ten years, and the level of difficulty is EXTREMELY CHALLENGING.

Breakthrough 35: Difficulty of deployment



37 Affordable wearable technology with broader functionality for patient adherence and monitoring of health status

Wearable technology (or simply, wearables) refers to a broad category of devices that can be integrated into day-to-day clothing or other accessories to capture health data and provide information on the user's personal fitness and activity. While a typical wearable is a fitness tracker that can be worn on the wrist, today there is a much wider array of devices, including implantable devices and an ingestible pill (recently approved by the US FDA) that can track specific markers of physical and mental health and adherence to drug regimens.

Today's common wearables (such as the Fitbit) track heart rate, blood pressure, breathing patterns, physical activity and sleep levels. However, the next generation of devices (still in prototype stage) aim to collect data on blood glucose, indicators of cardiovascular disease, and even cancer. For example, Apple recently released the KardiaBand, an Apple Watch accessory with an inbuilt EKG to detect irregular heartbeat and share the information with caregivers.

Current State

Development Stage: Engineering

Time to market (years)

<3 4-6 7-10 10+

Deployment: Complex

Associated 50BT Chapters

Global Health

SDG Alignment

3 GOOD HEALTH AND WELL-BEING

Impact

Lives Saved (# of People/Year)

<1M 10M+ 100M+ 1B+

Health Improved (# of People)

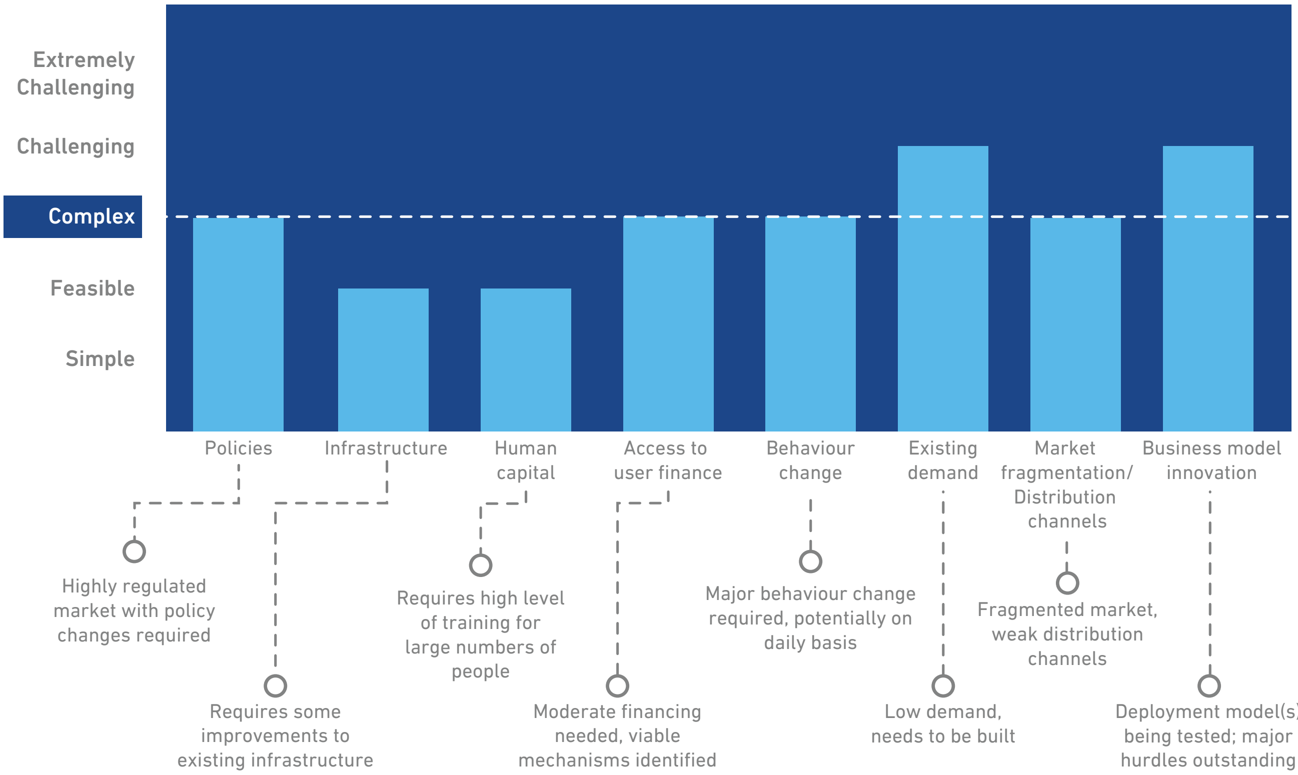
<1M 10M+ 100M+ 1B+

Commercial Attractiveness

- **Attractive for industrialized markets (high profits)**
- Attractive for emerging markets (lower profits)
- Emerging markets potential; requires derisking (sustainable)
- Non-commercial (unprofitable)

Early indications are that such wearables, especially if combined with game-based incentives, can increase positive health-improving behaviors (Shmerling, 2017). While it is too early to understand the long-term impact of such technologies, an increasing number of health insurance companies and employers who provide health insurance are encouraging their use.

Breakthrough 37: Difficulty of deployment



DATA SOURCES FOR ANALYSIS OF MORTALITY FROM DRUG-SENSITIVE TB AND MDR-TB

The data available for this analysis had many shortcomings. Required figures were often unavailable, incomplete or inconsistent with other published figures. For example, The Global TB Report reports that there were 450,000 new and re-treatment cases of MDR-TB in 2010, of which only 94,000 or 21 percent were detected. However, it also states that MDR-testing rates are 5 percent for new TB infections and 9 percent for re-treated infections, significantly below 21 percent inferred from the global new case and treated case figures.

We began with data on the global number of new cases and global mortality, drawn from the Global TB Report 2013. From there we worked inwards, identifying the rate of DOTS versus non-DOTS treatment and mortality rates for various clinical scenarios.

After this stage the data became increasingly unavailable or unreliable. In some cases, we calculated figures (for example, percentage of patients outside of DOTS who are successfully treated), in order to reconcile the resulting mortality rates with the global mortality rate. Specific figures and their sources are explained below. All decimal percentage points were rounded to the nearest percent and all incidence and mortality figures were rounded to the nearest thousand.

DRUG-SENSITIVE TB

New infections (7.1 million)

The number of cases is the incidence of non-drug-resistant, non-HIV-TB co-infection cases in 2012, as reported in the Global TB Report 2013.

Tested, notified to DOTS and treated
Global case detection rate (66 percent) taken from the Global TB Report 2013. All notified patients were assumed to seek treatment.

- Successfully treated: Reported as 87 percent in the Global TB Report 2013.
- Died in treatment: Reported as 4 percent of all treated cases in the Global TB Report. The Global TB Report also states that 4 percent of treated cases were "not evaluated" and had no associated outcome. We distributed this 4 percent in a weighted manner across the Died in treatment, Failure and Default scenarios, bringing the Died in treatment rate to 5 percent of treated cases.
- Failure: Reported as 1 percent of all treated cases in the Global TB Report. The report also states that 4 percent of treated cases were "not evaluated" and had no associated outcome. We distributed this 4 percent in a weighted manner across the Died in treatment, Failure and Default scenarios, bringing the Failure rate to 2 percent of treated cases.
- Default: Reported as 4 percent of all treated cases in Global TB Report. The Global TB Report also states that 4 percent of treated cases were "not evaluated" and had no associated outcome. We distributed this 4 percent in a weighted manner across the Died in treatment, Failure and Default scenarios, bringing the Default rate to 6 percent of treated cases (this number is higher than the 5 percent in the Died in treatment scenario due to rounding).

Tested outside of DOTS
All individuals that were not among the 66 percent who were Tested, notified to DOTS and treated are assumed to have been tested outside the formal sector where DOTS is practiced. We assumed the number of patients who were never tested to be negligible.

- Correctly diagnosed/False negative: The false negative rate is assumed to be 20 percent, drawn from a literature review which highlighted very high (30 percent plus) rates of false negatives in certain high TB burden regions (parts of South Asia and Africa), and a false negative rate of around 10 percent for non-DST tests such as skin tests elsewhere in the world.

- Treated non-DOTS program/Not treated: We found limited high-quality data for patients treated outside of DOTS. We assumed 95 percent seek some form of treatment.

- Successfully treated/Died in treatment/Failure or default: We found limited high quality data for patients treated outside of DOTS. We assumed the rate of patients who died in treatment to be twice that of DOTS due to less regulated and less effective treatment outside of DOTS. We then calculated a 65 percent/25 percent split between successful treatment and failure and default rates in order to reconcile final mortality rates with global figures.

Mortality rates

Successfully treated/Died in treatment
Patients who are successfully treated by definition survive. See above for further explanation of 87 percent successful completion and 4 percent mortality in treatment figures for DOTS and 65 percent and 10 percent figures for non-DOTS coverage.

Failure/Default/Not-treated
WHO estimates 22.5 percent of untreated TB patients will die in the first 2 years (70 percent 10 year mortality rate for smear positive TB and 20 percent for smear negative TB). We assume smooth rates of infection and mortality such that while 22.5 percent of new infections will not die this year, the number who die last year and this year will be 22.5 percent. We initially ran the analysis with the figure 22.5 percent figure for treatment scenarios in which treatment fails, is not completed or is not initiated, and then increased this rate to 30 percent to reconcile mortality rates to meet global mortality figure of 840,000.

While this analysis is focused on drug-sensitive, non-HIV-TB co-infection, the figures are calculated including patients with HIV-TB co-infection.

MDR-TB

Total new infections (450,000)
The Global TB Report 2013 estimates 450,000 new cases of drug-resistant TB. This is the sum of new and relapse infections.

New infections
The Global TB Report states that 3.6 percent of all new TB cases are MDR-TB cases. With 8.6 million new TB cases per year, this implies 310,000 new MDR-TB cases.

DOTS tested
Global case detection rate is reported as 66 percent in the Global TB Report 2013. All patients not under DOTS coverage are assumed to go untreated, as MDR-TB testing is still uncommon in DOTS, and particularly outside of DOTS.

TB re-treatment

We calculated TB re-treatment cases by subtracting the number of new infections, 310,000 from the total number of estimated infections, 450,000, according to the Global TB Report.

DOTS tested
Global case detection rate is reported as 66 percent in the Global TB Report 2013. All patients not under DOTS coverage are assumed to go untreated, as MDR-TB testing is still uncommon in DOTS, and particularly outside of DOTS.

- Tested for MDR-TB: See explanation under new infections.

Treated

The Global TB Report states that 82 percent or 77,000 patients were treated for MDR-TB, of the 94,000 who were tested and eligible.

Successfully treated
Reported as 48 percent in the Global TB Report 2013.

Died in Treatment
Reported as 15 percent of all treated cases in Global TB Report. The Global TB Report also states that 14 percent of treated cases were "not evaluated" and had no associated outcome. We distributed this 14 percent in a weighted manner across the Died in treat- ment, Failure and Default scenarios, bringing the Died in treatment rate to 20 percent of treated cases.

Failure
Reported as 9 percent of all treated cases in Global TB Report. The Global TB Report also states that 14 percent of treated cases were "not evaluated" and had no associated outcome. We distributed this 14 percent in a weighted manner across the Died in treat- ment, Failure and Default scenarios, bringing the Failure rate to 12 percent of treated cases.

Default
Reported as 14 percent of all treated cases in Global TB Report. The Global TB Report also states that 14 percent of treated cases were "not evaluated" and had no associated outcome. We distributed this 14 percent in a weighted manner across the Died in treatment, Failure and Default scenarios, bringing the Default rate to 20 percent of treated cases.

Mortality rate

Successfully treated/Died in treatment
Patients who are successfully treated by definition survive. See above for further explanation of 48 percent successful completion and 20 percent mortality in treatment figures.

All other scenarios
Mortality for untreated MDR-TB is calculated to be 40 percent (compared to 30 percent for untreated drug-sensitiveTB), to fit the overall mortality figure in the Global TB Report.

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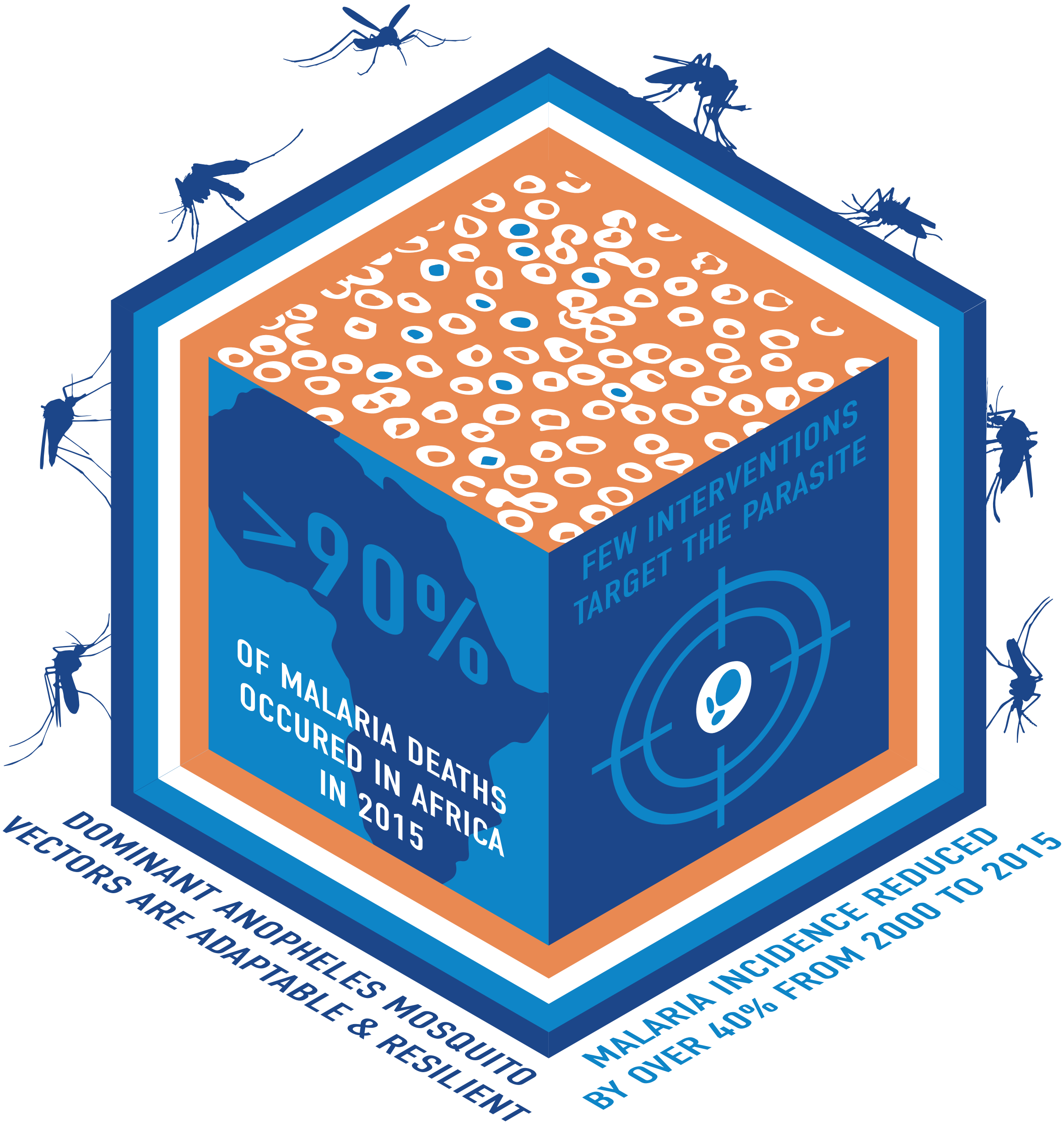

>90%
OF MALARIA DEATHS OCCURED IN AFRICA IN 2015
FEW INTERVENTIONS TARGET THE PARASITE
DOMINANT ANOPHELES MOSQUITO VECTORS ARE ADAPTABLE & RESILIENT
MALARIA INCIDENCE REDUCED BY OVER 40% FROM 2000 TO 2015

MALARIA

INTRODUCTION

Malaria has proven to be one the most persistent and lethal diseases in human history, responsible by some accounts for more deaths than any other disease.

In 2017, the global tally of malaria reached 219 million cases and 430,000 deaths (WHO, 2018). Disproportionately affecting vulnerable populations like pregnant women and children, malaria is the third leading cause of death among children under 5.

The disease is transmitted from person to person through infective bites from female *Anopheles* mosquitoes. Malaria's persistence and virulence are due to the behaviors of these mosquitoes, which are difficult to control. Furthermore, the parasites they carry (*Plasmodium falciparum* in particular) are highly complex and resilient.

The vast majority of the cases were in the WHO African Region (92 percent), followed by the WHO Southeast Asia Region and Eastern Mediterranean Region. The incidence rate of malaria is estimated to have decreased by 41 percent globally between 2000 and 2015, and by 21 percent between 2010 and 2015 (WHO, 2016).

Of 91 countries and territories with malaria transmission in 2015, 40 are estimated to have achieved a reduction in incidence rates of 40 percent or more between 2010 and 2015, and can be considered on track to achieve the GTS milestone of a 40 percent further reduction by 2020.

Despite this progress, a number of major challenges remain. These include the threat of vector resistance to insecticides and existing control methods; the development of parasite resistance to antimalarials, which results in a delayed or incomplete clearance of parasites from a patient's body; and the presence of a large, asymptomatic reservoir of parasites in successfully treated and otherwise healthy individuals, who continue to carry the parasite in their bodies for years and contribute to malaria transmission in their communities.

There are three scientific and technological advances that can help control, eliminate and eventually eradicate malaria.

- Breakthrough 23. Vaccines that can effectively control and eventually help eradicate the major infectious diseases of our time—HIV/AIDS, malaria, tuberculosis and pneumococcus
- Breakthrough 29. A single-dose complete cure for malaria
- Breakthrough 30. New long-lasting spatial mosquito repellents or attractants (chemical and non-chemical) for vector control

Malaria has proven to be one the most persistent and lethal diseases in human history, responsible (by some accounts) for more deaths than any other disease. Currently each year, there are about 220 million cases and 430,000 deaths of malaria. Disproportionately affecting vulnerable populations like pregnant women and children, malaria is the third leading cause of death among children under 5.

CORE FACTS AND ANALYSIS

Malaria is caused by protozoan parasites of the genus *Plasmodium*, belonging to the parasitic phylum Apicomplexa. Mosquitoes act as the vector, transmitting the disease from one human to another. This disease disproportionately affects vulnerable populations like pregnant women and children. It is the third leading cause of death among children under 5, who constitute more than 85 percent (more than 560,000) of total malaria-related deaths worldwide (WHO, 2013).

1. Malaria-related deaths are highly concentrated in a small number of countries and population segments

In 2015, it was estimated that there were 429,000 deaths from malaria globally. Most of those deaths are estimated to have occurred in the WHO African Region (92 percent), followed by the WHO South-East Asia Region (6 percent) and the WHO Eastern Mediterranean Region (2 percent) (**Exhibit 1**).

Of 91 countries and territories with malaria transmission in 2015, 39 are estimated to have achieved a reduction of 40 percent or more in mortality rates between 2010 and 2015. A further 10 countries had zero indigenous deaths in 2015 (WHO, 2016).

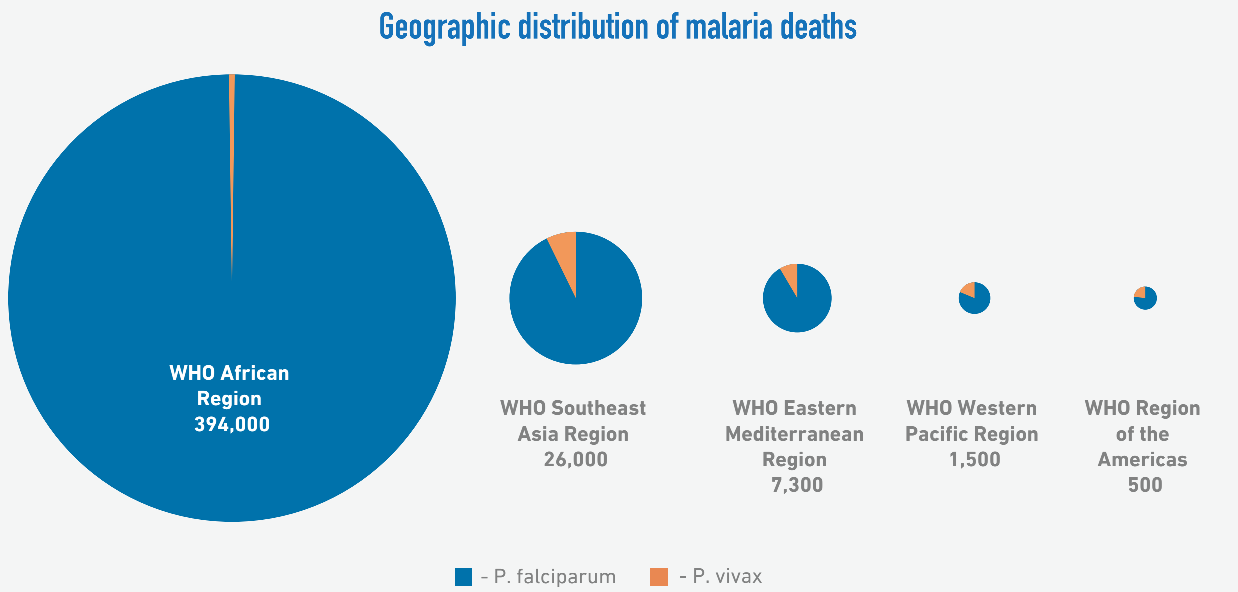


Exhibit 1: Estimated malaria deaths due to *P. falciparum* and *P. vivax* respectively, by region, in 2015. (Source: WHO, 2015).

It is estimated that 13 countries accounted for 75 percent of malaria deaths in 2015 (**Exhibit 2**). The global burden of mortality is dominated by countries in sub-Saharan Africa, with Democratic Republic of the Congo and Nigeria together accounting for more than 36 percent of the global total of estimated malaria deaths.

Four countries (Ethiopia, India, Indonesia and Pakistan) accounted for 81 percent of estimated deaths due to *P. vivax* malaria.

Estimated country share of total malaria and *P. vivax* deaths, 2015

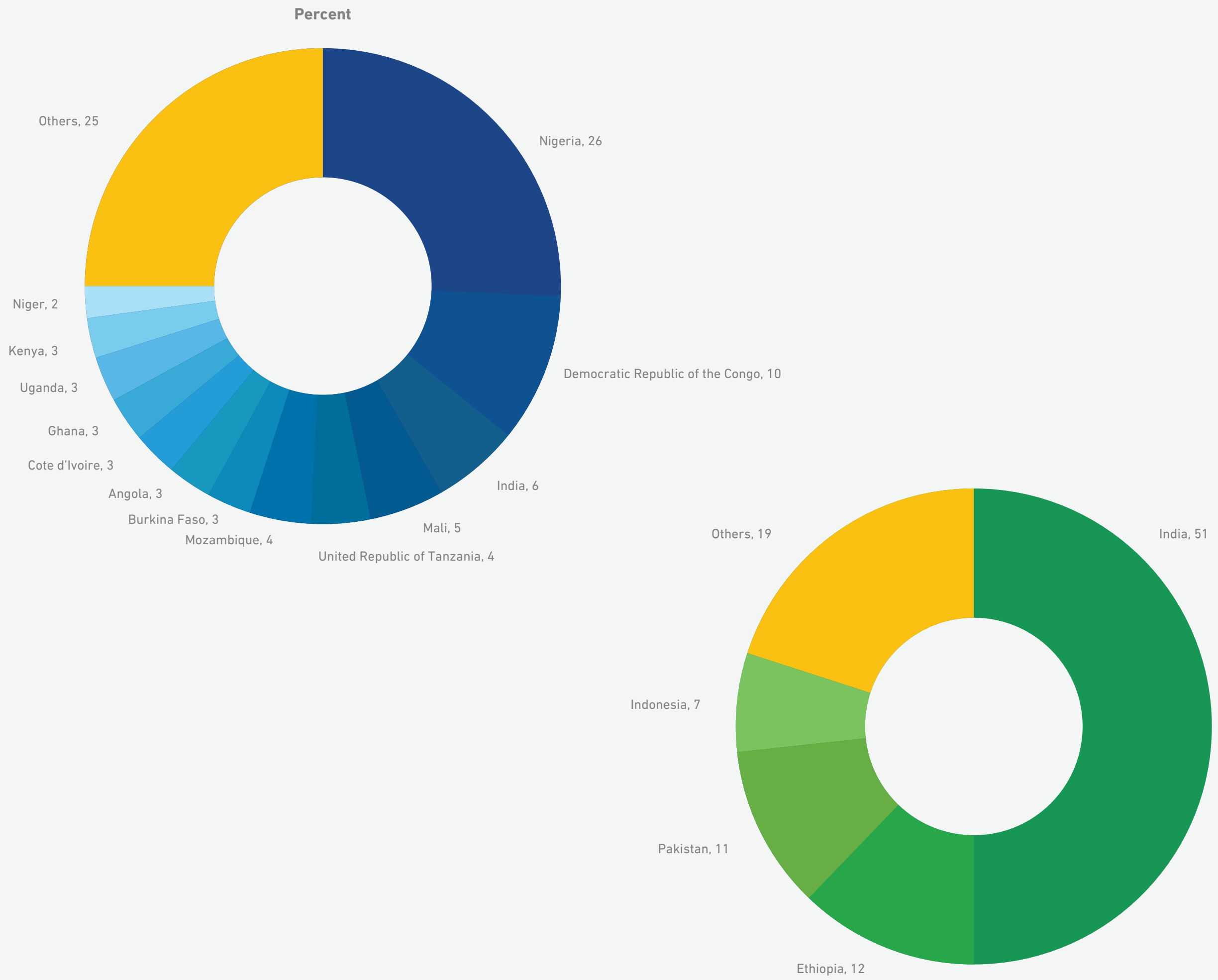


Exhibit 2: Estimated percentage of total malaria deaths by country (top), and *P. vivax* deaths by country (bottom). (Source: WHO, 2015)

If malaria-related mortality in the 10 worst-affected African countries were to be brought in line with the rest of sub-Saharan Africa, overall mortality would be reduced by almost 20 percent (WHO, 2013).

There are three major reasons for the concentration of mortality and morbidity in Africa (Feachem, et al., 2010), as outlined below.

Prevalence of *Plasmodium falciparum*, the most lethal form of the parasite

Of the more than 200 known species of *Plasmodium* parasite (Rich & Ayala, 2006), five are known to cause human malaria. These are *P. falciparum, P. vivax, P. ovale,* and *P. malariae*; in addition, a species of primate malaria, *P. knowlesi*, has recently been documented to cause human infection and fatality in many countries of Southeast Asia (Aneshvar, 2009).

Of the four common malaria species, *P. falciparum* is the most lethal and accounts for 90 percent of globally reported malaria mortality. The other species are known to usually cause sickness and significant morbidity but not death. *P. falciparum* is also far more prevalent in Africa than in other parts of the malaria-endemic world (WHO, 2013). An estimated 85 percent of malaria cases in Africa are due to *P. falciparum*, compared with around 50 percent in South and Southeast Asia, where the less fatal species, *P. vivax*, is also prevalent (WHO, 2013).

It is interesting to note that *P. falciparum* is more virulent and causes significantly higher mortality in Africa, than in comparable communities in Southeast Asia. This may be partly due to lower transmission and earlier treatment outside of Africa, but may also be explained in part by epidemiological differences and variations in the pattern of disease across the two continents (Maitland & Williams, 1998).

Dominance of resilient and highly efficient malaria vectors

There are 3,500 known species of mosquitoes, across 41 genera. Of these, females of only 30 to 40 mosquito species (from the genus *Anopheles*) transmit malaria in humans, and only seven have been found in Africa. The major malaria vectors in Africa are the *Anopheles gambiae* and *Anopheles funestus*. These vectors are particularly difficult to control because they occur in high densities in tropical climates, live in close proximity to human populations and have a strong preference for feeding on humans.

They have relatively long life spans and breed readily in water bodies of varying size, from lakes to tiny puddles (White, et al., 2013). The *Anopheles gambiae* can lay viable eggs in bodies of water as tiny as animal hoof prints, which means that there can be thousands of such water accumulations—after every rainfall—in even the smallest village. This makes larval control in Africa extremely difficult. There are also numerous secondary vector species prevalent in sub-Saharan Africa. The unique behavioral traits of these different Anopheles species, the difficulty of distinguishing between them, and the existence of multiple species in a single geography adds to the complexity of developing effective vector control strategies.

Conflict has historically been a driver of malaria

Conflict displaces entire populations (a key driver of malaria transmission), erodes health systems and thus poses significant impediments to any large-scale efforts to control the disease. With the notable exception of Burkina Faso, most of the countries with high caseloads and mortality rates in Africa (like Nigeria, the Democratic Republic of Congo, Mozambique, Cote d'Ivoire, Chad and Uganda), have witnessed very destructive civil wars in recent years.

Malaria mostly affects children

Malaria also disproportionately affects specific, vulnerable populations (WHO, 2002; WHO, 2013)[1]. More than 85 percent of malaria deaths globally were among children under 5. Children have low immunity and are particularly susceptible to the disease. Malaria during pregnancy causes as many as 10,000 maternal deaths each year. *P. falciparum* infection during pregnancy increases the chance of maternal anemia, abortion, stillbirth, prematurity, intrauterine growth retardation and low infant birth weight—the greatest risk factor for death in the first month of life. Eight to 14 percent of all low birthweight babies, and three to eight percent of all infant deaths in certain parts of Africa are the result of malaria during pregnancy.

[1]WHO defines the following high-risk groups, based on vulnerability to infection and death: pregnant women, infants and children under 5, HIV/AIDS patients and migrant or mobile populations.

2. Current and historic interventions have targeted both mosquito and parasite

WHO defines Malaria elimination as "a reduction to zero of the incidence of infection caused by human malaria parasites in a defined geographical area as a result of deliberate efforts." Malaria control is defined as "reducing malaria morbidity and mortality to a locally acceptable level through deliberate efforts using the preventive and curative tools available today." Globally, between 2000 and 2015, both malaria caseload incidence and mortality rates have decreased by 41 percent (WHO, 2016). This is largely a result of both institutional and individual interventions described below.

The most commonly used methods to prevent mosquito bites are sleeping under an insecticide-treated net (ITN) and spraying the inside walls of a house with an insecticide–indoor residual spraying (IRS). These two core vector-control interventions are considered to have made a major contribution to the reduction in malaria burden since 2000, with ITNs estimated to account for 50 percent of the decline in parasite prevalence among children aged 2 to 10 years in sub-Saharan Africa between 2001 and 2015 (World Malaria report, WHO 2016).

Interventions aimed at preventing transmission

Bed-nets, particularly long-lasting insecticide treated bed-nets (LLINs)

In such nets, particular insecticides (deltamethrin, alphacypermethrin or permethrin) are either incorporated in to the fibers of the net (during extrusion of the polymer) or coated with a binder onto the surface of the netting fabric. Currently, 13 manufacturers make WHO-recommended LLINs. These nets provide both individual and household levels of protection, especially against vector species that predominantly bite at night or rest indoors.

The netting protects the individuals sleeping underneath from mosquitoes that are either killed or repelled by the insecticide. By killing mosquitoes, the household as a whole is offered some protection. While high coverage of LLINs has been associated with some level of community-wide protection, LLINs cannot protect individuals from being bitten when they are outside the net.

Further, a key challenge with LLINs is emerging insecticide resistance. Because LLIN campaigns to date have mostly targeted children, caseloads may shift towards older individuals in the future. Still, scale-up of LLINs is credited with having made a significant contribution to the overall reduction in malaria cases and fatalities by targeting the most vulnerable section of the population, children.

Indoor residual spraying (IRS)

Small pre-defined amounts of insecticides (like dichlorodiphenyltrichloroethane, pyrethroids, carbamates or organophosphates) are sprayed indoors and on the walls of dwellings. As in the case of LLINs, IRS is only effective indoors and is a significant contributor to the reduction of caseload and fatalities.

However, its full potential is realized only if at least 80 percent of houses in the targeted areas are sprayed. One challenge with IRS is that it requires repeated applications, which may not happen. Once the sprayed insecticide weakens, mosquitoes quickly reappear. Indoor spraying is effective for three to six months, depending on the insecticide used and the type of surface on which it is sprayed. Newer formulations of pyrethroids and organophosphates can last up to nine months, and DDT can in some cases be effective for nine to 12 months.

Skin repellents

These include sprays and ointments and are used extensively for personal protection (though not malaria control) in many parts of the world, with varying levels of efficacy depending on the brand. Some of them are available at a price point that can be affordable for low-income families.

However, adoption in communities not accustomed to using such repellents will likely be difficult and efficacy will be highly dependent on education, behavior change and compliance with instructions for use. A recent randomized control trial testing the effectiveness of skin repellents in combination with LLINs found that topical repellents are not an effective incremental intervention if LLINs are already in place (Chen-Hussey, et al., 2013).

Spatial repellents

These include flammable incense and coils and are used extensively around the world with varying levels of effectiveness. Such repellents tend to give off an unpleasant smell and can increase the risk of respiratory disease.

An alternative is the use of vaporizing mats or small cardboard tablets which, when heated in a small electrically-powered device, release a pyrethroid vapor. This is more effective than coils but is significantly more expensive and can only be used where electricity is available (Pates, et al., 2002). Importantly, while skin and spatial repellents have proven effective for personal protection, neither have demonstrated community-level protection against malaria.

Large-scale draining of water bodies and swamps

This has been a key component of elimination strategies in high-income countries. However, this method only works when the vector mosquitoes primarily breed in larger bodies of water, and where potential breeding sites are easy to map and treat. Some targeted efforts to reduce large mosquito breeding grounds, like controlled irrigation of rice fields, have shown promise.

However, the *Anopheles gambiae* can lay viable eggs in very tiny pools of water, making large-scale draining irrelevant to the African context. Recently, there have been some efforts to educate populations about how to identify and eliminate small, but obvious, breeding sites[2].

Improved housing construction

This has contributed to the elimination of malaria in high-income countries, where most homes also have window screens that can keep mosquitoes out. Unfortunately, this remains a luxury the poor cannot afford.

There have been only two interventions aimed at the parasite itself

Treatment of infected patients

The WHO recommended treatment for *P. falciparum* infection is Artemisinin-based Combination Therapy (ACT).[3] Originally derived from sweet wormwood, Artemisia can now be manufactured synthetically.

In this treatment regimen, artemisinin administered in combination with another antimalarial (amodiaquine, lumefantrine, mefloquine, sulfadoxine-pyrimethamine, dihydroartemisinin-piperaquine) reduces the likelihood that the parasite will develop resistance to an individual drug, as had happened earlier with antimalarial treatments like chloroquine (now largely inefficacious in much of the malaria-endemic world).

Resistance represents an acquired (or selected) genetic difference in parasite population structure, and occurs by selecting out a subpopulation of parasites with drug pressure. Emergence of resistant parasite strains also happens when individuals with low immunity and a heavy parasite load receive small amounts of drugs, especially through monotherapy (treatment with a single drug).

The biggest challenges in malaria treatment include the continued use of poor-quality or counterfeit treatments, the use of monotherapies and lack of patient compliance to treatment regimens. All of these factors lead to the development of drug resistance and all are common in Africa, where the majority of patients with fever and other malaria symptoms seek treatment through informal channels or unregulated street vendors.

Use of malaria rapid diagnostic tests (RDTs)

Related to the treatment challenges described above, treatment with antimalarials has tended to be presumptive rather than relying on a confirmed diagnosis. A significant portion of antimalarials dispensed are used for non-malarial illnesses. A recent study conducted in Gabon found that 30 percent of children with fever received unprescribed antimalarials, and that 80 percent of these children were not actually infected with malaria (Mawili-Mboumba, et al., 2013).

These children failed to receive the treatment they required and the antimalarials were wasted on non-malarial illness. To address this challenge, the WHO has launched a new initiative called T3—test, treat, track—to ensure that all suspected malaria cases are tested and that only confirmed cases are treated with quality-assured antimalarials. This initiative is also expected to slow the emergence of drug resistance to ACTs.

[2] For example, the Student Leaders Against Malaria (SLAM) initiative.
[3] The recommended treatment regimen during pregnancy is different.

KEY CHALLENGES

There are a number of reasons why malaria has been among the most resilient and lethal diseases in human history, and why achieving a sustained reduction in disease transmission and deaths has been difficult.

The two-part lifecycle of *P. falciparum*

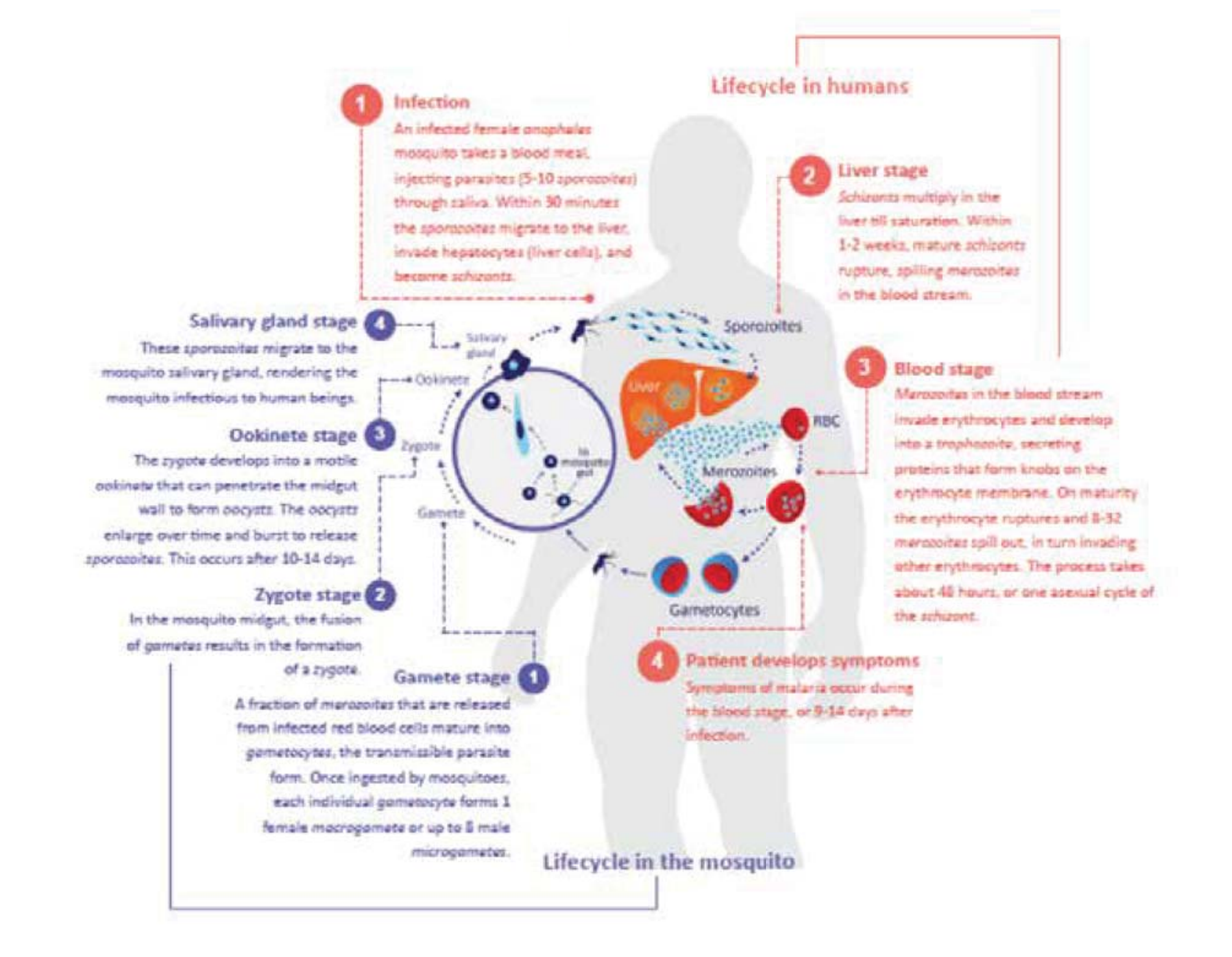


Exhibit 3: Malaria parasites have two separate life cycles: in the mosquito between the gamete and sporozoite stages, and in the human body from the time of being bitten to having the parasite fully mature into gametocyte.

1. A highly complex parasite makes developing vaccines and medications difficult

The *Plasmodium* parasite has two different lifecycles: in the mosquito and in the infected human (**Exhibit 3**). In both lifecycles, it goes through significant transformations. To this day, there are considerable gaps in the understanding of the basic immunology and host response to the disease. Among the known complexities are:

- The parasite can use antigenic switching under selective immune pressures, to evade the immune system. In other words, it changes the antigens it expresses, while maintaining the same underlying genetic composition.
- The parasite is intracellular and hence not exposed to the immune system consistently through its lifecycle.
- Infection does not automatically result in future immunity. Partial immunity against malaria builds slowly over time, is developed over years of exposure and never provides complete protection. Further, immunity can be lost in a few years if individuals move outside of endemic areas.
- Different parasitic loads can lead to dramatically different levels of sickness in different individuals. Many infected individuals remain asymptomatic and hence are not aware they have malaria, or that they are capable of transmitting it. Mosquitoes first become malaria vectors only after biting an infected human. In the long-term, if asymptomatic infection is not addressed, the reservoir of infection will continue to grow and malaria resurgence will be inevitable.

Mimicking the antigen under such complexities in order to produce a protective, artificial immune response is extremely difficult. As a result, developing an effective vaccine has proven elusive. New vaccine development programs are focused on either blocking parasite transmission from infected humans to mosquitoes or on preventing gametes from developing in the mosquito gut itself.

2. Transmission intensity is determined by a complex and variable set of factors

Malaria persistence is due to the complexity of factors underlying disease transmission and the resilient and complex nature of the parasites that are carried by mosquito vectors. Transmission factors vary across geographies and include mosquito density, longevity, propensity to bite humans, frequency of feeding, the acquisition and loss of immunity in susceptible populations, and the availability of effective treatment (WHO, 2010).

Specifically, the rate of malaria transmission depends on the human biting rate (HBR) of the mosquito, the density of mosquitoes engaged in blood feeding (which in turn is a function of overall mosquito density), propensity of prevalent vectors to bite humans, and frequency of feeding.

The product of the HBR and the percentage of infectious mosquitoes (sporozoite rate) yields what is known as the entomological inoculation rate (EIR), which represents the average number of infectious mosquito bites a person receives per unit of time. The EIR is widely considered the measure that best represents malaria transmission intensity in various geographies (White, et al., 2013; Hay, et al., 2000).

In Africa, malaria transmission intensity is variable and annual EIRs can range from less than one to more than 1,000 infective bites per person per year. While there is a linear relationship between annual EIRs and the prevalence of malaria infection (Overgaard, et al., 2012),[4] this relationship is complex and impacted by the acquisition and loss of immunity to malaria and the existence of effective drug treatment (WHO, 2010).

Malaria transmission intensity is a critical driver of prevalence of infection, incidence and symptomatic presentation of clinical disease and development of immunity and drug resistance (Kelly-Hope & McKenzie, 2009).

[4]When EIRs exceeded 15 infectious bites per year, prevalence of *P. falciparum* was never found to be less than 50 percent and annual EIRs of 200 bites or higher consistently yielded prevalence rates of greater than 80 percent.

Transmission intensity is thus central to the design and implementation of effective malaria control measures. In low transmission areas, symptomatic patients account for the vast majority of the infectious reservoir, and declines in transmission rates translate proportionally to a decline in malaria incidence and prevalence.

By contrast, in high transmission areas, much larger declines in transmission rates are needed to reduce overall malaria incidence and prevalence, and targeting symptomatic individuals alone is unlikely to achieve this (WHO, 2010). The implication is that while they may have a major impact on mortality reduction, drug strategies to reduce malaria prevalence will be effective in high transmission areas only if used in combination with other effective interventions targeting the vector.

Drug strategies increase in importance for overall malaria control only as transmission intensity declines, and the majority of patients become symptomatic. Programs then need to adapt to target the remaining parasite reservoirs, by finding and treating individual infections (Sturrock, et al., 2013).

Today, only half the countries of sub-Saharan Africa have data available on transmission intensities. What data is available suggests that EIRs and malaria transmission intensity appear to vary greatly based on the presence of different Anopheles species, the extent of urbanization, land use, population density, elevation and climate.

Improved and standardized data on EIRs and an increased understanding of the drivers of differences in transmission intensity across neighboring geographies are critical to the design and effective monitoring of malaria control interventions (Hay, et al., 2000).

3. The dominant *Anopheles* mosquito vectors are pervasive, adaptable and resilient

A mosquito's lifecycle has four stages: egg, larva, pupa and adult (**Exhibit 4**). The first three stages are aquatic and last five to 14 days. The mosquito becomes a vector only once it reaches adulthood, and only females are vectors.

Adult females feed on sugar sources for energy, but require a blood meal to develop eggs. After a full blood meal, the female rests for a few days while the blood is digested and eggs are developed. In tropical conditions, this takes two to three days. Once the eggs are fully developed, the female lays them and resumes host seeking.

Only if the mosquito has taken a blood meal from a human infected with the malaria parasite and survives the 10 to 14 days it takes the parasite to complete the incubation period and render the mosquito infectious, does the mosquito become an active malaria vector.

Female *Anopheles* mosquito life-cycle

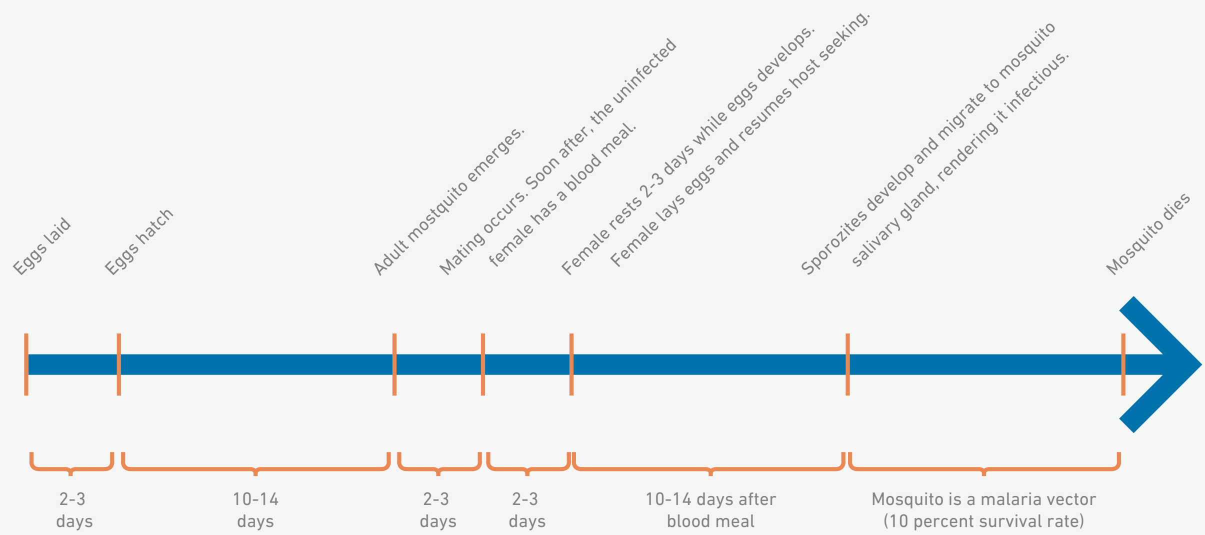


Exhibit 4: Female *Anopheles gambiae* become a vector about a month after being laid as eggs. What little data there is suggests that fewer than 10 percent survive to become vectors.

The dominant vector, *Anopheles gambiae*, has a number of characteristics that makes it an extremely efficient malaria vector.

Strong preference for human blood, combined with highly efficient feeding habits

Most *Anopheles* mosquitoes are neither strongly anthropophilic (prefer feeding on humans) nor zoophilic (prefer animal blood). However, *Anopheles gambiae* are strongly anthropophilic and, therefore, highly efficient malaria vectors. They are also endophilic (meaning they rest indoors) and nocturnal, which means that they have unfettered access to sleeping humans unless they are under appropriate bed-nets or are otherwise well-protected.

Relatively long life span

Adult *Anopheles gambiae* females tend to live one to two weeks in nature (Kileen, et al., 2000), a lifespan that is considered relatively long. Furthermore, studies in Tanzania showed *Anopheles gambiae* mosquitoes have a 77 to 84 percent daily survival rate. Extrapolating from this limited evidence, less than 10 percent of female *Anopheles gambiae* are likely to survive longer than the 14-day extrinsic incubation period it takes for them to become malaria vectors.

Thousands of breeding sites, which are very difficult to eliminate

Each adult female lays 50 to 200 eggs per oviposition, directly on water. These eggs have floats on their sides and hatch in a few days. Larvae of *Anopheles gambiae* (unlike those of most other species) can breed in very diverse habitats: fresh or salt-water marshes, mangrove swamps, rice fields, grassy ditches, edges of streams and small, temporary rain pools like tire tracks (CDC, 2014).

Without repeated and large-scale spraying, or other such expensive and environmentally destructive methods, it is extremely difficult to eliminate all these breeding sites. Recent studies have explored other methods for targeting oviposition and gravid (carrying eggs) females as a vector control strategy. Some have suggested that shiny, sticky surfaces may attract gravid females because they can be visually mistaken as aquatic habitats, and this could potentially be exploited in the development of gravid traps or novel mosquito trapping strategies (Dugassa, et al., 2012).

Mosquitoes may be capable of behavioral plasticity

Numerous anecdotal reports of mosquitoes changing their behavior and adapting feeding patterns as a result of IRS and LLINs exist. There is insufficient data to assess whether these are genetic or adaptive responses (Ranson, et al., 2011). The implication of such adaptability is that the effectiveness of LLINs may diminish over time, if, in order to minimize contact with indoor insecticides, the *Anopheles gambiae* mosquitoes begin feeding earlier in the day or do not remain exclusively endophilic. If this does happen, new control tools and strategies may be required.

4. The complex distribution of primary, secondary and tertiary *Anopheles* vector species makes design of effective vector control strategies difficult

Anopheles mosquitoes can be divided into several species complexes, which are composed of numerous morphologically indistinguishable sibling species. The *Anopheles gambiae senso stricto* is a complex of at least seven morphologically indistinguishable, but behaviorally distinct, sibling mosquito species, which include two genetically distinct species of *Anopheles gambiae senso strictu* (*Anopheles gambiae A.* and *Anopheles gambiae S.*) and *Anopheles arabiensis*, which are the dominant vector species in sub-Saharan Africa[5].

Anopheles funestus is also a dominant vector species, and further complication is introduced by the existence of primary, secondary and even tertiary vector species existing in sympatry within a single geography.

Effective control strategies depend on proper identification of the mosquito vector(s) and an understanding of each species' distinct feeding and biting preferences. Interventions need to be properly adapted to the local environment, taking into account the behavior and ecology of the main vector species as well as the resistance status of both parasite and vector.

[5]This species complex consists of *Anopheles arabiensis, Anopheles bwambae, Anopheles merus, Anopheles melas, Anopheles quadriannulatus* and *Anopheles gambiae senso stricto.*

The importance of this is underscored by the fact that neighboring villages can have vastly different malaria transmission intensities, depending on number of mosquito vectors present in that location. Where *Anopheles funestus* vectors are present alongside *Anopheles gambiae*, malaria transmission rates have been found to be twice as high.

In Senegal, a village only five kilometers from its neighbor was found to have transmission rates 10 times as high, due to the presence of *Anopheles funestus* (Kelly-Hope & McKenzie, 2009). Further, *Anopheles arabiensis*—also endemic in much of Africa—have become more prevalent after broad introduction of bed-nets and IRS (Bayoh, 2010), likely because they have less preference for feeding and resting indoors.

Today, large knowledge gaps exist about mosquito ecology and behavior in many highly endemic areas due to the difficulty of identifying and monitoring mosquito vectors in the field.

5. Limitations of treatment with antimalarials

Effective treatment with ACTs is a key component of reducing malaria-related mortality. The biggest challenges in malaria treatment include the continued use of poor quality or counterfeit treatments that are abundant in the marketplace, the use of monotherapies and lack of patient compliance to treatment regimens. All of these factors favor the development of drug resistance and are particularly common in Africa.

Yet another limitation of treatment strategies for broader malaria control efforts is the fact that symptomatic individuals constitute only a portion of the infectious reservoir, an important determinant of the number of infectious mosquitoes in an area and therefore the EIR. In a high transmission area, there are a large number of asymptomatic individuals due to the development of partial immunity resulting from frequent infectious bites.

Targeting symptomatic individuals alone is unlikely to achieve large declines in transmission rates or a reduction in overall malaria incidence and prevalence (WHO, 2010).

In low transmission areas, symptomatic patients account for the majority of the infectious reservoir, and declines in transmission rates are proportional to a decline in malaria incidence and prevalence. Clearly, drug strategies to reduce malaria prevalence will be effective in high transmission areas only if used in combination with other effective interventions targeting the vector.

Drug strategies increase in importance for overall malaria control only as transmission intensity declines, the majority of patients become symptomatic and programs adapt to target remaining parasite reservoirs—finding and treating asymptomatic individuals (Sturrock, et al., 2013).

6. Limitations of LLINs and IRS and increasing resistance

As described earlier, LLINs and IRS—despite their effectiveness when scaled up sufficiently—have drawbacks with respect to the breadth and longevity of the protection they offer, and carry the risk of emerging longer-term operational insecticide resistance.[6] Managing resistance is particularly challenging when an intervention is dependent on a single chemical class as in the case of LLINs.

Even in the case of IRS, which relies on four currently available insecticide classes (resistance has been reported to all four of these in some populations of *Anopheles gambiae*), managing resistance and providing sustainable vector control with existing chemicals is unlikely (Ranson, et al., 2011). In addition, there are significant portions of affected populations in remote areas, which are proving difficult to reach with these tools. New classes of insecticides and delivery tools are urgently needed to maintain the gains achieved over recent years.

[6]WHO defines insecticide resistance as the ability of an insect to withstand the effects of an insecticide by becoming resistant to its toxic effects by means of natural selection and mutations. The Insecticide Resistance Action Committee (IRAC) defines operational resistance as a heritable change in the sensitivity of a pest population that is reflected in the repeated failure of a product to achieve the expected level of control when used according to the label recommendation for that pest species.

In some malaria-endemic areas, resistance to all four classes of insecticides has been detected. Of the 73 malaria endemic countries that provided monitoring data to WHO for 2010 onwards, 60 reported resistance to at least one insecticide in one malaria vector from one collection site and 50 reported resistance to two or more insecticide classes (**Exhibit 5**).

Resistance to pyrethroids–the only class currently used in LLINs–is the most commonly reported; in 2015, more than three quarters of the countries monitoring this insecticide class reported resistance.

Evidence of geographical spread of resistance and intensification in some areas underscores the need to urgently take action to manage resistance and reduce reliance on pyrethroids (WHO, 2016).

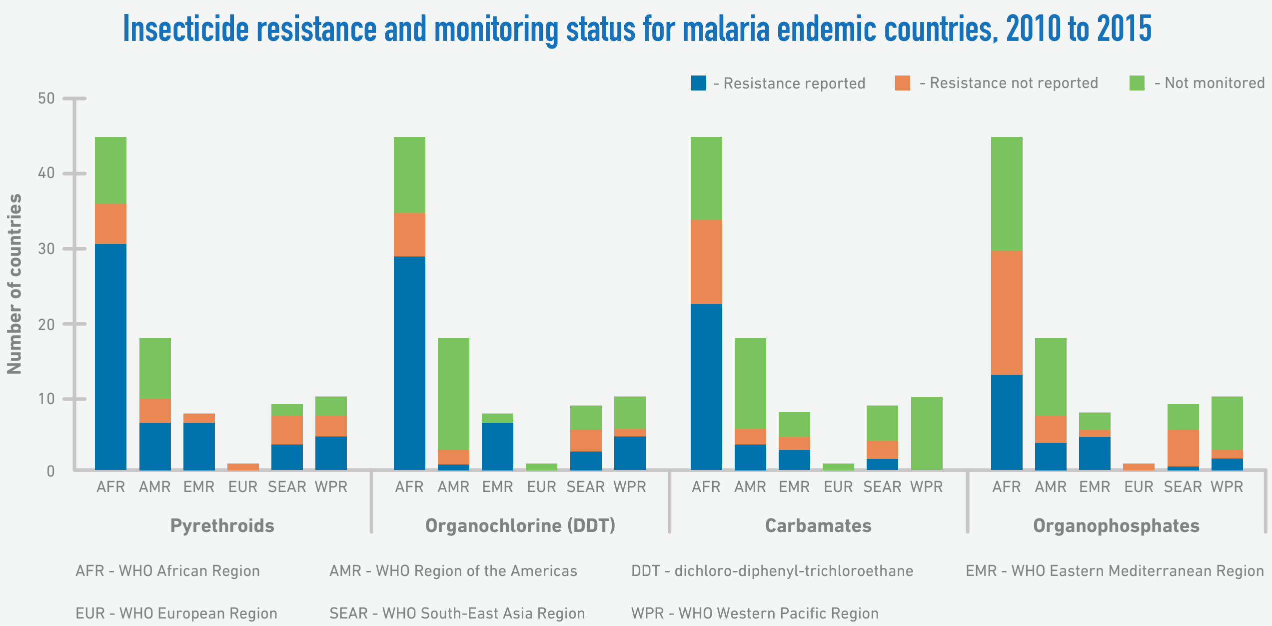


Exhibit 5: Africa is the region that faces greatest insecticide resistance among malaria endemic countries. (Source: WHO, 2015)

7. Large-scale programs to control or eliminate malaria require heavy, sustained public investment and coordination

Gains against malaria have historically relied on scale-up of successful interventions, and these gains have proven to be highly fragile. This is particularly true in high transmission settings, which have large asymptomatic reservoirs of infection (Stresman, et al., 2010).

Although malaria transmission can be dramatically reduced with effective control strategies, resurgence is inevitable in the absence of sustained interventions.

The common denominator among instances of malaria resurgence has been the weakening of malaria control programs due to reduced funding (Cohen, et al., 2012). The economic sustainability of interventions is, therefore, critical to maintaining any gains achieved in mortality reduction.

SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

Global malaria efforts have necessarily had a dual focus, control in highly endemic regions and elimination on the margins. The widely accepted malaria eradication strategy is two-pronged: it relies on aggressive control strategies to reduce transmission intensity and mortality in high-burden countries and on progressive elimination of malaria from the endemic margins (Feachem, et al., 2010).

To achieve dramatic results, the dual aims of control and elimination are being considered in parallel. Short-term interventions—no matter how successful in reducing mortality—will inevitably fail to control malaria in the long run, due to the inevitability of malaria resurgence and the possibility of cross-border transmission.

Regional elimination is a long way from being a reality in much of sub-Saharan Africa, and malaria eradication will likely take several decades.

It should be recognized that as sustainable malaria control is achieved and malaria transmission intensity is reduced in highly endemic countries, the character of malaria in these countries may change. In the long-term, if *P. falciparum* incidence is controlled, the relative proportion of *P. vivax* may increase, along with the proportion of malaria affecting adult men.

New challenges will require dramatically different strategies and technologies, in order to:

- move towards elimination by targeting *P. vivax*, including addressing new populations of affected individuals.
- identify and address remaining (asymptomatic) reservoirs of malaria parasites.
- manage emerging parasite species, in particular, the simian malaria species *P. knowlesi*, which has been infecting humans in Southeast Asia.
- control cross-border malaria transmission to sustain regional elimination. Sustain funding (such as for surveillance and response) through elimination.
- better identify and monitor mosquito species in the field.

In the meantime, there continue to be large numbers of malaria-related fatalities, especially among children in African countries. As described above, the investment required to maintain and scale-up current interventions is unlikely to be sustainable in the long-term. The limitations of current interventions need to be addressed with new solutions targeted for high-burden countries and populations.

As such, this analysis focuses on identifying technologies with the highest potential to reduce malaria mortality in high transmission settings, while recognizing that these may need to evolve over time as malaria transmission rates decline in high-burden countries.

Breakthroughs:

1 2 3 4 5 6 7 8 9 10
11 12 13 14 15 16 17 18 19 20
21 22 23 24 25 26 27 28 29 30
31 32 33 34 35 36 37 38 39 40
41 42 43 44 45 46 47 48 49 50

23 Vaccines that can effectively control and eventually help eradicate the major infectious diseases of our time—HIV/AIDS, malaria, tuberculosis and pneumococcus

Collectively, HIV/AIDS, malaria, tuberculosis and pneumonia kill more than five million people a year, and represent a significant disease burden for low income populations in sub-Saharan Africa and South Asia. Effective and affordable vaccines for these diseases do not exist yet due to the intrinsic complexity of the pathogens causing them, and a lack of understanding of the specific mechanisms through which our immune systems protect against these diseases. The process of vaccine development—basic research on disease etiology, vaccine construction, pre-clinical and clinical testing—is technically challenging, expensive and time consuming.

23b. A malaria vaccine specifically for *P. falciparum*

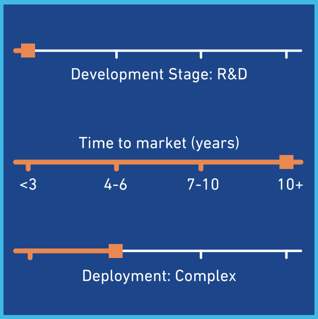
Given the difficulty in controlling *Anopheles* mosquitoes, it is clear that children will continue to be bitten and infected. Therefore, providing artificial protective immunity in the form of an anti-infective vaccine specifically for the *P. falciparum* parasite would represent a significant breakthrough in the area of malaria control.

Vaccines, in general, have a very long development lead-time; vaccines for malaria have proven particularly elusive. There are many complexities that increase the difficulty of developing a malaria vaccine that offers immunological protection. These include antigenic switching by the parasite under selective immune pressures to evade the immune system, the complex lifecycle and intracellular nature of the parasite and the lack of natural long-lasting immunity in humans against the parasite.

Consequently, mimicking the antigen to produce a protective but artificial immune response has proven extremely difficult. To account for the differential expression of antigens across the parasite lifecycle and to deepen understanding of effective or ineffective immune responses, a range of approaches to vaccine development are underway.

However, to date, only one has reached Phase III trials and 13 have had limited effectiveness. Given the current lack of a vaccine developmental candidate and the historical lack of success, experts believe it is 20 years or more away (WHO, 2018).

Current State

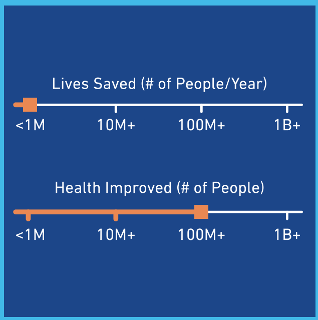


Associated 50BT Chapters

Global Health

SDG Alignment

Impact



Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

A different approach currently being explored is the development of transmission-blocking vaccines. These would reduce the number of blood stage parasites and specifically limit the presence and expansion of the infectious gametocyte form of the parasite in the mosquito, thus blocking ongoing transmission.

Such vaccines will not offer protection to the immunized individual, but will prevent the individual from passing parasites onto others, which represents an important breakthrough for dramatically lowering malaria transmission rates.

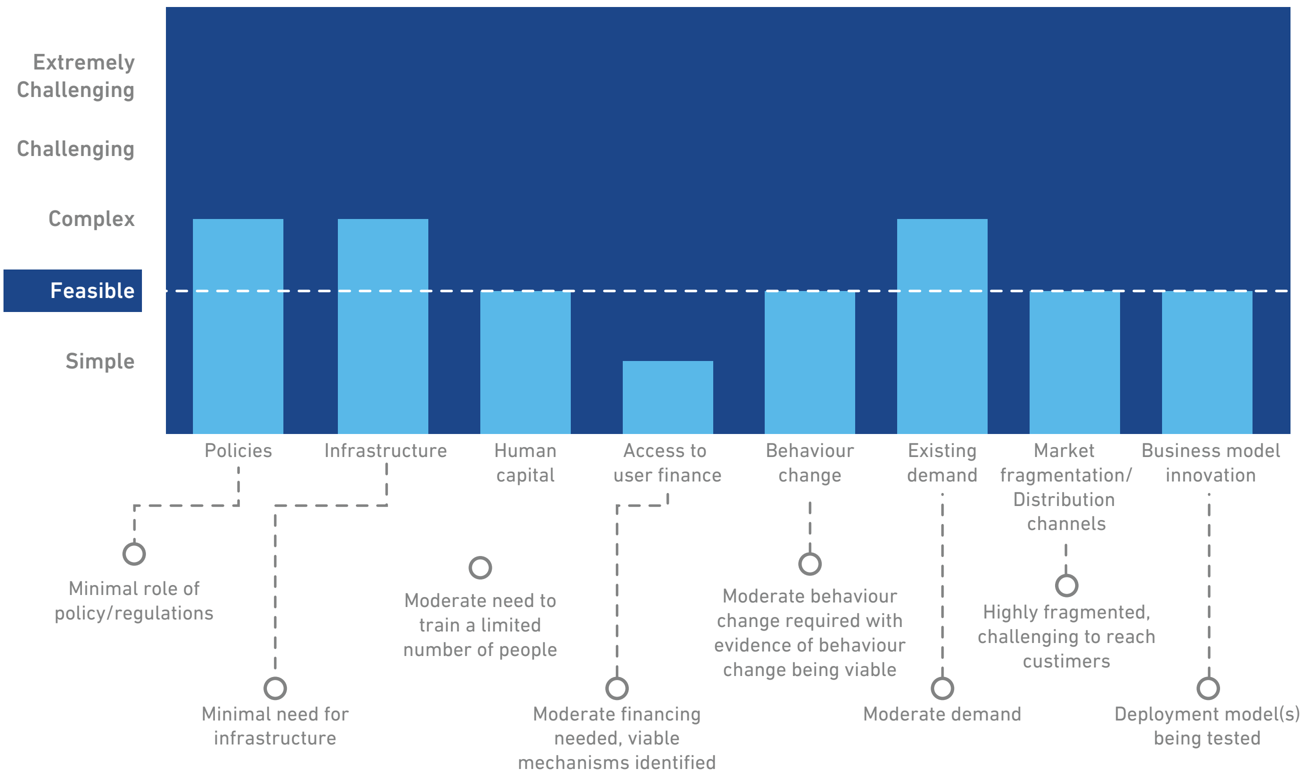
Deployment of new vaccines

Once any of these vaccines is developed, it can be deployed to children through existing, reasonably established, vaccine delivery channels. However, there are few mechanisms for delivering vaccines to adolescents and adults, and successful vaccination campaigns for these population segments would require significant government coordination, behavior change and financial investment.

Furthermore, even today vaccine delivery remains a challenge in many remote locations where supporting infrastructure like cold storage facilities are either few or non-existent. While vaccines are expected to be made available to patients at a low cost, financing for the vaccines by national governments or international donors would need to be secured in order to support widespread distribution. Policy changes would also need to support its introduction and distribution through public health systems.

Based on the above assessment, the projected time to market readiness is more than ten years, and the difficulty for deployment is FEASIBLE.

Breakthrough 23: Difficulty of deployment



29

A single-dose complete cure for malaria

Effective treatments for malaria exist. The majority of safe medications for malaria target the blood stage of the parasite, but not stages of the parasite lifecycle, such as the gametocyte stage. The persistence of the gametocytes following treatment creates a human reservoir of parasites, which remain viable for years in an otherwise asymptomatic and healthy person.

While this does not cause disease directly, it does pose challenges for malaria control and elimination. As such, a single-dose complete cure to eliminate all malaria parasites in the human body—both blood stage and liver stage and both sexual and asexual—represents a significant breakthrough in malaria control.

There is a fairly well-developed pipeline for improved antimalarial treatments, including drugs that are targeting other stages of the parasite life-cycle. In 2018, the FDA approved tafenoquine (Krintafel) for the radical cure of Plasmodium vivax malaria in patients aged 16 or older.

This drug has been manufactured by GlaxoSmithKline. Another candidate known as OZ439 that may also be effective against artemisinin-resistant strains of malaria is in the works, with Phase IIb study scheduled to be completed in 2019 (MMV, 2018).

Current State

Development Stage: R&D

Time to market (years): <3 | 4-6 | 7-10 | **10+**

Deployment: Feasible

Associated 50BT Chapters

Global Health

SDG Alignment

3 GOOD HEALTH AND WELL-BEING

Impact

Lives Saved (# of People/Year): **<1M** | 10M+ | 100M+ | 1B+

Health Improved (# of People): <1M | 10M+ | **100M+** | 1B+

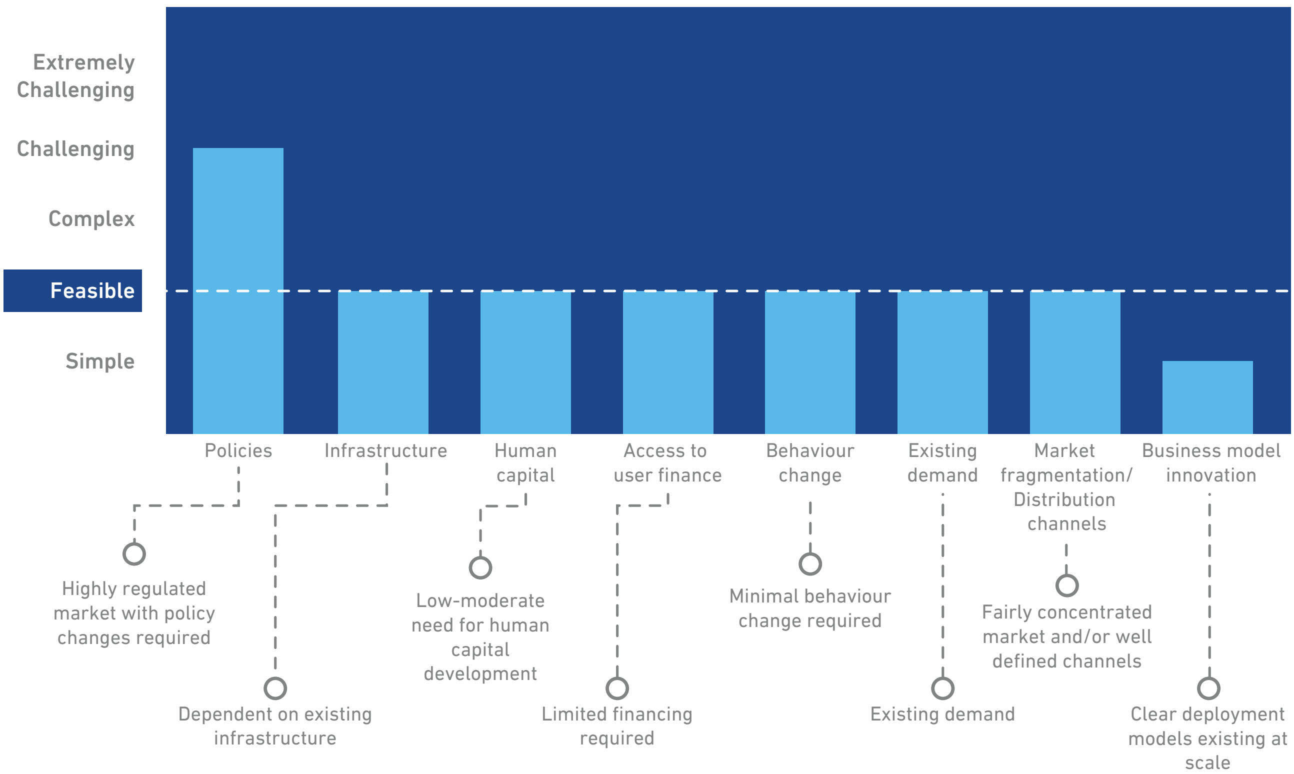
Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

Once available, these drugs will need to be approved by the WHO and incorporated into international and national level malaria treatment guidelines. As many of those who will require treatment are asymptomatic, the drugs will likely need to be introduced in combination with a highly sensitive rapid diagnostic test that can help identify these asymptomatic individuals.

Finally, sustained funding for these interventions will need to be secured. Based on the above assessment the difficulty of deployment is FEASIBLE.

Breakthrough 29: Difficulty of deployment



30 New long-lasting spatial mosquito repellents or attractants (chemical and non-chemical) for vector control

There are great opportunities for novel spatial mosquito repellents or attractants for vector control and improved health. Breakthroughs may be chemical-based or non-chemical, such as sound-based. It is unlikely that existing chemicals will provide sustained control while limiting the development of resistance.

New classes of long-lasting chemical repellents are required and need to be delivered through novel mechanisms that are easy to use and adopt. Delivery strategies must provide community-level protection. Control methods should be optimized for the most lethal African vectors—*Anopheles gambiae*, *Anopheles arabiensis* and *Anopheles funestus*—but will ideally be effective across all primary and secondary vector species.

High coverage of non-chemical spatial repellents could enhance the impact of existing interventions such as LLINs and IRS, particularly in areas where mosquitoes are biting individuals outdoors. Non-chemical repellents or attractants also have the potential to overcome the challenge of insecticide resistance. Non-chemical spatial repellents (for example those based on sound) exist in the market but have not proven effective, particularly at the community-level. It is unclear whether these products are based on rigorous science.

Effective spatial repellents can be difficult to design and their benefits to individual households need to be considered in the context of benefits to the community (Achee, et al., 2012). In particular, a repellent that is very effective in a household setting may simply drive the mosquitoes to other areas and households that do not have an equally effective repellent, potentially intensifying malaria in less protected, likely poorer, areas.

Therefore, such repellents should ideally be used through a 'push-pull' mechanism (Takken, 2010), which would push mosquitoes away from at-risk households and pull them towards an area where they can easily be destroyed. Alternatively, attractants can offer the potential to easily lure and kill mosquitoes. Methods to do so by exploiting mosquito mating behaviors (like pheromones and wing beat frequency) and sensory sensitivities (odors) are being explored.

Research is progressing on chemical-based solutions, and some existing chemicals (like transfluthrin) are showing promise. Efforts aimed at providing individual-level protection include transfluthrin-treated strips (Ogoma, et al., 2012) and the under-development Kite PatchTM that relies on chemicals to disrupt a mosquito's carbon dioxide receptors. However, the potential of these devices for long-term spatial efficacy has not been demonstrated.

Current State

Development Stage: Engineering

Time to market (years): <3 | 4-6 | 7-10 | 10+

Deployment: Challenging

Associated 50BT Chapters

Global Health

SDG Alignment

3 GOOD HEALTH AND WELL-BEING

Impact

Lives Saved (# of People/Year): <1M | 10M+ | 100M+ | 1B+

Health Improved (# of People): <1M | 10M+ | 100M+ | 1B+

Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

As the sensory sensitivities of mosquitoes are better understood, developing repellent and attractant technologies can be more easily developed. However, to be effective, the control method will need to be considered in the broader context of the community and not just the individual household.

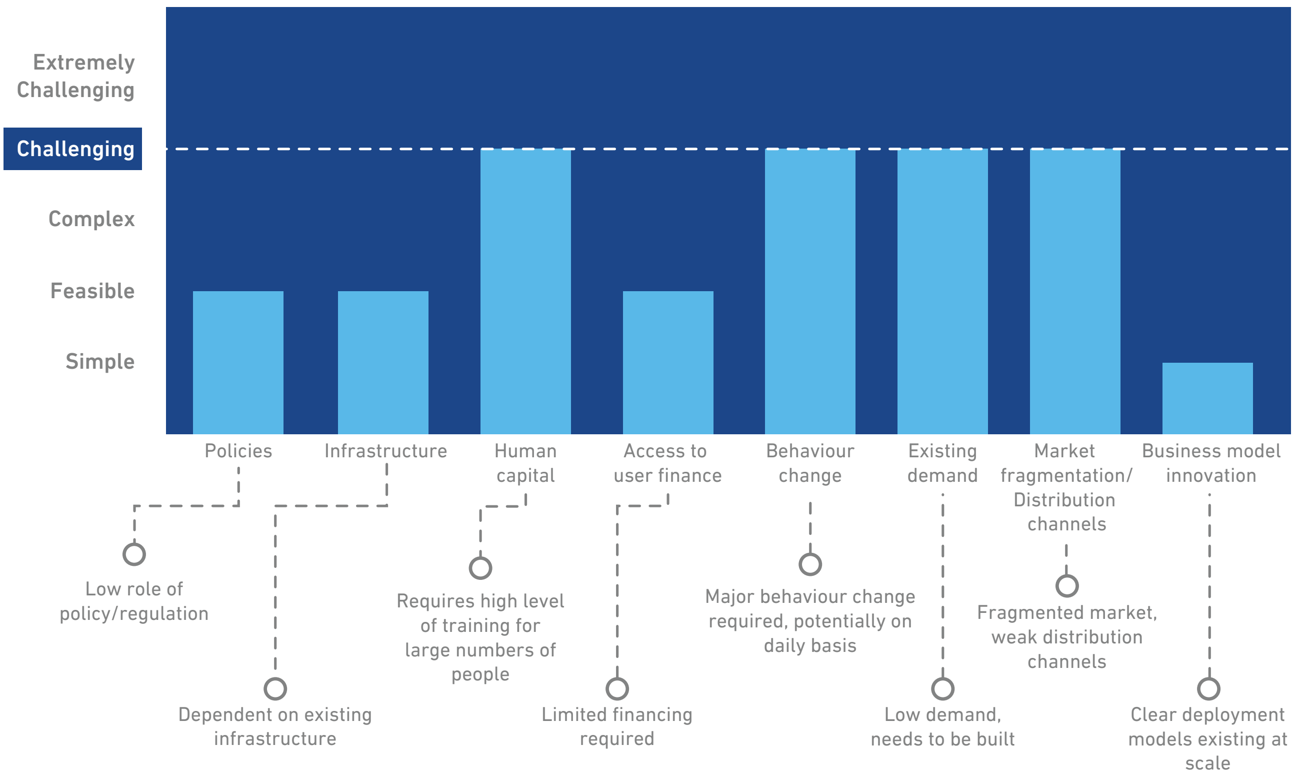
This will likely require some form of governmental coordination. Community-level protection will need to be demonstrated and this will require significant investment in operational research.

Furthermore, optimum usage may require some training (depending on the nature of the repellent or attractant) and adherence to appropriate protocol.

Importantly, non-chemical repellents should be designed such that they do not require frequent replenishment or investment in supply chain infrastructure.

Based on the above assessment, the projected time to market readiness is seven to 10 years and the difficulty of deployment is CHALLENGING.

Breakthrough 30: Difficulty of deployment



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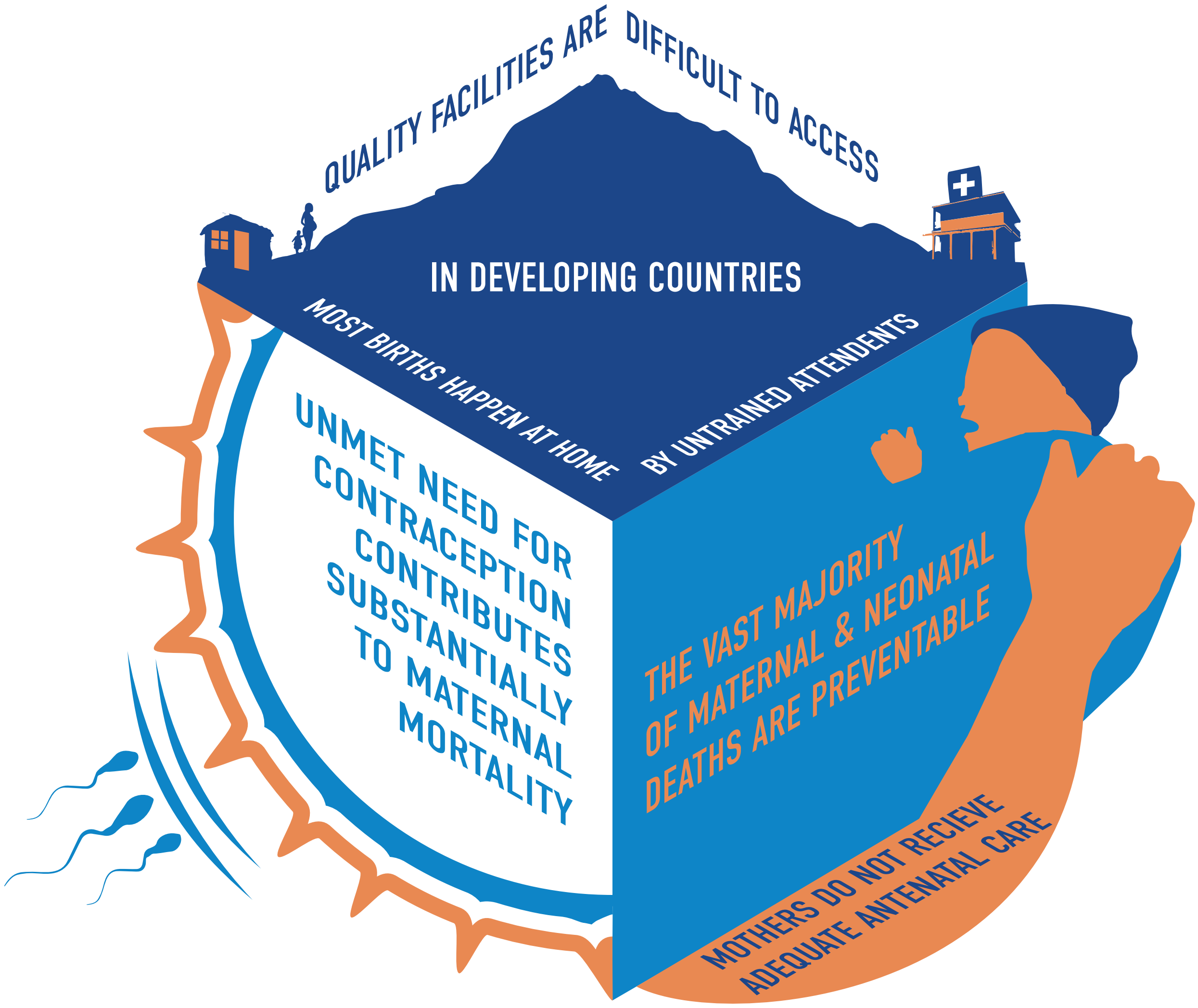


MATERNAL AND NEONATAL HEALTH

INTRODUCTION

In 2017, 308,000 women died from pregnancy or childbirth-related complications, and 2.7 million infants died in their first month of life.

The vast majority (99 percent) of these deaths occur in developing countries and most are preventable (Guttmacher, 2017).

Maternal mortality is caused by a wide range of conditions (WHO, 2018), including severe bleeding (mostly post-partum hemorrhaging), infections (usually after childbirth), hypertension during pregnancy (pre-eclampsia and eclampsia), complications from delivery, unsafe abortion, and association with diseases such as malaria and HIV/AIDs.

Of these conditions, hemorrhage and hypertensive disorders are the largest causes of mortality, accounting for 27 percent and 14 percent of mortality respectively (Say, et al., 2014). Among women who experience medical complications during pregnancy or delivery, only one in three (35 percent) receives the care they or their newborns need (Guttmacher, 2017).

Neonatal mortality is caused by three main conditions: preterm birth complications, birth asphyxia and infections, which represent 24 percent, 20 percent and 7.5 percent of mortality, respectively (IHME GBD, 2017). Underlying all of these conditions are four broad challenges:

- Approximately 43 percent of the pregnancies are unintended, with the majority due to unmet family planning needs.
- Many mothers lack skilled care during childbirth.
- Most mothers do not receive sufficient antenatal care, or care and support after childbirth.
- Many mothers are malnourished.

Interventions need to focus on reducing preventable maternal and newborn mortality. They include sexual, reproductive, maternal, newborn and adolescent health care, family planning, attention to infectious and chronic noncommunicable diseases and social determinants that contribute to maternal and neonatal mortality.

Timely management and treatment can make the difference between life and death for both the mother and the baby. Most importantly, maternal health care services have to be contextualized within the broader comprehensive primary health care approach. Action is required at all levels: individual, family and community, health systems and structural in terms of developing the requisite policies and programs.

In light of the above challenges, one technological breakthrough can help reduce maternal and neonatal mortality by strengthening primary health care in developing countries:

- Breakthrough 31. Integrated suite of digitally enabled primary care devices including point-of-care diagnostics (for basic blood, urine, and vitals tests), therapeutic devices for common conditions, and clinical operations (such as sterilization, refrigeration)

Maternal and neonatal health have been an important global health priority. As the following discussion shows, the specific conditions and root causes of mortality and morbidity are structural and systemic, and there are no 'silver bullets' that can make a substantial difference by themselves.

CORE FACTS AND ANALYSIS

Each year, maternal and neonatal medical conditions cause 308,000 and 2.7 million deaths respectively (Guttmacher, 2017), the vast majority of which—99 percent in the case of maternal deaths—occur in developing countries.

The Global Burden of Disease study estimated that neonatal conditions are the fifth largest cause of disease burden in developing countries and maternal health is the 21st highest cause of disease burden in those countries; although this seemingly lower rank does not reflect the large impact of maternal mortality on the infant or the family (IHME GBD, 2017).

Access to maternal health care is a key component of the global Universal Health Coverage (UHC) movement. WHO indicators for measuring the level of equity of UHC across countries include coverage of family planning, antenatal and delivery care, full child immunization services, and health-seeking behavior for pneumonia. There is hope that UHC reforms in many countries will help speed up equitable access to maternal health care services.

1. Most births in developing countries take place at home and are administered by untrained health workers

More than half the childbirths in developing countries take place at home with the assistance of traditional birth attendants, who, unlike skilled birth attendants, have limited or no formal training.

A 2011 study found that in sub-Saharan Africa and South Asia, 74 percent and 84 percent of women in the bottom two economic quintiles gave birth at home with the assistance of unskilled birth attendants, compared with 21 to 22 percent in the top quintile (Montagu, et al., 2011).

Since then, major progress has been made in increasing facility-based deliveries. UNICEF estimated that in 2016 the number of births that took place without the assistance of a skilled birth attendant had reduced to about one in five births (22 per cent).

Some countries, like India, have seen dramatic changes within a few years after the government started providing cash incentives to women opting for facility births.

That said, the frequency of home birth is still particularly high for the poor in these countries (**Exhibit 1**).

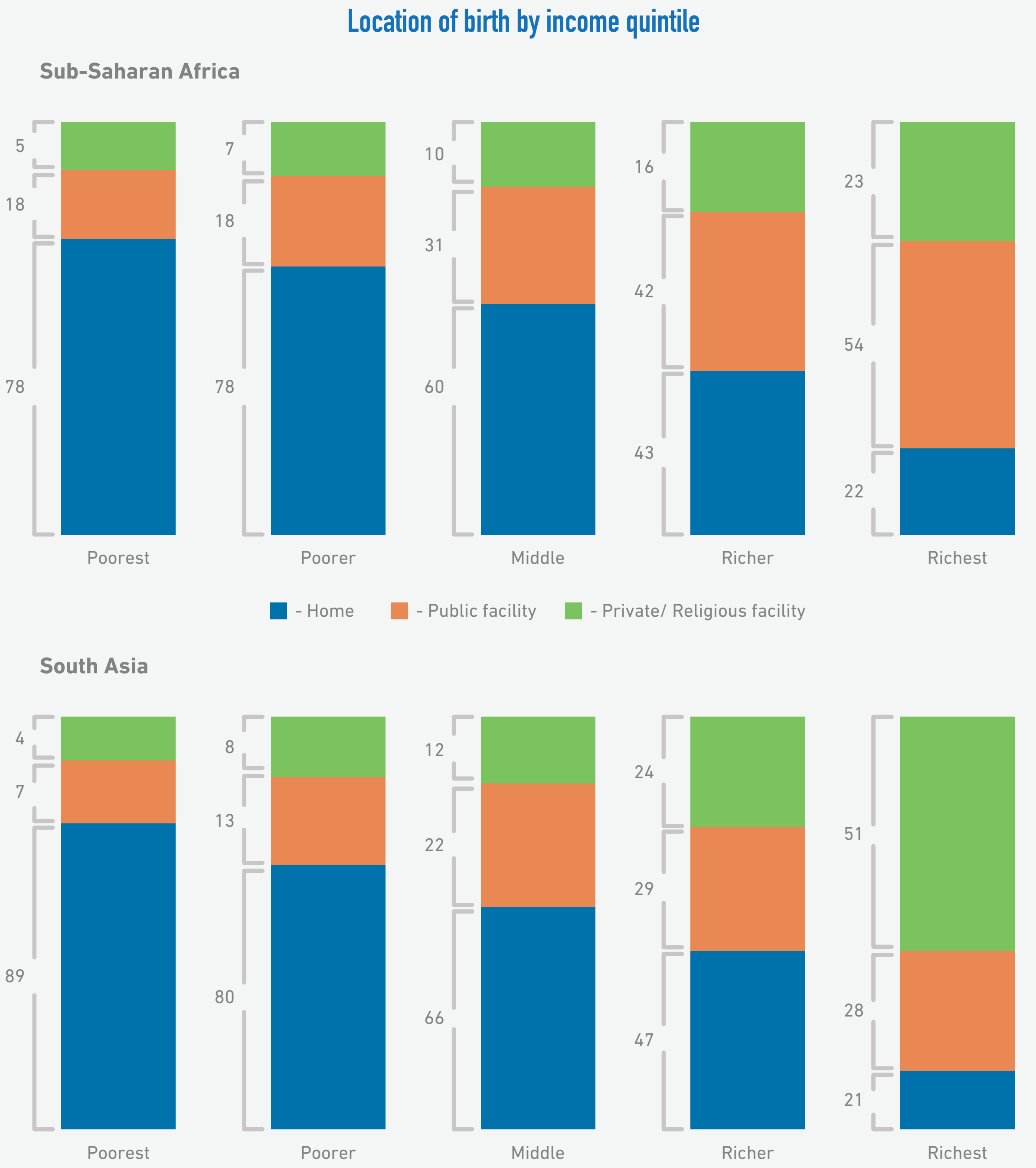


Exhibit 1: The majority of births in lower-income populations take place at home. (Source: Montagu, et al., 2011)

2. Expectant mothers do not receive antenatal care and are often malnourished

Across the largest countries in sub-Saharan Africa and South Asia, an increasing number of pregnant women are receiving antenatal care, although the numbers are still low, with the majority of women (86 percent) receiving at least one antenatal care visit, but only 62 percent receive at least four antenatal visits, the minimum number of visits recommended by WHO (UNICEF, 2016).

Rates of malnutrition among women in developing countries are high. Some 30 percent of women and 40 percent of pregnant women in the world suffer from iron-deficiency anemia (JustActions.org, 2018) and a significant number of women are stunted or undernourished, which can lead to delivery complications and preterm births.

3. Maternal mortality is driven by multiple conditions

Maternal mortality and morbidity are driven by fewer than 10 medical conditions (**Exhibit 2**). Importantly, each of these causes of maternal mortality have different clinical needs. The underlying causes and treatment needs of the two leading clinical conditions of maternal mortality are listed below.

Conditions leading to maternal mortality

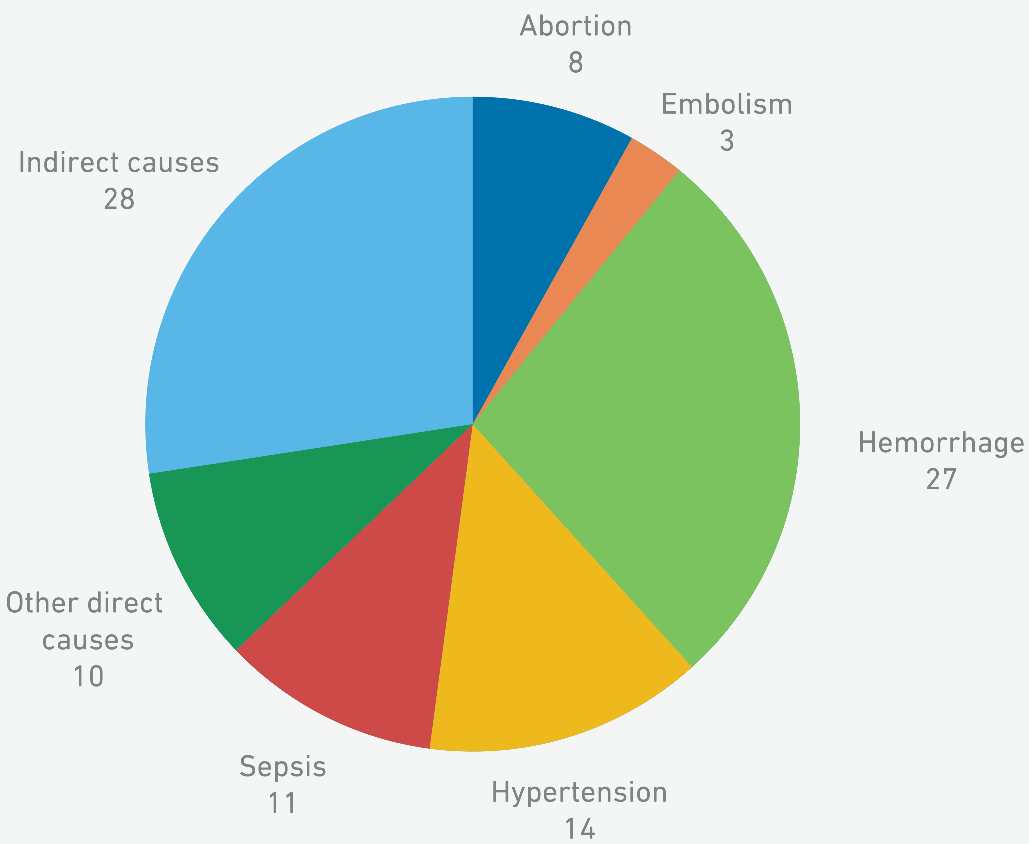


Exhibit 2: There is no single cause of maternal mortality. Several different clinical conditions, of which post-partum hemorrhage (PPH) and hypertensive diseases are the leading, are the causes. However, even these causes of mortality result from a broad range of underlying conditions and are influenced by numerous risk factors. (Source: Say, et al., 2014)

Post-partum hemorrhage

Characterized by excessive blood loss following childbirth, post-partum hemorrhage is the largest cause of maternal mortality, accounting for 27 percent of all maternal deaths. The primary cause of PPH is uterine atony, which occurs when the uterus does not contract and help stop post-partum bleeding. PPH can also be caused by abruption, retained placental tissue, coagulation abnormalities and other factors.

The WHO recommended approach to prevention of PPH is Active Management of the Third Stage of Labor (AMTSL), which includes the administration of an uterotonic that makes the uterus contract. The WHO recommends Oxytocin as the first line uterotonic, but using it at many low-resource facilities is problematic since it must be kept refrigerated.

Other thermostable uterotonics like Misoprostol are possible alternatives. However, due to its use in abortions, Misoprostol is heavily regulated or banned in several countries. Adequate community-level care, training birth attendants to administer AMTSL and sufficient distribution of uterotonics are additional challenges to reducing PPH.

It is important to note that uterotonics work in less than half of PPH cases, indicating a need for secondary treatments like balloon tamponades, anti-shock garments and hemostatic agents.

Hypertensive disorders of pregnancy

At 14 percent, hypertensive disorders of pregnancy constitute the second leading cause of maternal mortality and a range of complications linked to high blood pressure. The major hypertensive conditions are preeclampsia, when a pregnant woman develops high blood pressure and protein in the urine after the 20th week of pregnancy, and eclampsia, characterized by seizures.

The placenta is a highly vascularized organ, and while it is believed that issues in the formation of blood vessels in the placenta are what lead to hypertensive diseases of pregnancy, the specific mechanisms are poorly understood. The prevalence of hypertensive diseases in pregnancy is no different in developing countries compared to developed countries, and there is no definitive treatment even in developed countries except inducing early birth.

If diagnosed early, the mother can be prescribed hypertensive medications The WHO has recommended prevention through calcium (where calcium intake is low) and/or aspirin supplements. However, traditional birth attendants in developing countries do not have the training or equipment to detect hypertensive diseases, administer appropriate medicines or induce early birth.

In the last decade, researchers have begun to discover a number of novel biomarkers that will allow for early diagnosis of the disease and outcome prediction (Armaly, et al., 2018) and also potentially lead to new treatment.

4. Three conditions are responsible for over half of neonatal mortality

The health of newborns is affected by many of the same underlying factors that influence maternal health—malnutrition in expectant mothers, the lack skilled birth attendants with appropriate equipment and the lack of antenatal care.

As a category, neonatal conditions are the single largest cause of disease burden in LMICs, responsible for 10.9 percent of DALYs and 2.7 million global deaths per year (IHME GBD, 2017). Three conditions—preterm birth complications, birth asphyxia and infection—are responsible for 51.5 percent of neonatal mortality (IHME GBD, 2017) (**Exhibit 3**).

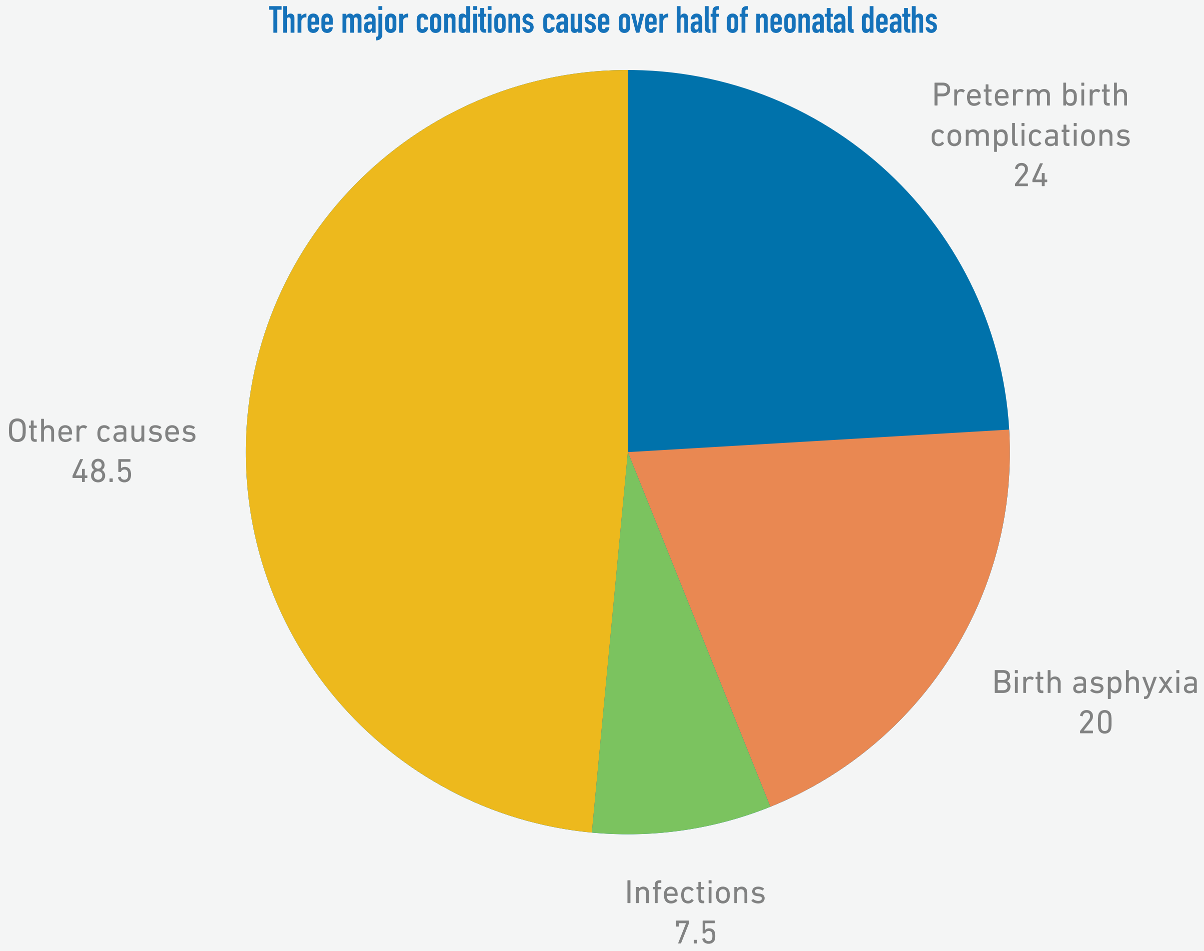


Exhibit 3: Preterm births, birth asphyxia and infections (pneumonia, sepsis and meningitis) cause more than half of all neonatal deaths. (Source: IHME GBD, 2017)

Preterm birth complications

Births are considered preterm when the infant has completed fewer than 37 weeks of gestation. In 2017, preterm birth complications caused 648,000 infant deaths (IHME GBD, 2017). Preterm infants are vulnerable to an array of conditions including respiratory distress, difficulty feeding orally, infection (most commonly sepsis and pneumonia) and hypothermia, among others. The frequency and severity of complications increase as the duration of gestation decreases (**Exhibit 4**).

Infants born very preterm (28 to 32 weeks of gestation) are particularly prone to respiratory distress syndrome (RDS), which is characterized by under-developed lungs that lack surfactant—a lipoprotein complex that helps lungs expand and contract. The weight of the infant at birth is another important indicator. Even infants who are born at or near full-term can be low birthweight and require special care.

The causes of premature birth are not well understood, even in developed countries. It is believed to be associated with multiple pregnancies, infections, genetic factors, and chronic conditions such as diabetes and high blood pressure (WHO, 2012). Though it is best to prevent preterm birth, this is difficult given the limited understanding of risk factors and the lack of antenatal care in developing countries. Since preterm birth is difficult to predict or prevent, it is more effective to focus on treating the complications at each level of prematurity

Frequency of preterm birth and major complications

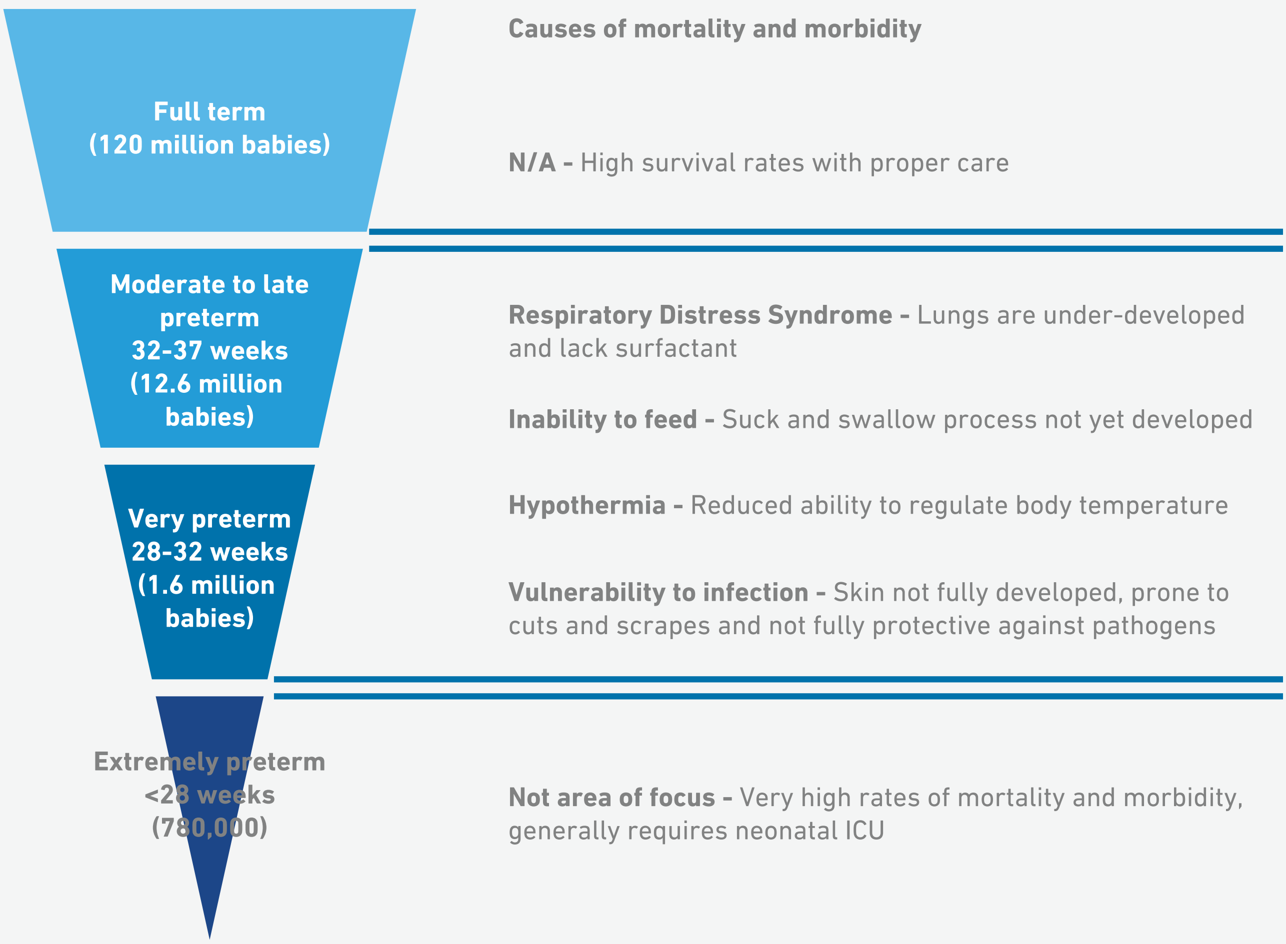


Exhibit 4: Infants born before 37 weeks experience an array of complications, which require specialized care. (Source: WHO, 2012)

Birth asphyxia

Birth asphyxia is defined as the inability to establish breathing at birth and is referred to in some studies as intrapartum-related events or complications of neonatal encephalopathy. Birth asphyxia was responsible for 540,000 deaths in 2017 (IHME GBD, 2017).

During birth, blood flow to the placenta is disrupted by contractions, which does not present a problem when the mother and fetus are healthy and labor progresses normally. Various conditions such as severe anemia and prolonged labor can exacerbate this disruption of blood and oxygen flow, however, leading to insufficient oxygen reaching the fetus and causing brain damage and death. Intrapartum complications are often addressable but require access to skilled care and equipment.

Specifically, when a fetus is deemed to be in danger of intrapartum asphyxia due to prolonged labor or another cause, asphyxia can usually be prevented through emergency cesarean section. This is often not an option in many developing countries due to lack of obstetric skills and equipment.

Newborns sometimes also need assistance in establishing breathing immediately after birth. It is estimated that 10 percent of newborns require some form of assistance in initiating breathing (Healthy Newborn Network, 2014), usually through simple resuscitation devices like self-inflating bags and masks or suction devices, to remove amniotic fluid that may be in the newborn's airway. These devices are inexpensive, but coverage is low and they require training to be properly used.

Infections

Major infections including pneumonia, sepsis and meningitis, are the third leading cause of neonatal mortality, responsible for 202,500 deaths in 2017 (IHME GBD, 2017). These major infections are often considered separately form tetanus and diarrhea, which cause another 58,000 and 50,000 deaths respectively, as they often have very different transmission pathways. Pneumonia, sepsis and meningitis are classified as early onset or late onset, depending on when the symptoms occur. Early and late onset infections are often contracted through different pathways.

The leading cause of neonatal infection is exposure to bacteria immediately before or during delivery. This occurs primarily when bacteria ascend from the birth canal during prolonged rupture of membranes and are aspirated by the infant.

Infants can also be exposed to pathogens during birth due to unhygienic delivery practices, such as use of dirty equipment, unwashed hands during delivery and improper cord care. Symptoms of early onset infection occur within seven days of birth. In late onset sepsis and pneumonia, symptoms occur 8 to 30 days after birth and can arise from community acquired infection or from bacteria contracted during birth.

5. Unmet need for family planning also contributes substantially to maternal mortality

Forty-three percent of the estimated 206 million pregnancies worldwide are unintended (Guttmacher, 2017). The majority of unintended pregnancies were caused by lack of access to, or utilization of, modern contraception—in developing regions, 214 million women of reproductive age who want to avoid pregnancy are not using a modern contraceptive method (WHO, 2018).

Unintended pregnancies due to lack of family planning increases the risk of maternal mortality in multiple ways. Contraceptive use has been shown to reduce maternal mortality rates, by decreasing the number of high-risk and high-parity births. There is evidence that women who have more than four children are at increased risk of maternal mortality (WHO, 2018). Women with unplanned pregnancies also tend to receive low-skilled care, which increases the risk of death during childbirth. Reducing unplanned pregnancies lessens the need for abortions, and in low-resourced settings that often means unsafe abortions, another leading cause of maternal mortality.

Closely spaced births also contribute to high infant mortality rates, and babies born to adolescent mothers suffer a higher rate of neonatal mortality. Adolescent mothers are also more likely to have pre-term or low birth weight-babies, which are risk factors for many early childhood health issues like pneumonia.

Fully meeting the unmet need for modern contraception would result in an estimated 25 percent, or 76,000, fewer maternal deaths each year (Guttmacher, 2017). Furthermore, family planning access and utilization is key to achieving SDG Goal 5.6, "universal access to sexual and reproductive health and reproductive rights" (UN, 2018).

KEY CHALLENGES

The challenges in maternal and neonatal health are systemic: There are too few adequately equipped clinics and adequately trained clinicians, and little regulation.

Access to quality family services, especially for adolescents, is inadequate.

Beyond the challenges of access to basic health services, it is important to note that there are also significant cultural barriers in many communities, which compel women to rely exclusively on informal, at-home care.

As a result, even when adequate clinics exist, the demand for them isn't necessarily guaranteed. This broad lack of access to basic care leads to a number of essential issues.

1. Many births in developing countries still take place at home, administered by poorly trained and poorly equipped traditional birth attendants. There is a widespread lack of skilled birth attendants.

2. Although facility birth rates are increasing, access and quality remains a concern. In low-resource settings, even where facilities are available, they tend to be overburdened and poorly equipped, lacking reliable electricity, lighting, necessary equipment, and access to clean water and sanitation.

3. Mothers do not receive adequate antenatal care. Only 62 percent of mothers in developing countries receive at least four antenatal care visits, as recommended by WHO, and this percentage is even lower in large countries in sub-Saharan Africa and South Asia.

4. Poor maternal nutrition and anemia during pregnancy make both mother and child more vulnerable to complications. Poor nutrition prior to the pregnancy itself can also affect maternal and neonatal health. Stunting in girls, occurring as early as the first two years of life, for example, increases the risk of preterm delivery and PPH later in life.

5. There is a high unmet demand for family planning. This means women who want to limit their family size, or space their pregnancies, are not able to do so, but lack of family planning also greatly increases a woman's risk of maternal death and her infant's neonatal health.

There are many barriers to ensuring that every woman has access to contraceptive methods that suit her needs. Currently, the choice of methods is limited. Many are hormonal methods that cause side effects, a major reason for discontinuation. Easier and discreet long-term methods currently require administration by health providers.

SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

Maternal and neonatal mortality and morbidity is driven by fewer than 10 conditions, the majority of which are treatable by a skilled clinician with appropriate equipment. Currently, there is a shortage of both.

Medical equipment in particular needs significant technological innovation and cost reduction to reach low-income populations, especially in rural areas. With high levels of unintended pregnancies, many of which lead to maternal deaths, contraceptive technologies and administration methods require new approaches.

Many existing low-cost technologies have the potential to reduce maternal and neonatal mortality and morbidity, such as uterine balloon tamponades, low cost antiseptics and kangaroo care, among others.

Over the last decade, there has been a large increase in leveraging the ubiquity of mobile phones to reach women of reproductive age, pregnant women and providers. While there are not enough rigorous evaluations of the effect of mHealth strategies on reducing maternal and neonatal morbidities and mortalities, modest evidence suggests that such tactics can improve mothers' education, and that decision support and training applications have positive effect on providers (Chen, et al., 2018).

Proper primary health care for women and children is a vital prerequisite for maternal and neonatal success. There must be more focus on innovative approaches to improve primary care. There is one technology breakthrough that can significantly improve maternal and neonatal health by strengthening primary health care.

Breakthroughs:

1 2 3 4 5 6 7 8 9 10
11 12 13 14 15 16 17 18 19 20
21 22 23 24 25 26 27 28 29 30
31 32 33 34 35 36 37 38 39 40
41 42 43 44 45 46 47 48 49 50

31 Integrated suite of digitally enabled primary care devices including point-of-care diagnostics (for basic blood, urine, and vitals tests), therapeutic devices for common conditions, and clinical operations (such as sterilization, refrigeration)

Among the many structural challenges in healthcare delivery in developing countries is the virtual absence of adequately equipped clinics needed to support the provision of primary care. The majority of clinics, especially in rural areas serving low-income populations, lack even the basic amenities, let alone the equipment necessary to provide essential services. With the shortage of human resources, it is particularly important to expand and maximize the capabilities of locally available providers (often mid-level providers like nurses or clinical officers with varying levels of training) for patient-centered care at primary care facilities.

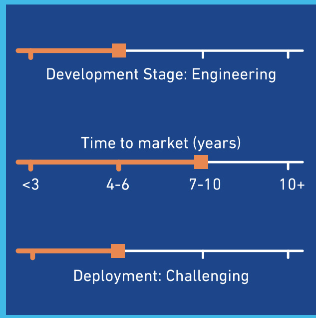
To build a clinic with the equipment necessary to provide basic primary healthcare would likely cost in excess of $100,000. This is based on preliminary research on costs of essential infrastructure (like solar panels and lighting), medical devices (like sterilizer and ultrasound) and diagnostics (such as rapid diagnostic tests and urine test analyzer) that are already available on the market, and the cost of constructing a basic building. In the absence of adequate public funding, this is too expensive for low-income populations by a factor of 10, based on our high-level assessment. In addition, the logistics of procuring the various components and assembling them into a functioning clinic require considerable effort.

A digitally-integrated suite of devices for primary care is needed, that includes point of care diagnostic devices for basic blood, urine and vitals tests. It would also include therapeutic devices for common conditions, for example, warming, phototherapy and oxygen concentration devices. It would also support clinical operations, such as sterilization devices and refrigeration for thermo-sensitive pharmaceuticals. A power management system would be integrated, including renewable energy supply where appropriate. A platform for patient and clinic management is at the core, and needs to be built using a provider- and patient-centered design approach. The focus should be on making the work of health professionals easier and better, and improving on the patient experience to ensure utilization. While maternal and neonatal intensive care devices are likely beyond the scope of this suite, health outcomes for mothers and newborns are nonetheless expected to be significantly improved, due to higher overall standards of primary care during prenatal and postnatal periods.

Such an integrated suite of devices could be a significant breakthrough if it:

- combines an integrated suite of low-cost and energy-efficient devices required to provide basic primary care:
  - Diagnostic devices and tests for relevant medical conditions including nutrition deficiencies, anemia, malaria, HIV, syphilis and hypertensive disorders

Current State



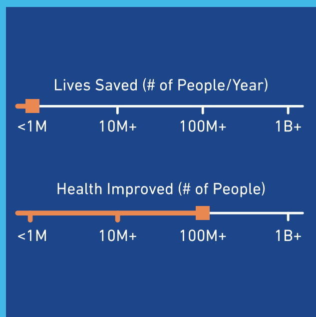
Associated 50BT Chapters

Global Health

SDG Alignment

3 GOOD HEALTH AND WELL-BEING

Impact



Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

- Sterilization devices for equipment
- Ultrasound devices
- Medical lighting
- Locally manufactured oxygen or oxygen concentrators
- Refrigeration to store vaccines and other thermo-sensitive pharmaceuticals;

- integrates power management, computation/imaging, data and communication so that the various devices can function in an easy-to-install plug-and-play mode;

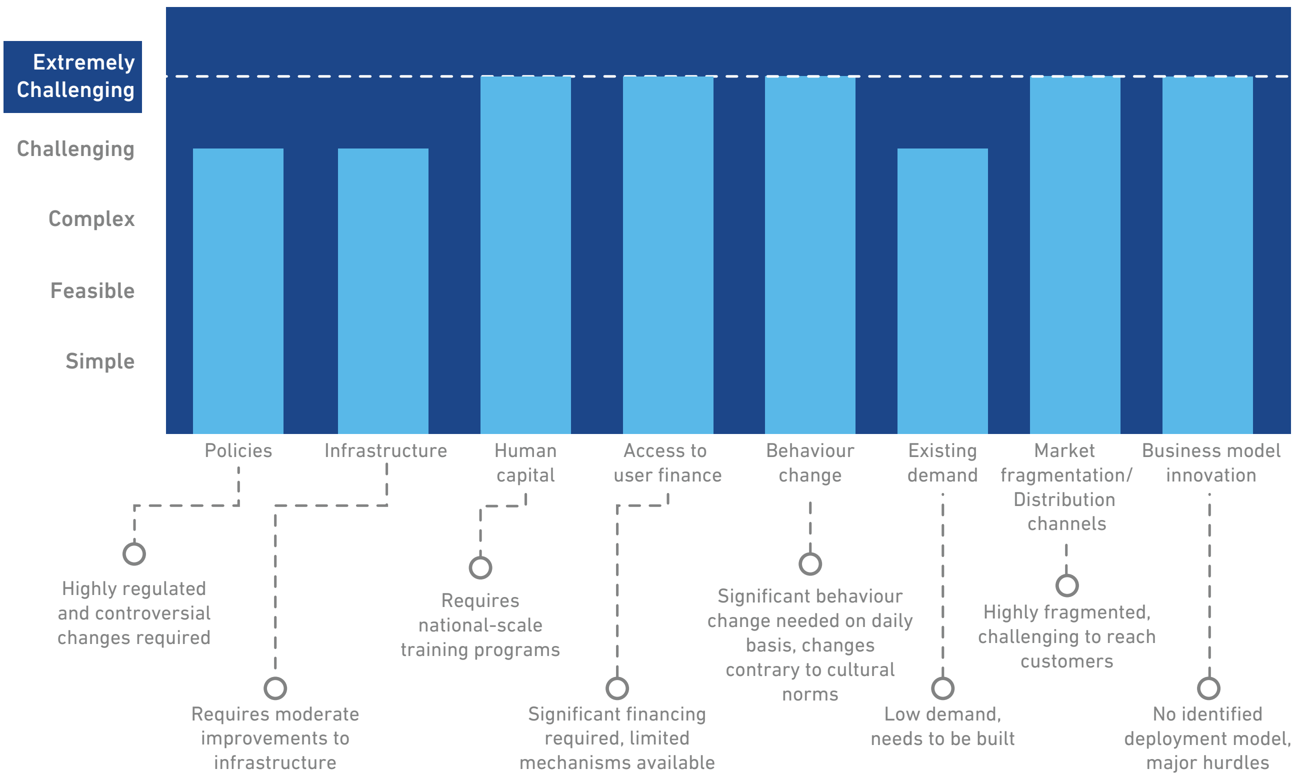
- builds on a digital platform that augments provider knowledge, experience and clinical workflows with decision support tools and diagnostic algorithms for more precise, patient-centered care; allows for remote consultation with clinicians and specialists; and enables data systems that collects and generate high-quality, timely information for decision-making and enables patient-centered care;

- costs approximately $10,000 to $15,000, based on our high-level assessment of financial feasibility, given published data on how much low-income rural families in sub-Saharan Africa and South Asia spend on healthcare.

While some of the listed devices are available at the appropriate price point, many are still priced for industrialized markets. Given the broad interest in developing individual devices, we believe enough of them are available at the right price point to begin assembling a suite of devices. There are also efforts underway to develop a digital platform to integrate the various devices. Many information and communication technology platforms exist or are in development, but most only focus on a particular area of the health delivery system or are focused around certain health conditions. It is important to note that there is no one-size-fits-all solution, particularly the design of the digital platform, across low-resource settings.

Even once such technology-enabled delivery system is developed, it will face a large number of deployment challenges. There is not enough public funding to procure a sufficient number of such clinics, the private market is underdeveloped and fragmented, and the regulatory requirements are unclear. Moreover, significant behavior change, encouraged by some form of insurance or financing to allow affordable access, is required for most low-income rural communities to seek regular and formal care. A dependable supply chain for consumables and maintenance of technologies will also be required. Hence, the difficulty of deployment will be EXTREMELY CHALLENGING.

Breakthrough 31: Difficulty of deployment



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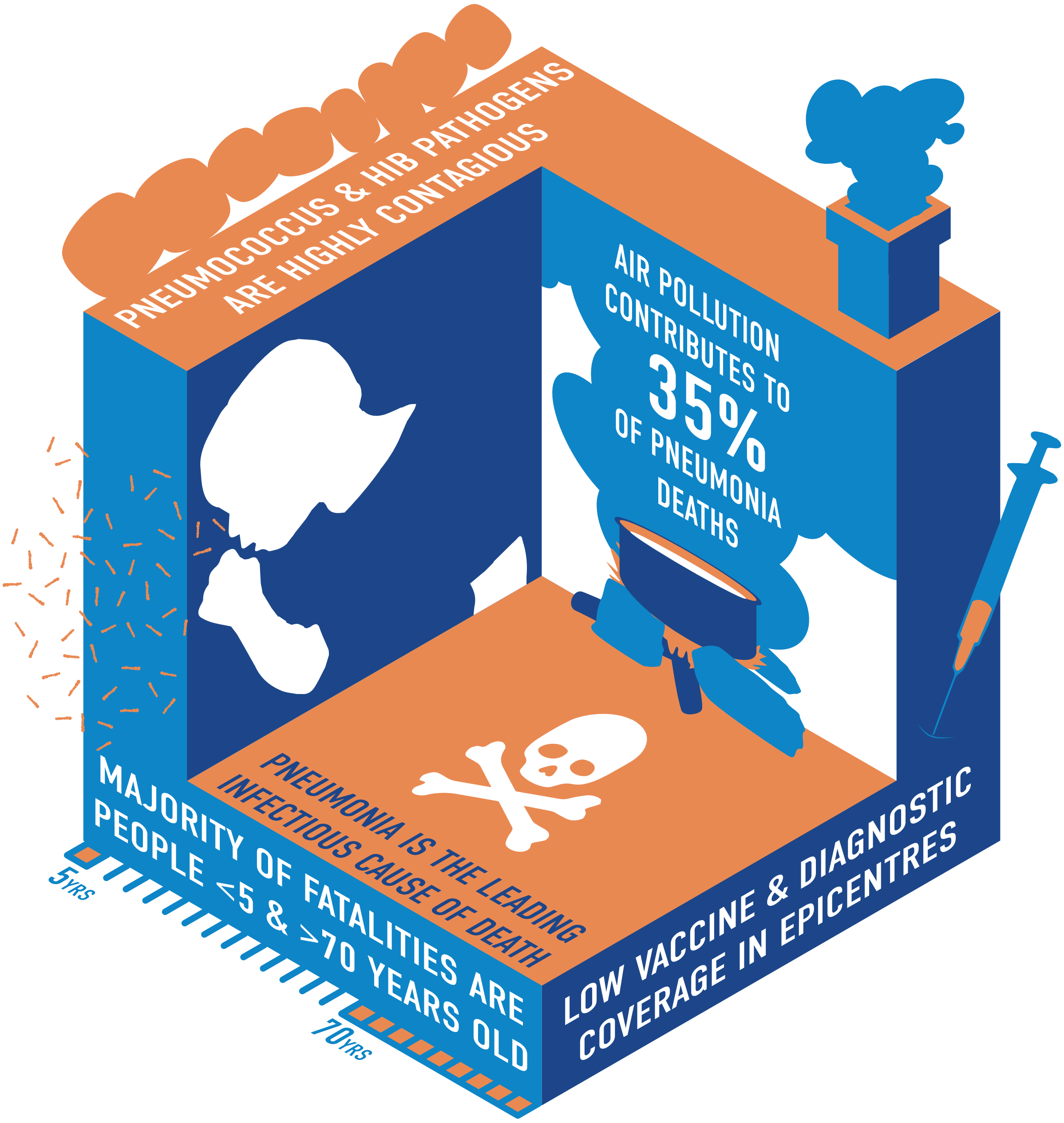


PNEUMONIA AND LOWER RESPIRATORY INFECTIONS

INTRODUCTION

Pneumonia, an infection of the lungs, is the leading cause of infectious mortality, killing an estimated 2.6 million people globally in 2017, according to the Global Burden of Disease (IHME GBD, 2017).

The burden of this disease falls heavily on two age groups: children under 5 with 809,000 deaths and adults aged over 70 years with 1.1 million deaths. In low-income countries, pneumonia is a leading cause of death among children, while in middle- and high-income countries deaths are concentrated among adults and elderly. Despite progress in reducing child pneumonia deaths, deaths among adults are increasing. Overall, pneumonia mortality rates have fallen more slowly than other major infectious diseases, by 25 percent between 1990 and 2017, compared to other top killers, such as HIV/AIDS (decreased by 47 percent) and diarrhea (decreased by 39 percent). Hence, the disease presents a major barrier to achieving at least two of the SDGs of reducing child deaths to at least 25 per 1,000 births (Goal 3.2), and to combatting the overall communicable disease burden (Goal 3.3) (Just Actions, 2018).

Streptococcus pneumoniae (pneumococcus) and *Hemophilus influenzae* type b (Hib), which are extremely common bacteria, cause the majority of pneumonia mortality. Pneumococcus, in particular, is frequently found in the nose and throats of otherwise healthy children. As a result of the ubiquity of these bacteria, risk factors that make children more susceptible to infection are critical drivers of pneumonia. Child wasting is the leading risk factor that underlies more than 50 percent of child pneumonia deaths, while air pollution (indoor and outdoor) contributes to 35 percent of total pneumonia deaths.

If pneumonia is identified early, antibiotics are an effective treatment, although only 30 percent of caretakers in low-resource settings can recognize just one of the many key symptoms and warning signs of pneumonia—a major impediment to

Moreover, just 60 percent of children under 5 years of age with symptoms of pneumonia are taken to an appropriate healthcare provider, according to UNICEF. Once infections are advanced, antibiotic therapy is less effective and oxygen therapy becomes necessary but is rarely available. Two highly effective vaccines, the Hib and pneumococcal conjugate vaccine (PCV), have been rolled out globally since 2000. Recent studies attributed the great reductions in deaths caused by these two bacteria from 2000 to 2015 to the vaccines (Wahl, et al., 2018).

In light of the above factors, eight technological breakthroughs can help reduce the disease burden from pneumonia and lower respiratory infections in low-resource settings:

- Breakthrough 23. Vaccines that can effectively control and eventually help eradicate the major infectious diseases of our time—HIV/AIDS, malaria, tuberculosis and pneumococcus
- Breakthrough 28. New generation of antibiotics capable of treating fast-mutating bacteria like MTB and MRSA
- Breakthrough 32. Low cost, novel diagnostics for pneumonia
- Breakthrough 33. Low cost, off-grid oxygen concentrators
- Breakthrough 46. Advanced biomass cookstoves that are desirable, affordable, robust and very clean
- Breakthrough 47. Novel ways of converting household or village waste products into clean cooking fuel or electricity
- Breakthrough 48. A mechanism to remove particulate emission from old trucks and other heavy-duty vehicles
- Breakthrough 49. Small-scale waste incinerators with efficient combustion and clean emissions

Pneumonia, an infection of the lungs, is the leading infectious cause of mortality globally, killing 2.68 million people in 2017. An estimated 810,000 of them are children under 5, almost all living in low- and middle-income countries. Another 1.1 million deaths are among adults aged over 70 across diverse geographies.

CORE FACTS AND ANALYSIS

1. Pneumonia is a serious lower respiratory infection that mainly affects children under 5

Pneumonia falls under the broader category of lower respiratory infections (LRIs), which can also occur in the trachea and bronchi. Upper respiratory infections (URIs), such as the common cold, occur in the nose, pharynx and larynx. LRIs are far more severe than URIs and are responsible for nearly all disease burden that results from respiratory infections.

Children under 5 are most affected by LRIs (**Exhibit 1**). The Global Burden of Disease 2010 study estimates that 65 percent of disease burden from LRIs in low- and middle-income countries (LMICs) occurs in children under 5 years, with 52 percent occurring in children less than a year old (IHME GBD, 2017). LRIs re-emerge as a major cause of mortality later in life, with pneumonia deaths rising for the elderly, even though impact on DALYs is low.

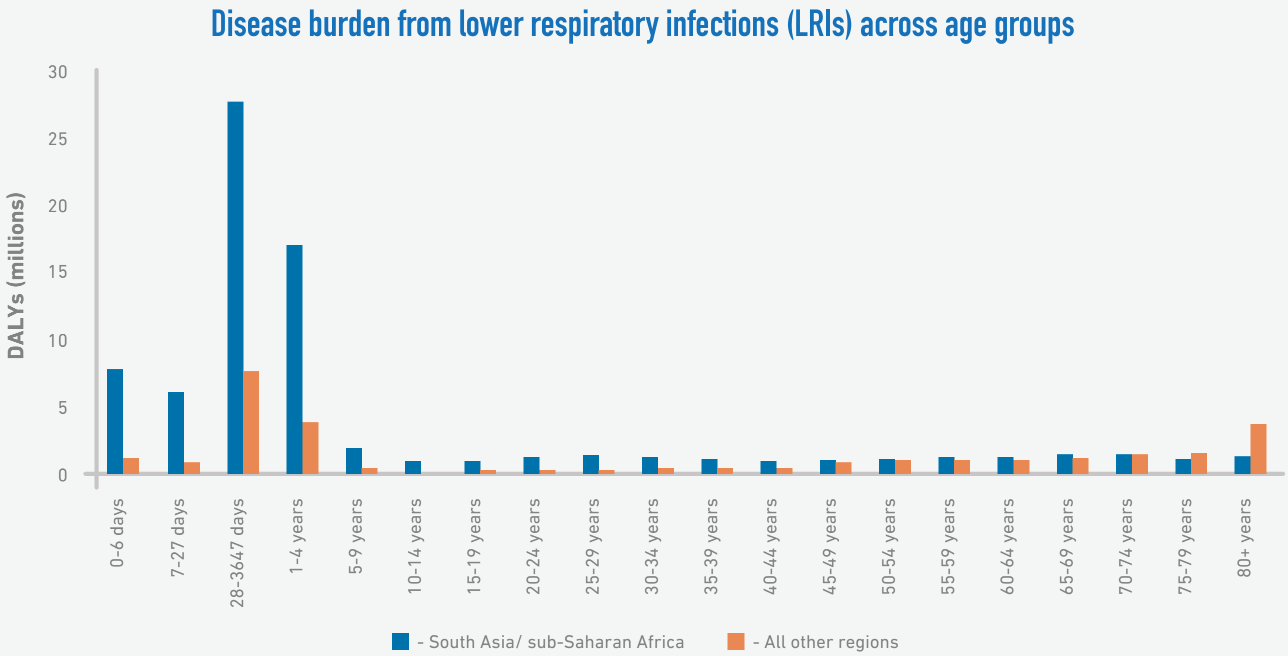


Exhibit 1: Disability adjusted life years (DALYs) for lower respiratory infection (LRIs) in South Asia and sub-Saharan Africa are highly concentrated in children under 5. (Source: IHME GBD, 2012)

Pneumonia is caused primarily by bacteria and viruses, with bacterial infections causing most severe cases, and viruses causing most non-severe cases. Often, pneumonia begins after an upper respiratory tract infection, with symptoms of pneumonia manifesting after two or three days of a cold or sore throat.

Of the two most common bacteria causing severe bacteria, the WHO and UNICEF estimate that pneumococcus may be the cause for more than half of severe cases of pneumonia and Hib could be responsible for 20 percent of the severe cases (WHO-UNICEF, 2006).

As of 2000, pneumococcus and Hib were responsible for 41 percent and 16 percent of pneumonia deaths, respectively, in children (Izadnegahdar, et al., 2013).

One vaccine study in The Gambia noted that vaccination against pneumococcus led to a 16 percent reduction in mortality from all causes (meaning, a 16 percent reduction in all childhood mortality, not just from pneumonia). The next most important pathogen is respiratory syncytial virus (RSV), which is an extremely common cause of pneumonia but generally causes less severe infections.

Prevalence of specific pathogens varies across regions, as do strains (more technically, serotypes) of pneumonia, but pneumococcus and Hib are considered to be the major drivers of mortality. The rollout of vaccines for these two bacteria will lead to the etiology of pneumonia shifting in coming years, likely toward more viral causes or toward non-vaccine strains[1].

Worldwide, pneumonia deaths occur in high-, middle- and low-income countries alike. Most pneumonia deaths in high income countries like Japan and USA occur among the elderly, while most deaths in low-income countries like Nigeria, Pakistan, DR Congo, Ethiopia, Bangladesh and Tanzania are among children under five years (Just Actions, 2018) (**Exhibit 2**).

Deaths due to pneumonia, across countries and ages

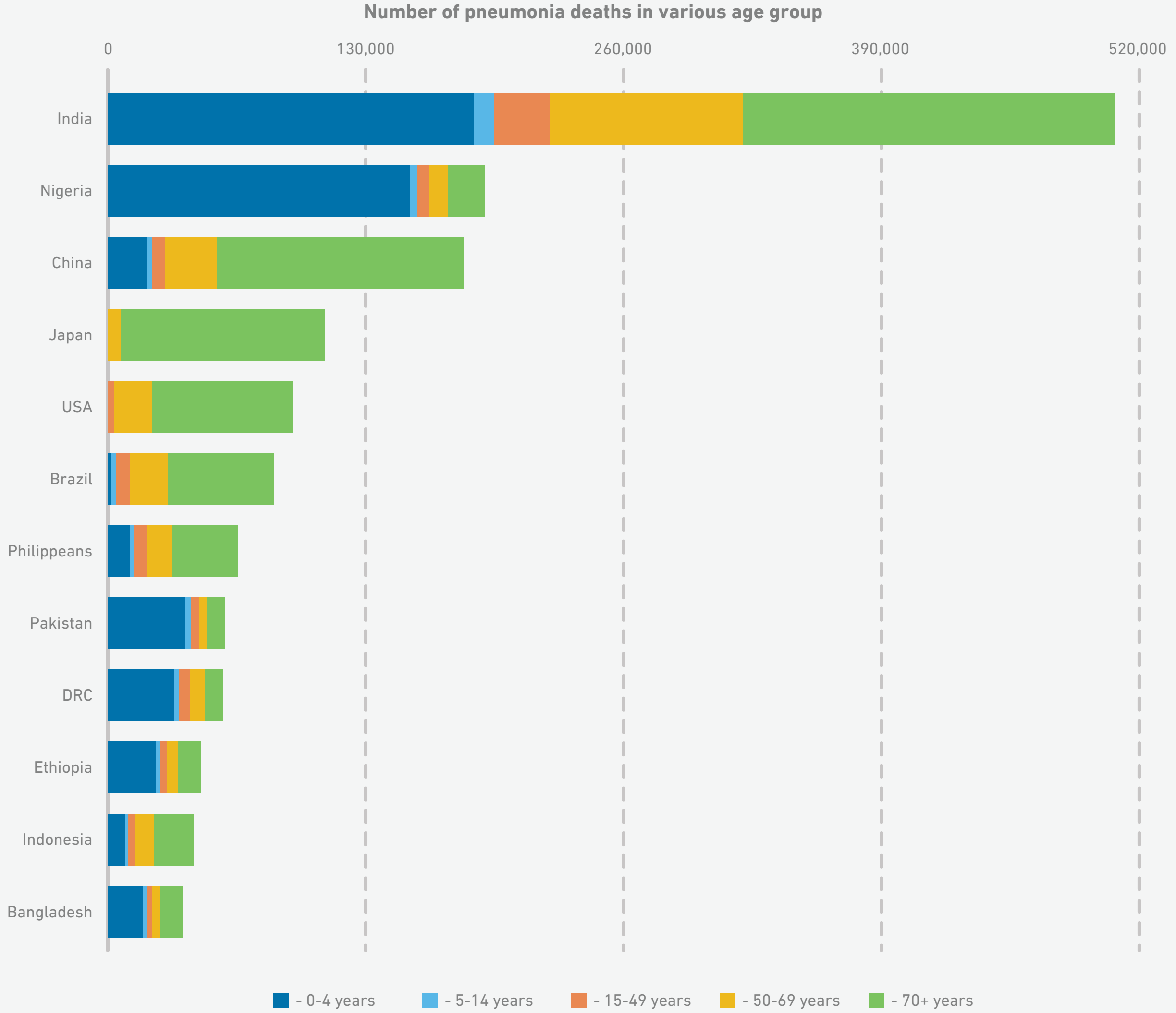


Exhibit 2: A dozen countries account for well over a half of all deaths from pneumonia. The age at deaths is typically lower in developing countries and higher in industrialized countries. (Source: Just Actions, 2018)

[1]In 2019, The Pneumonia Etiology Research for Child Health (PERCH) will release new data that aims to determine risk factors and etiology for severe and very severe pneumonia in children hospitalized in seven different countries including Bangladesh, Kenya, The Gambia, Mali, South Africa, Zambia and Thailand. Additionally, the Child Health and Mortality Prevention Surveillance (CHAMPS), aims to determine the causes of overall deaths in children and the etiology of fatal cases of pneumonia.

KEY CHALLENGES

Pneumonia is primarily driven by the ubiquity of the infecting pathogens and risk factors that increase susceptibility, especially among children and elderly adults, to these pathogens. Once children are infected, low awareness of the disease and its symptoms by caretakers and limited access to treatment are critical drivers of mortality.

Outdoor air pollution, smoking and alcohol consumption are major risk factors for adult pneumonia, and are contributing to the rapidly increasing rates of elderly deaths from pneumonia. Vaccination efforts against the two most important pneumonia-causing bacteria will markedly reduce disease burden in the coming years.

1. Many children are already carriers of pathogens that can cause pneumonia

The pathogens that cause pneumonia are highly contagious and very prevalent in the population. Pneumococci and Hib in particular colonize the nose and throat, where they reside harmlessly until the bacteria have an opportunity to penetrate the body's defense system and travel into the lungs, blood or cerebrospinal fluid. This is often spurred by another infection, usually URIs or inflammation of the lungs from smoke inhalation.

Poor populations in sub-Saharan Africa and South Asia often live in crowded and poorly ventilated conditions, which facilitates the spread of bacteria. Newborns can also become infected by exposure to microbes in the birth canal during delivery. The ubiquity of these pathogens is evident in the fact that children develop pneumonia very frequently. In LMICs, a child will develop an average of 0.29 episodes of pneumonia per year, compared with 0.05 episodes per child per year in developed countries (WHO-UNICEF, 2008).

2. Several risk factors increase vulnerability of children to respiratory infections, and worsen health outcomes

Although risk-related child pneumonia deaths are declining, major risk factors including malnutrition, preterm birth and suboptimal breastfeeding continue to contribute to childhood pneumonia deaths, with air pollution (outdoor air pollution in particular) being a growing contributor (**Exhibit 3**).

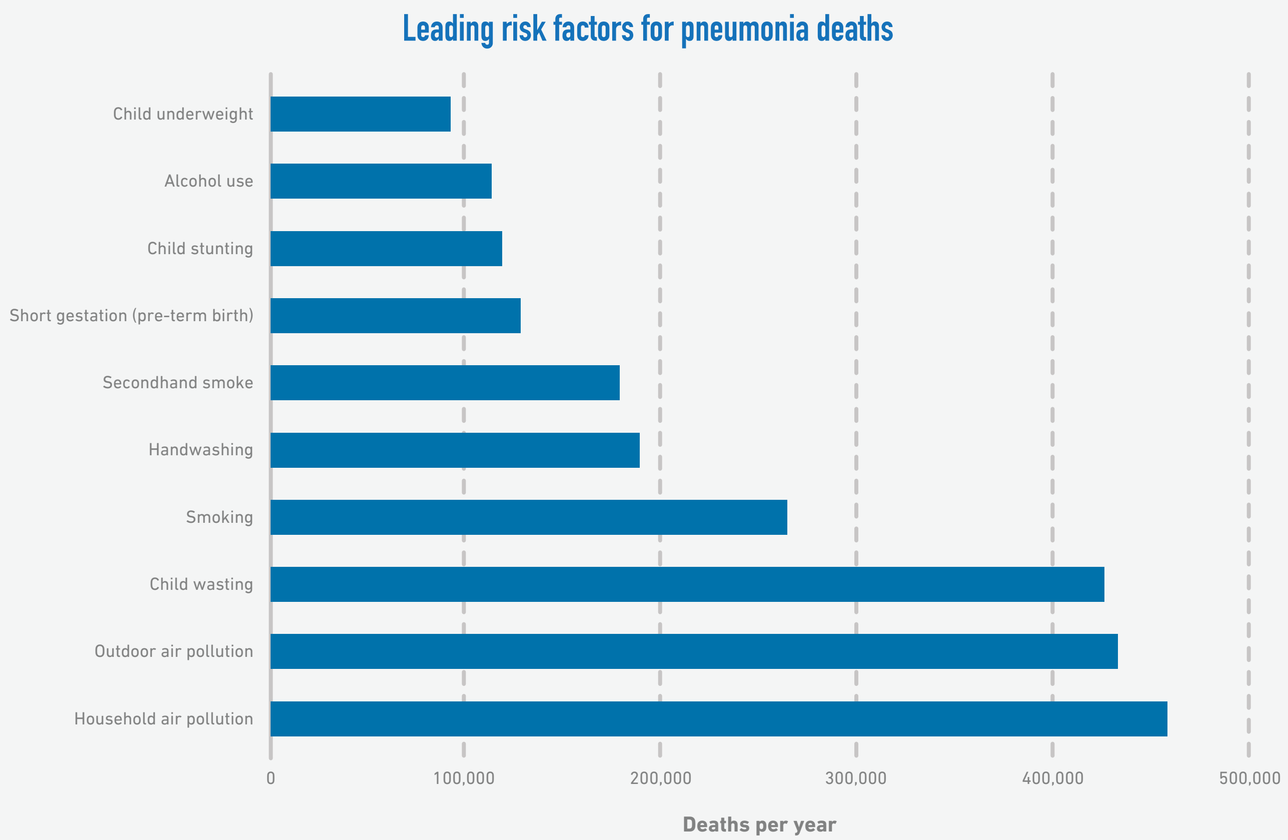


Exhibit 3: Leading risk factors for pneumonia deaths. (Source: Just Actions, 2018; IHME GBD, 2017)

Malnutrition (child wasting)

Malnutrition weakens a child's still-developing immune system, and significantly increases the risk of death from pneumonia. Studies have shown the prevalence of multiple pathogens (viral and bacterial) in children who die from pneumonia in hospital settings, but the interplay of these conditions and pathogens is not well understood. Childhood underweight, stunting, and in particular wasting, are estimated to be a factor in more than 80 percent of childhood deaths from pneumonia (Just Actions, 2018)

Second-hand smoke and household and outdoor air pollution

Outdoor air pollution, household air pollution and tobacco smoke cause inflammation of the lungs, which increases susceptibility to infections. The Global Burden of Disease study estimates that more than 28 percent of LRI burden can be attributed to indoor air pollution from solid fuels (IHME GBD, 2017).

Forty-three percent of the population in developing Asia, and almost 80 percent in sub-Saharan Africa still rely on biomass fuels for cooking (IEA, 2017), which are burned indoors without chimneys or adequate ventilation, causing high levels of particulate matter inside homes. Smoking is also highly correlated with increased rates of pneumonia. Incidence rates for pneumococcus are 1.9-4.1 times higher for active smokers and 1.9 times higher for children of smokers relative to non-smokers (van Zyl-Smit, et al., 2011).

Suboptimal breastfeeding

Breast milk provides infants with antibodies that help protect them until their immune systems develop more fully. The WHO recommends exclusively breastfeeding infants for the first six months of life, and partial breastfeeding for the following 18 months accompanied with age appropriate foods.

Infants who are not breastfed in the first six months are six times more likely to die from pneumonia as children who are even partially breastfed (Black, et al., 2013). Suboptimal breastfeeding contributes to 7.45 percent of LRI-related deaths in children under 5 (IHME GBD, 2017). Globally, only 30 percent of infants are exclusively breastfed (WHO, 2016).

HIV

Children with HIV, due to increased susceptibility to pathogens, are 40 to 50 times more likely to contract pneumonia, and three to six times more likely to die of the disease (World Lung Foundation, 2010). In sub-Saharan Africa, nearly 1.6 million children live with HIV (UNAIDS, 2017) .

3. Low vaccination coverage, particularly for pneumococcal pneumonia

Vaccines are available for both Hib and pneumococcus, the latter of which is fairly new and have only been available in low- and middle- income countries since 2009. While the rollout for the pneumococcus vaccine—pneumococcal conjugate vaccine (PCV)—has been rapid, its coverage remains low (most countries have less than 90 percent coverage) relative to the large potential benefit it can deliver.

Globally, 44 percent of children are protected with three doses of the PCV, 72 percent of children receive three doses of the Hib vaccine and 67 percent receive two doses of the measles vaccine, according to the WHO. Among the high-burden pneumonia countries, PCV coverage is below 44 percent in India, China, Nigeria, Thailand and Indonesia. Although the price of PCV has already been brought down by roughly 90 percent, it still costs $2.95 per dose, compared with other vaccines that cost between a few cents to a dollar.

According to one manufacturer, it takes nearly 2.5 years to make a dose of multi-valent conjugate vaccines from start to finish. Currently two companies supply GAVI with PCV, but total demand exceeds their production capacities. To help these companies ramp up production GAVI, in 2010, introduced an Advanced Market Commitment (AMC) pilot to provide guaranteed purchasing and create demand stability.

An evaluation of the AMC pilot in 2015 showed that collective efforts of the AMC and PneumoADIP, Gavi's Accelerated Vaccine Introduction initiative, and strong WHO recommendation for PCV, greatly accelerated PCV supply availability, coverage and Gavi country demand (The Boston Consulting Group, 2015).

4. Caretakers do not recognize early symptoms and seek treatment or medical care only when the infection is too advanced

Parents often do not recognize the most common early symptoms of pneumonia—difficult and fast breathing. A study published in 2017 found that only 30 percent of caregivers in sub-Saharan Africa recognize either one of these key early warning signs of pneumonia (Noordam, et al., 2017).

This is driven by the subtlety of these symptoms, and further compounded by the fact that often pneumonia begins as a URI, with obvious symptoms of pneumonia presenting only after a few days. Parents are more likely to react to severe symptoms, such as fever or altered mental state, at which point antibiotic therapy is less effective and children may need more supportive care like oxygen therapy.

An additional challenge is that even when a child is recognized to have pneumonia, lack of access to affordable healthcare and lack of awareness about the severity of the disease means that the child may still not be taken to receive appropriate treatment. It is estimated that only 60 percent of children under 5 in LMICs are taken to an appropriate care provider when symptoms are present (WHO-UNICEF, 2012), with rates as low as 24 percent in a high burden country like Nigeria.

Apart from costs of seeking care, studies have shown that improving mother's literacy and education levels have a direct impact on survival through childhood (Uwemedimo, et al., 2018).

5. Medical facilities do not have equipment to provide pulse oximetry or oxygen therapy

Oxygen therapy is a powerful intervention for children with severe pneumonia and has been shown to reduce case fatality rates by as much as 35 percent in LMICs (Duke, et al., 2008). However, current oxygen delivery systems are not appropriate for low-resource settings. Oxygen cylinders are difficult to transport, likely to run out and require a logistics system to ensure they are continually supplied to healthcare facilities, especially for those in remote areas.

Oxygen concentrators, the alternative, are expensive and require a reliable electricity source, training and ongoing maintenance that hospital staff are rarely able to perform.

Administering oxygen requires ongoing patient monitoring, which most clinics and hospitals in small towns and villages lack the staff for.

Either system requires a pulse oximeter to measure oxygen in the bloodstream and a splitter so oxygen can flow from a single source to multiple patients. Cheap pulse oximeters exist on the market, but are rarely found in hospitals or clinics. Splitters by contrast are expensive and can be challenging to find. Notably, oxygen therapy is rarely seen as a high priority need. This explains its scarcity in hospitals and near absence from clinics. Most concentrators, particularly in sub-Saharan Africa, have been donated with insufficient training imparted to those operating them. A 2018 study by the Clinton Health Access Initiative (CHAI, 2018) of 78 hospitals across three states in Nigeria found that only 2 percent had pulse oximeters and 25 percent of pediatric wards had functional oxygen systems. In Ethiopia, the situation was only slightly better. 45 percent of hospital pediatric wards had pulse oximeters and 64 percent had fully functional oxygen delivery devices.

6. Medical facilities lack equipment necessary to make an accurate diagnosis

Chest radiographs are considered the gold standard for diagnosing pneumonia but are not practical in low-resource settings. Instead, care providers rely on clinical diagnoses, and while this practice does not drive mortality (as clinical diagnosis is usually sufficient) it does tend to result in over-treatment. The 2018 CHAI study mentioned above also found that among the children with pneumonia who reached a health facility in Nigeria, 47 percent of non-severe pneumonia cases were missed, only 4 percent of severe pneumonia cases were correctly diagnosed and just one in 10 children received the oxygen they needed.

In particular, cases of viral pneumonia and upper respiratory infections may be prescribed antibiotics, which are ineffective and can lead to drug resistance. Recent studies have shown lung ultrasound (LUS) as a feasible alternative diagnostic to chest radiographs, some even suggest that LUS demonstrate superior sensitivity although more research is necessary to differentiate between bacterial from viral pneumonia (Balk et al., 2018). Improved diagnostics will also allow better understanding of the epidemiology of the disease and its variations across geographies.

SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

As the above analysis shows, improvements in care seeking behavior can greatly reduce mortality rates for children under 5 in high burden countries. Behavioral risks can be addressed through education and awareness, including improving mother's literacy, teaching parents and caregivers to recognize and act on early symptoms of pneumonia and preventing malnutrition.

Household air pollution is driven largely by cooking activities, particularly with solid fuel sources. Among devices that can help reduce household air pollution are advanced biomass cookstoves, gas stoves, electric stoves and electric rice cookers in regions with high rice consumption. Please see more details on indoor air pollution and cookstove innovations in the Clean Cooking section of the Access to Energy chapter.

One major risk factor that is on the rise is outdoor air pollution, the negative effects of which are well-beyond pneumonia deaths alone. Reduction in ambient air pollution will be key to controlling both child and adult pneumonia. Please see more details in the Resilience to Global Change chapter.

Vaccinations are an effective solution for stemming pneumonia cases but are dependent on sustaining and increasing coverage, which is primarily a policy and supply issue. Quick gains can be made by further reducing the cost of PCV, which is driven by the complexity of the manufacturing process as well as the fact that it is proprietary.

While the price of PCV has dropped dramatically, additional efforts are needed to bring it down further from its current cost of $2.95 a dose. An additional and significant challenge will soon emerge for countries that graduate out of Gavi support and must then finance the purchase of vaccines independently.

Affordability and quality of care are equally important in ensuring accurate diagnosis and effective treatment once a sick child is brought in. Increased focus on quality of care at the primary level, and current momentum in implementing Universal Health Coverage (UHC), will improve accessibility of pneumonia diagnosis and treatment, thus contributing to reducing pneumonia mortality.

Frontline providers need to be better equipped with diagnostic and curative technologies to ensure timely care. Increased R&D investments is needed for the development of rapid diagnostic tests, pulse oximetry, respiratory rate monitors and improved oxygen delivery.

There are eight scientific and technological breakthroughs that can significantly reduce the burden of pneumonia and lower respiratory infections.

Breakthroughs:

1	2	3	4	5	6	7	8	9	10
11	12	13	14	15	16	17	18	19	20
21	22	23	24	25	26	27	28	29	30
31	32	33	34	35	36	37	38	39	40
41	42	43	44	45	46	47	48	49	50

23 Vaccines that can effectively control and eventually help eradicate the major infectious diseases of our time—HIV/AIDS, malaria, tuberculosis and pneumococcus

Collectively, HIV/AIDS, malaria, tuberculosis and pneumonia kill more than five million people a year, and represent a significant disease burden for low income populations in sub-Saharan Africa and South Asia. Effective and affordable vaccines for these diseases do not exist yet due to the intrinsic complexity of the pathogens causing them, and a lack of understanding of the specific mechanisms through which our immune systems protect against these diseases. The process of vaccine development—basic research on disease etiology, vaccine construction, pre-clinical and clinical testing—is technically challenging, expensive and time consuming.

23d. An improved, lower cost vaccine for pneumococcus

UNICEF and the WHO estimate that the pneumococcus bacteria (Streptococcus pneumonia) is the pathogen causing more than half of severe cases of pneumonia. The WHO recommends that vaccination against pneumococcus should be added to all national immunization programs, and particularly in countries with high child mortality. The availability of low-cost, effective pneumonia vaccines and their rollout to low- and middle-income countries would be a significant advancement and has the opportunity to save an estimated 1.5 million lives through 2020.

The current vaccine for pneumonia—pneumococcal conjugate vaccine (PCV)—is a complex vaccine, designed to provide protection against multiple strains of pneumonia. More than 90 strains of pneumonia (referred to as serotypes) exist. Each of these present different antigens, which the immune system uses to recognize the bacteria and mount a defense. Consequently, vaccination against one strain often does not provide protection against another. To provide broader protection, PCV contains antigens for multiple strains (generally polysaccharides), which are attached to a carrier protein molecule. This conjugation process is complex and hence the vaccine is expensive relative to other types of vaccines. Currently available vaccines provide protection against as many as 13 strains depending on the manufacturer (CDC, 2016).

Deployment and adoption of improved pneumonia vaccines face two critical challenges. First, even though the price per vaccination has come down from $3.50 to $2.95 (future price is expected to reduce to $2.90), the current conjugate vaccines are still very expensive. While this is 90 percent less than the cost they are sold at in developed countries, PCV remains the single most expensive vaccine GAVI provides. Other vaccines, by contrast, can cost as little as a few pennies. This high price is due to the complexity of the conjugation process and the fact that there are only two manufacturers. (There are other manufacturers who have entered into agreement with GAVI, but do not yet have WHO-prequalified vaccines.) While the cost may be a manageable challenge for GAVI, it poses a significant problem for countries that graduate out of GAVI support, and must then procure vaccines on their own.

Current State

Development Stage: R&D

Time to market (years): <3 | 4-6 | 7-10 | 10+

Deployment: Complex

Associated 50BT Chapters

Global Health

SDG Alignment

3 GOOD HEALTH AND WELL-BEING

Impact

Lives Saved (# of People/Year): <1M | 10M+ | 100M+ | 1B+

Health Improved (# of People): <1M | 10M+ | 100M+ | 1B+

Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

Second, current vaccines do not provide protection against all strains of pneumonia. These strains, and the importance of each strain, vary by region. This means that protection against pneumonia is incomplete on an individual level, and in some regions the strain coverage is suboptimal. There is also concern about strain replacement, where strains that are currently less significant causes of mortality may become more important as a result of protection against strains that are included in the vaccine.

These challenges can be addressed in two ways. The first would be an advancement in the conjugation process. This will allow manufacturers to provide the vaccine at a lower cost, and increase the likelihood that other manufacturers will be able to offer competing vaccines. It may also allow the development of vaccines that can provide protection against a larger number of strains. Single dose vaccines that do not require refrigeration will also lower costs.

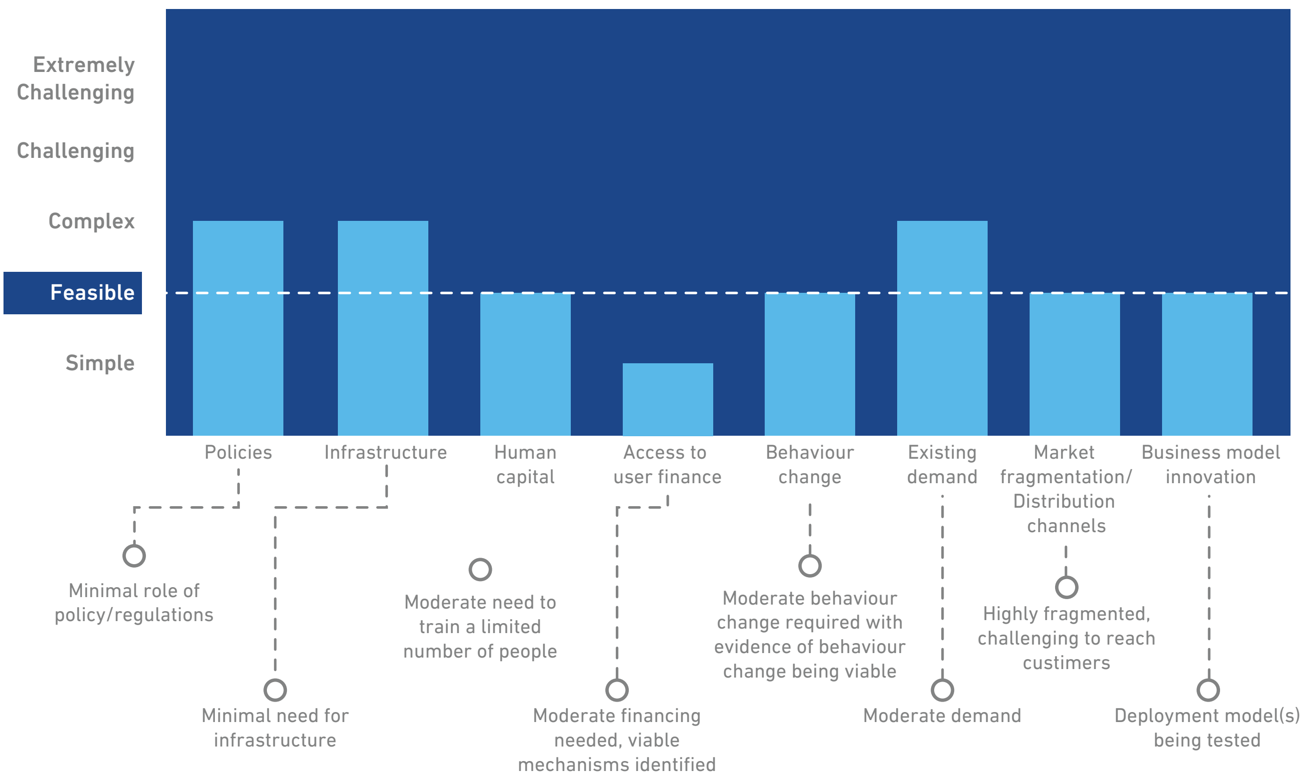
The second way is the development of an entirely new type of vaccine. This would not be a conjugate vaccine, and instead would produce immunity through another mechanism, most likely through a common protein that is present in all strains of pneumonia.

While this opportunity could be revolutionary, providing broader protection and likely a lower cost, the appropriate protein has not been identified yet. Significant primary research still needs to be conducted.

Deployment of new vaccines

Once any of these vaccines is developed, it can be deployed to children through existing, reasonably established, vaccine delivery channels. However, there are few mechanisms for delivering vaccines to adolescents and adults, and successful vaccination campaigns for these population segments would require significant government coordination, behavior change and financial investment. Furthermore, even today vaccine delivery remains a challenge in many remote locations where supporting infrastructure like cold storage facilities are either few or non-existent. While vaccines are expected to be made available to patients at a low cost, financing for the vaccines by national governments or international donors would need to be secured in order to support widespread distribution. Policy changes would also need to support its introduction and distribution through public health systems. Based on the above assessment, the projected time to market readiness is more than ten years, and the difficulty for deployment is FEASIBLE.

Breakthrough 23: Difficulty of deployment



28 New generation of antibiotics capable of treating fast-mutating bacteria like MTB and MRSA

Antibiotic resistance is reaching dangerously high levels in all parts of the world, with some of the most common infections becoming difficult to treat. This occurs when bacteria develop the ability to defeat the drugs that are designed to kill them, making the drugs ineffective.

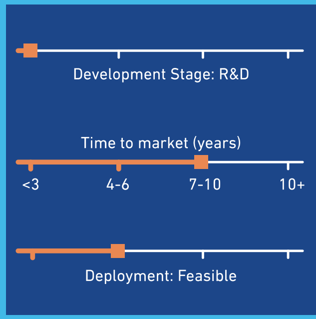
Antibiotic resistance does not mean the body becomes resistant to antibiotics; instead, it means that bacteria have become resistant to the drugs designed to kill them. Each year, hundreds of thousands of people die from drug-resistant strains of common bacterial infections, and the number is increasing steadily. Important examples of resistant bacteria include:

- Multidrug-resistant tuberculosis (MDR-TB), a form of TB that is resistant to the two most powerful anti-TB drugs, and extensively drug-resistant tuberculosis (XDR-TB) that is resistant to at least four of the core anti-TB drugs.
- The bacteria *E. coli*, which is gaining resistance to fluoroquinolone antibiotics that are widely used to treat urinary tract infections.
- The common intestinal bacteria *Klebsiella pneumoniae*, which is becoming resistant to a last resort treatment, carbapenem antibiotics, in all regions of the world.
- The bacteria *Staphlylococcus aureus*, which has widespread resistance to first-line drugs, causing growing numbers of deaths due to MRSA (methicillin-resistant *Staphylococcus aureus*).
- The bacteria *Neisseria gonorrhoeae*, responsible for the sexually-transmitted disease gonorrhea, is gaining resistance to the last resort medicine, third generation cephalosporin antibiotics, in at least 10 countries.

Antibiotic resistance is a complex problem that is driven by many interconnected factors, and coordinated effort is required to minimize its emergence and spread. Without urgent and effective action, there is a risk of returning to an era in which common infections and minor injuries can cause death.

Action on several fronts is needed, including improving awareness and understanding of antibiotic resistance, strengthening surveillance and research, reducing the incidence of infection through improved hygiene and sanitation, improving diagnostics to reduce unnecessary prescription of antibiotics, and optimizing the use of existing antibiotic medicines. Critically, there is also a need for a new generation of antibiotics that are effective against the bacteria that are resistant to current drugs.

Current State



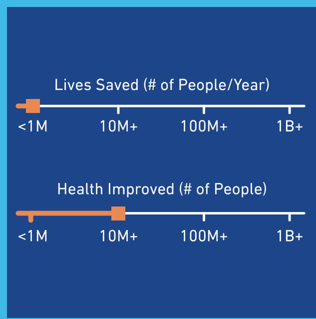
Associated 50BT Chapters

Global Health

SDG Alignment

3 GOOD HEALTH AND WELL-BEING

Impact



Commercial Attractiveness

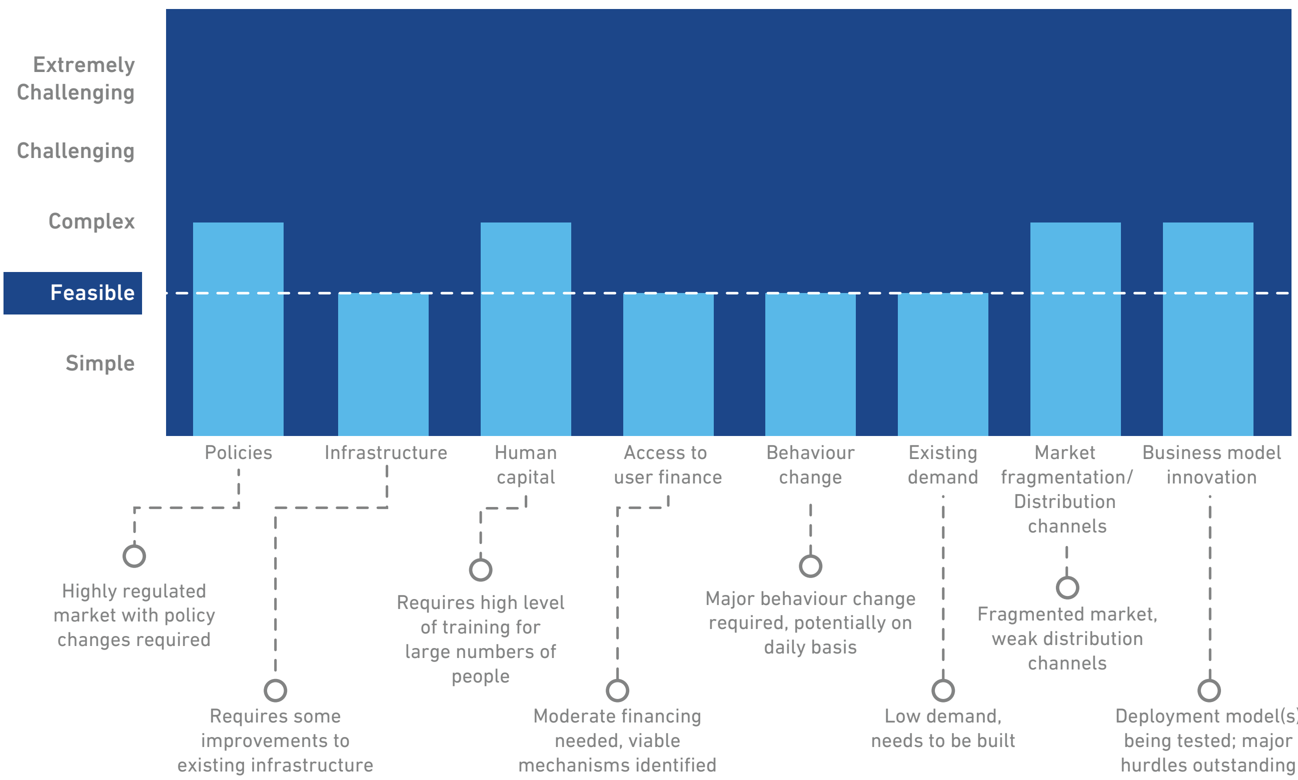
- **Attractive for industrialized markets (high profits)**
- Attractive for emerging markets (lower profits)
- Emerging markets potential; requires derisking (sustainable)
- Non-commercial (unprofitable)

While there are some new antibiotics in development, none of them are expected to be effective against the most dangerous forms of resistant bacteria. There is a need for better incentives to promote investment in new drugs, because the commercial return on R&D investment in new antibiotics is currently unattractive.

Although the total market for antibiotics is relatively large, with annual sales of about $40 billion, only about $4.7 billion of this is from sales of patented antibiotics. Between 2003 and 2013, less than 5 percent of venture capital investment in pharmaceutical R&D was for development of antimicrobials.

Even with adequate funding, the development of improved antibiotics is scientifically challenging, and we expect it will take up to 10 years for new drugs to be market ready. Once developed, the deployment of new antibiotics can use existing supply chains and is expected to be FEASIBLE.

Breakthrough 28: Difficulty of deployment



32 Low cost, novel diagnostics for pneumonia

Pneumonia is currently diagnosed by a clinic consultation, not by a specific diagnostic test. This makes it difficult for care providers to identify different clinical scenarios, such as whether a patient has viral or bacterial pneumonia or quickly determine the infecting pathogen, which can help indicate the potential severity of the illness. Accurate diagnostics also has the potential to reduce medicine wastage, and reduce the risk of antimicrobial resistance.

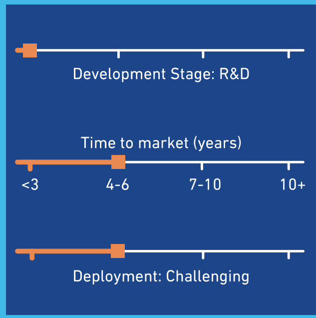
While the gold standard for diagnosis is through a chest X-ray, the imaging test is not practical for clinics in low- and middle-income countries. Most diagnoses are made based on evaluation of respiratory rate and chest in-drawing. The technological challenges and time to market for a novel pneumonia diagnostic vary depending on what the clinical goal of the diagnostic would be.

A urine-based diagnostic for pneumococcus bacteria, for example, is now available. However, a diagnostic that can discriminate between bacterial and viral pneumonia, and severe and non-severe pneumonia, is much more technologically complex; in some cases, biomarkers have not been identified yet. The primary benefit of diagnostics that provide deeper information about the infecting pathogen would likely be a better understanding of the disease and its epidemiology, as opposed to reduced mortality.

Reducing mortality from severe pneumonia would likely rely on improvements in pulse oximetry and respiratory rate timers. Both are effective technologies, and while they could be refined further, and can be incorporated into multimodal devices that also measure other vitals, the key challenge is distribution to, and adoption at, the clinics, as opposed to major improvements in either the cost or technology.

However, even the impact from better oximetry and respiratory rate timers, or any accurate rapid diagnostic tests are likely muted, as a reduction in mortality will only happen if patients seek care, are diagnosed in time and in some cases have subsequent access to oxygen therapy, which is currently rare.

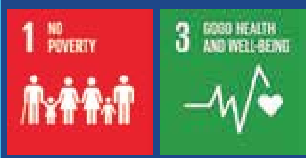
Current State



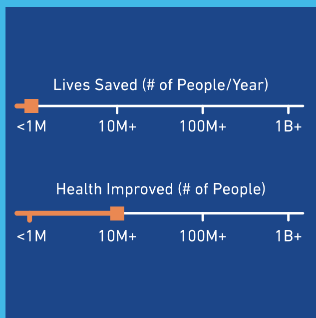
Associated 50BT Chapters

Global Health

SDG Alignment



Impact



Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

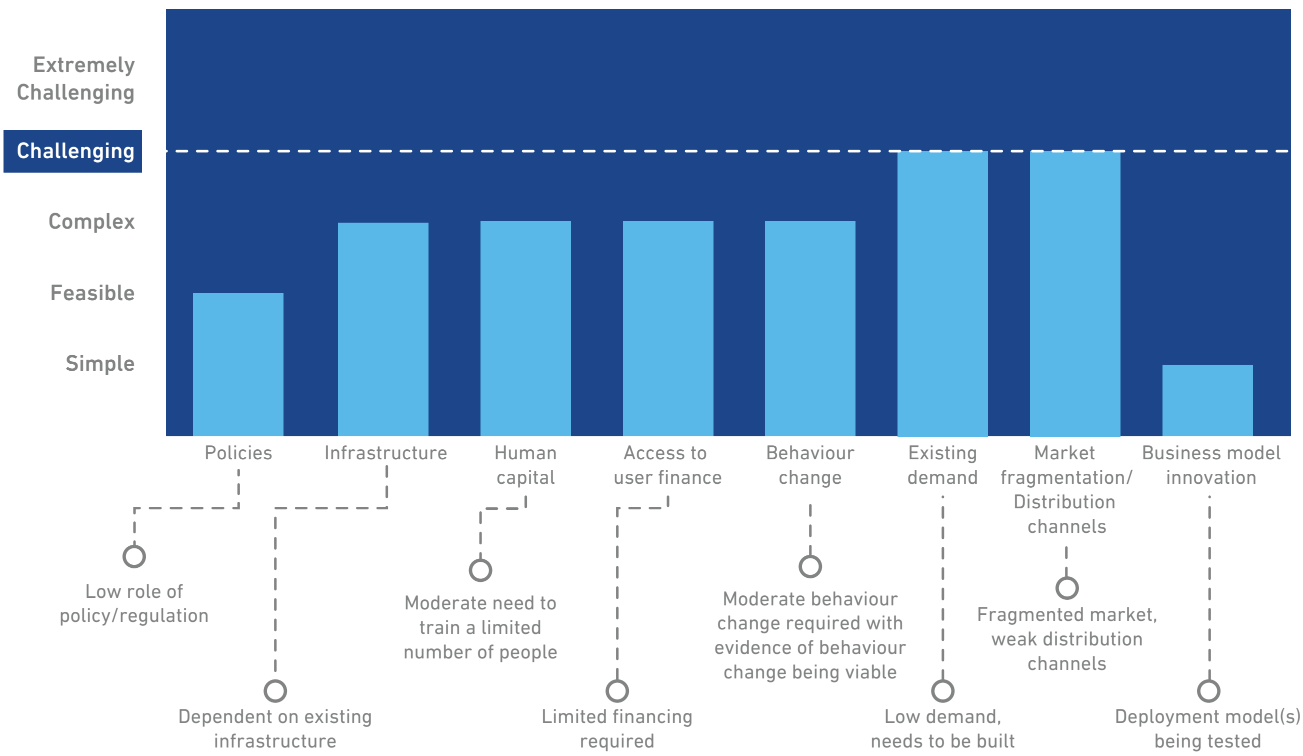
Ease of deployment varies by diagnostic type. In general, simpler devices like improved respiratory rate timers and pulse oximeters have fewer deployment barriers; they need less access to grid energy, less access to financing and less training. In each case however, lack of existing demand and market fragmentation are major hurdles in achieving scale.

There is currently no existing base for deployment of pneumonia diagnostics to rural clinics where they are most needed, so distribution of a new diagnostic would require creation of new channels as well as educating healthcare workers on the need and value of pneumonia diagnostics.

Since clinical diagnosis generally remains effective, and the downside to clinical diagnosis (like drug resistance) is neither immediate nor obvious, it will be challenging to convince healthcare funders and clinicians to devote scarce resources to purchasing and using pneumonia diagnostics.

Based on the above assessment, improved diagnostics for pneumonia are likely to be market ready in four to six years, and the difficulty of deployment is CHALLENGING.

Breakthrough 32: Difficulty of deployment



33 Low cost, off-grid oxygen concentrators

Oxygen concentrators create oxygen-enriched airflow from ambient air, and are often the most practical solution to provide critically needed oxygen therapy at hospitals, clinics and potentially even outposts (as opposed to oxygen cylinders, which require robust logistics systems). Despite the fact that oxygen therapy reduces case fatality rate of children with severe pneumonia by as much as 35 percent in low- and middle-income countries (Duke, et al., 2008), there is a noticeable lack of awareness of the opportunity that oxygen therapy could provide.

Many hospitals often do not realize that pneumonia is one of their biggest killers, or understand the sheer reduction in case fatality they could achieve with oxygen therapy.

Oxygen concentrators are an existing technology that must be redesigned to be more appropriate for low-resource settings. Concentrators usually cost several hundred to over a thousand dollars, need constant energy supply to operate and require sophisticated maintenance.

A novel oxygen concentrator would have to be dramatically cheaper, robust, and easy to maintain, or delivered in tandem with a service model. It should be able to provide oxygen in the absence of reliable grid power. This may require an oxygen storage system or a battery. Oxygen provision needs to be delivered alongside oxygen measurement. An effective oxygen concentrator should also incorporate an oximeter.

Current State

Development Stage: R&D

Time to market (years)

<3 4-6 7-10 10+

Deployment: Challenging

Associated 50BT Chapters

Global Health

SDG Alignment

Impact

Lives Saved (# of People/Year)

<1M 10M+ 100M+ 1B+

Health Improved (# of People)

<1M 10M+ 100M+ 1B+

Commercial Attractiveness

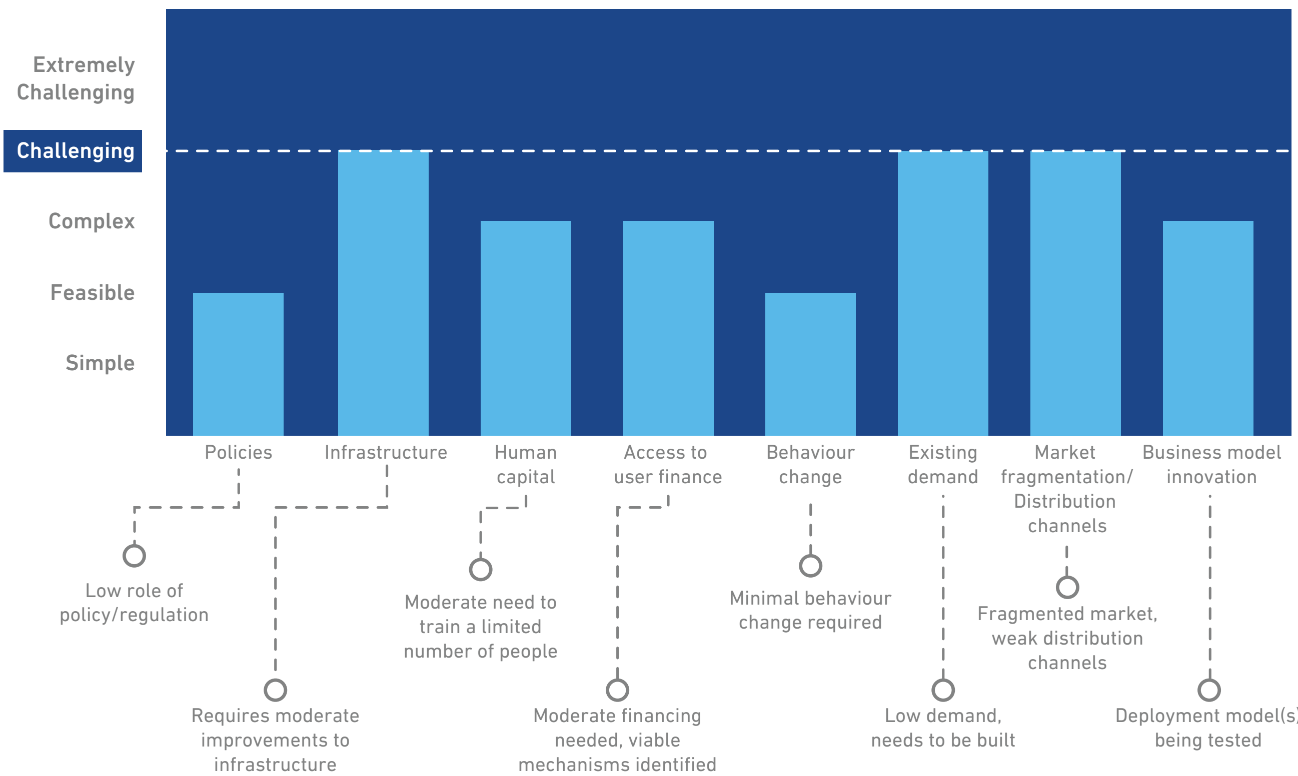
- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

While there are no major fundamental scientific or engineering challenges that need to be overcome, design must be approached from a perspective of cost, durability, ease of maintenance and minimal dependence on infrastructure. Given the lack of priority for oxygen therapy at the healthcare policy level as well as on-ground at clinics and hospitals, the current market is small, and demand will have to be built.

At the clinic level, distribution channels are not well defined, and while there is some centralization for purchasing through ministries of health, achieving wide-scale distribution is challenging. Compared with oxygen cylinders, oxygen concentrators are sophisticated and expensive devices and will require a greater element of training and financing.

The projected time to market readiness is four to six years. Based on existing and emerging technologies, the difficulty of deployment is CHALLENGING.

Breakthrough 33: Difficulty of deployment



46 Advanced biomass cookstoves that are desirable, affordable, robust and very clean

Biomass such as wood, straw and dung is the primary cooking fuel for about 2.5 billion people, or a third of the world's population. Household air pollution caused by these fuels causes millions of deaths each year, due to illnesses such as lower respiratory infection, lung cancer, ischemic heart disease, stroke and chronic obstructive pulmonary disease.

Despite major initiatives to extend access to cleaner cooking fuels like gas and electricity, more households currently use solid fuels for cooking today than at any time in human history, due to growing population size. It is likely that billions of people will continue to cook with biomass for the foreseeable future, due to economic, logistical and cultural barriers to change.

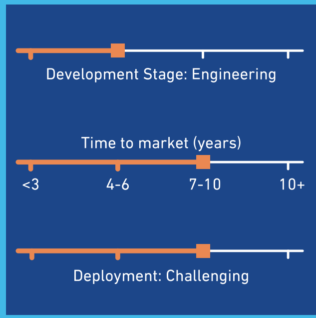
Design and deployment of improved biomass cookstoves has been an important goal of global development efforts for many decades. A wide range of biomass cookstove improvements have been proposed and trialed, with significant reduction in emissions of air pollutants like particulate matter and carbon monoxide. Some of these improved stoves have reached moderate levels of deployment in low-income countries.

However, recent research has shown that the exposure-response relationship for household air pollution is non-linear, thus the large reduction in emissions from current improved stoves brings only a modest decrease in health risk. To effectively eliminate the serious health risk of household air pollution, stove emissions must be reduced much further than is possible with current biomass stove designs.

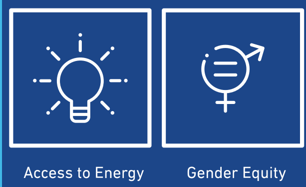
A new generation of advanced biomass cookstoves is needed, with greatly reduced emissions so they have low health risk that is comparable to other clean cooking solutions like gas and electricity. Advanced biomass cookstoves typically use complex, multiple stage combustion methods in order to burn fuel efficiently and minimize harmful emissions.

Current versions of advanced biomass cookstoves often have high upfront costs, offer less cooking flexibility, need pre-processed fuels and require an electricity supply to power built-in fans, yet still do not reliably achieve emission levels low enough to eliminate health risk in people's kitchens.

Current State

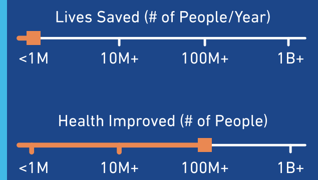


Associated 50BT Chapters



SDG Alignment

Impact



Commercial Attractiveness

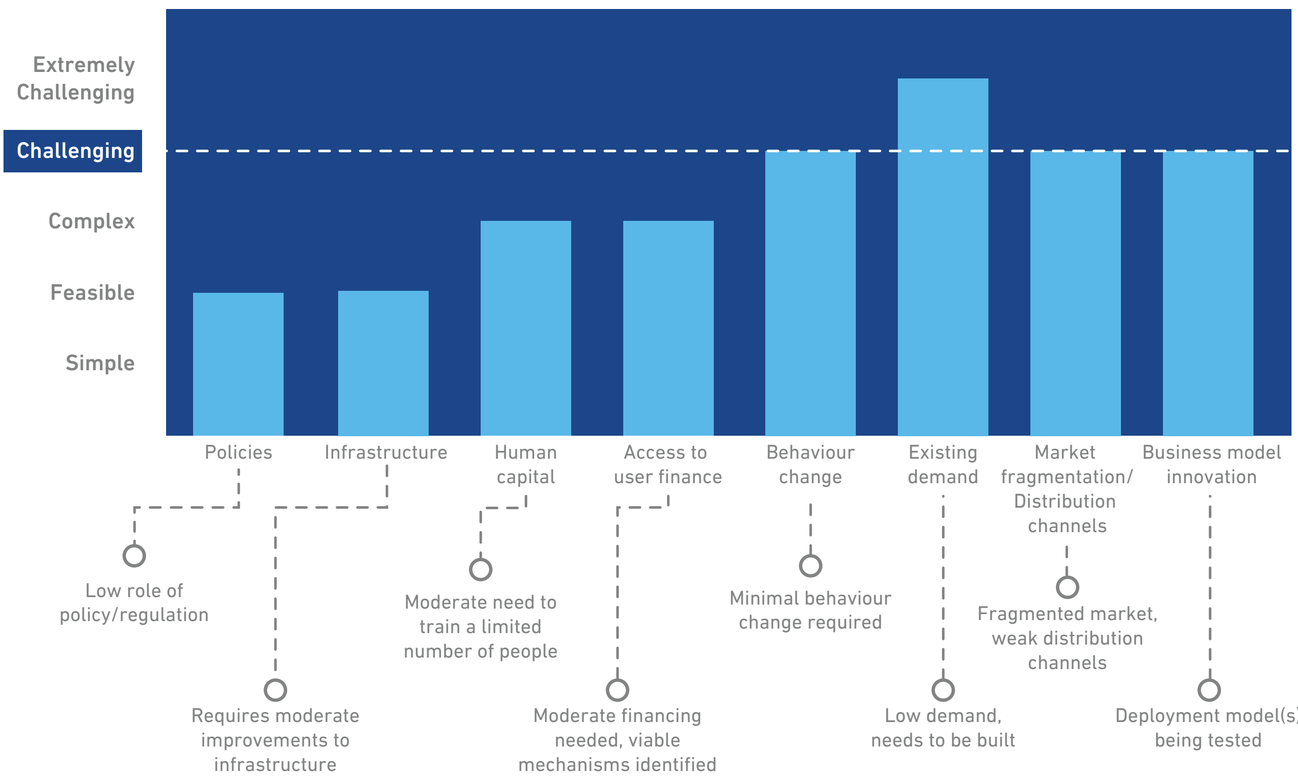
- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

An effective advanced biomass cookstove must be durable, low-cost and low maintenance. It will preferably use unprocessed fuel, or fuels that can be processed locally with available equipment. It will be compatible with traditional foods and cooking styles and not require major behavioral change by the users.

Above all, it must employ extremely efficient combustion processes and emit very low levels of dangerous pollutants. This breakthrough will require significant advances in thermodynamic and combustion sciences, as well as outstanding user-centric design.

Innovative business models will be required, and significant outreach will be needed in some regions to ensure sufficient demand. The projected time to market readiness of a breakthrough advanced biomass cookstove is five to seven years, and the difficulty of deployment is CHALLENGING.

Breakthrough 46: Difficulty of deployment



47 Novel ways of converting household or village waste products into clean cooking fuel or electricity

Gas and electricity are recognized as very clean and safe cooking fuels, yet their usage remains very low in rural areas of developing countries. This is mainly due to the high cost and logistical challenges involved in extending the required infrastructure to these areas. Liquified petroleum gas (LPG) is typically transported in cylinders, which requires an adequate road network and sufficient truck fleet that are lacking in many areas.

Natural gas is typically transported in pipelines, which are very expensive and therefore limits the use of natural gas in areas distant from gas wells. The price volatility of LPG and natural gas makes it difficult for low-income households to have consistent access to the fuels. Electrification of rural areas is a longstanding challenge, and even in areas that are nominally connected to the power grid, electric cooking is seldom practical due to unreliable supply and the high power requirement of electric cookers.

Decentralized production of biogas by means of anaerobic digestion of organic materials such as manure and crop waste is an established practice, but is used by only a small fraction of households, mainly in China where it is supported by government subsidies. Use of anaerobic biogas digesters requires a large upfront cost, and most biogas systems require skilled installation and maintenance which is unavailable in most developing countries.

While clean cooking fuel is lacking in rural regions, many areas have abundant organic waste materials such as human waste, animal waste, crop residue or household garbage. A breakthrough is needed in the form of an affordable, robust process to convert diverse organic waste products into clean and reliable gas or electricity for cooking. Such a process would not only provide clean cooking fuel, but would safely dispose of waste products and result in cleaner surroundings. In principle, this could be achieved by various conversion routes, such as biochemical, thermochemical or electrical.

- Biochemical processes would use living organisms to produce biogas. This could take the form of improvements to existing anaerobic digestion processes to make them less capital-intensive with easier installation and maintenance. Advances in genetic editing might be used to create microorganisms capable of digesting a wider range of input materials. If human waste were used as input material for fuel production, cultural concerns among some population segments would need to be addressed.

Current State

Development Stage: Engineering

Time to market (years): <3 | 4-6 | 7-10 | 10+

Deployment: Challenging

Associated 50BT Chapters

Access to Energy | Global Health | Gender Equity

SDG Alignment

Impact

Lives Saved (# of People/Year): <1M | 10M+ | 100M+ | 1B+

Health Improved (# of People): <1M | 10M+ | 100M+ | 1B+

Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

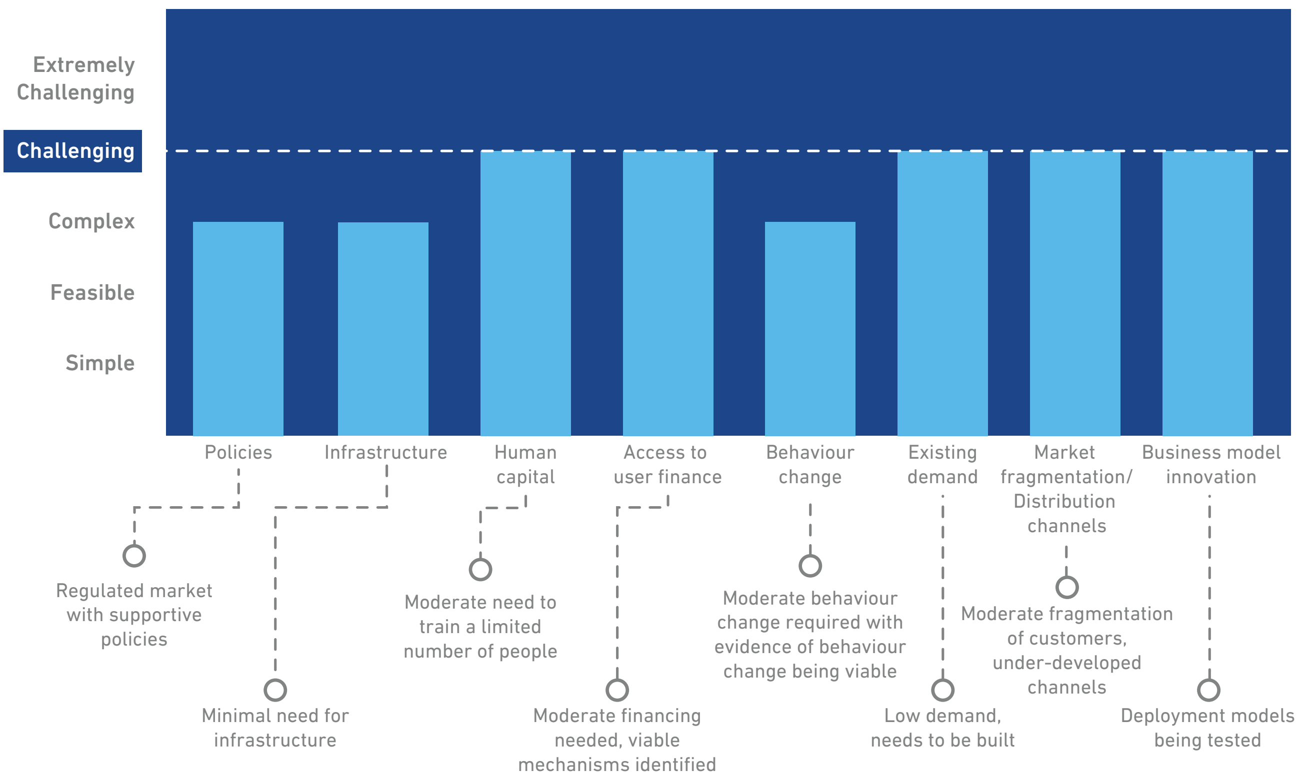
- Thermochemical methods, such as pyrolysis or gasification, use high-temperature processing to produce syngas. These methods are well established at industrial scales, but are less well developed at smaller scales suitable for villages and households. Current small-scale methods are quite polluting, and are relatively complex and require skilled operation and maintenance. In addition to cooking fuel, thermochemical processes typically produce biochar that could be used as a soil amendment.

- Electrical methods would convert the chemical energy of the waste products into electricity, which is a clean and safe form of cooking. Because cooking requires a relatively high electric current, and is typically practiced only at certain times during the day, the most suitable form of village-level electricity production for cooking may be a small-scale "peaker plant" that only operates during limited hours when meals are prepared, and would supplement a solar powered mini-grid that provides continuous power for lighting and other uses. For example, a batch-fired thermochemical gasifier could be combined with an electrical generator to provide a village with sufficient electricity for cooking during several hours in the morning and again in the evening.

There are numerous technology pathways by which this breakthrough could be realized. It will likely require advances in relevant disciplines, such as biological or mechanical engineering. It will also require a thorough understanding of the needs and wishes of the users, and innovative design and implementation to ensure satisfaction. Appropriate business models will be needed to provide economic sustainability.

The projected time to market readiness of this breakthrough is seven to 10 years, and the difficulty of deployment is CHALLENGING.

Breakthrough 47: Difficulty of deployment



48 A mechanism to remove particulate emission from old trucks and other heavy-duty vehicles

Particulate emission from heavy duty vehicles like trucks and buses are a major source of outdoor air pollution in low-income (UNEP, 2014). In Delhi, India, for example, 23 percent of all particulate emissions come from the transport sector (Sharma, et al., 2016). This is mainly due to the large number of operating older vehicles coupled with poor vehicle maintenance, inadequate infrastructure and low fuel quality.

Vehicles in developing countries are typically older than those in industrialized countries. The average age of the vehicle fleet in Tanzania is about 15 years, and in Kenya and Uganda it is about 13 years (UNEP, 2009). Some vehicles, especially diesel-powered trucks and buses, operate for more than 40 years.

These older heavy-duty vehicles are responsible for a high percentage of air pollution, despite their low fleet numbers. These vehicles continue to operate because of the high cost of new vehicles, and the existence of strong maintenance and supply lines for older technology. Due to the inherently slow turnover of vehicle fleets, and the limited economic means of many truck and bus owners to obtain cleaner replacements, existing heavy-duty fleets are likely to remain in operation for many years.

In the longer term, many improved technologies may enable cleaner urban transport systems. These include electric battery and fuel-cell vehicles and prioritized rapid urban transit with light rail or other modes. Having a cleaner transport system requires an appropriate regulatory framework and involves economic and behavioral trade-offs. Long-term policies and investments are needed to support cleaner transport as a means to reduce urban outdoor air pollution.

In the medium term, cleaner diesel fuels (with reduced sulfur and lead content) should be used, as well as incentives toward renewal of the heavy-duty vehicle fleet such as subsidies and inspection regimes. Nevertheless, many authorities are reluctant to force older heavy-duty vehicles off the road because of the national economic importance of the logistic services they provide. There is a need for an immediate alternative.

Urban air pollution could be significantly improved if these older vehicles could be easily and inexpensively retrofitted with a technology to reduce particulate matter emission. A number of retrofit emission technologies currently exist for heavy-duty diesel vehicles, such as catalyzed diesel particulate filters, which remove 95 percent of particulate matter from exhaust but cost up to $10,000 per vehicle (UNEP, 2009).

Particulate filters are mandatory on new diesel trucks in Europe, North America and other industrialized regions, costing about $3000 each. Current particulate filters impose an energy penalty on the vehicle, increasing diesel fuel consumption by about 3 percent (Reitz, 2013). Existing particulate emission controls are too expensive for widespread adoption by existing fleets in low-income countries.

Current State

Development Stage: R&D

Time to market (years)

<3 | 4-6 | 7-10 | 10+

Deployment: Challenging

Associated 50BT Chapters

Global Health

Global Change

SDG Alignment

3 GOOD HEALTH AND WELL-BEING

7 AFFORDABLE AND CLEAN ENERGY

Impact

Lives Saved (# of People/Year)

<1M | 10M+ | 100M+ | 1B+

Health Improved (# of People)

<1M | 10M+ | 100M+ | 1B+

Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- **Attractive for emerging markets (lower profits)**
- Emerging markets potential; requires derisking (sustainable)
- Non-commercial (unprofitable)

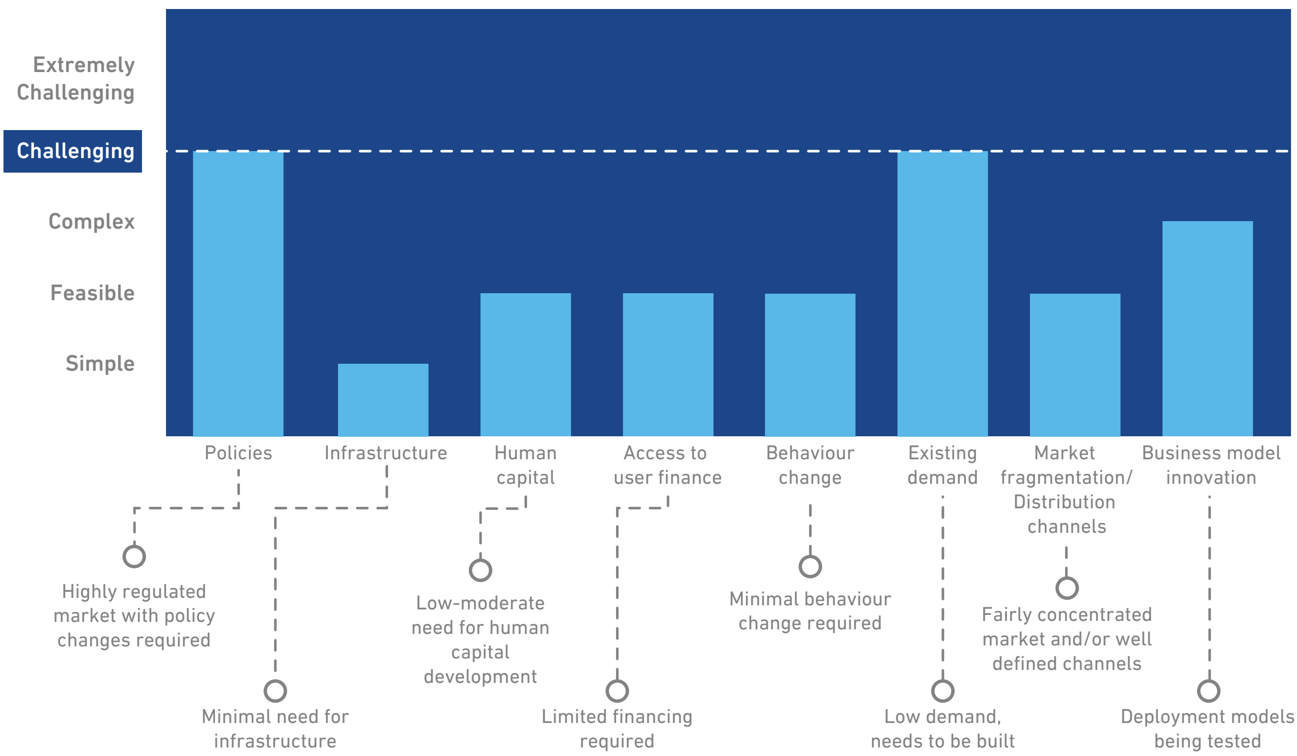
There is a need for a robust, low-cost device that can be retrofitted onto old heavy-duty diesel vehicles to reduce particulate matter exhaust. This engineered solution must be inexpensively produced—less than $1,000—with simple retrofitting onto existing fleets of trucks and buses. Operation of the device must not impose significant load on the vehicle, in terms of exhaust back pressure or electricity demand.

A successful breakthrough technology would use inexpensive and abundant materials (for example, no expensive catalysts), would require only simple installation and maintenance and would produce no harmful byproducts. A range of technical approaches may be appropriate, including filtration, electrostatic precipitation and wet scrubbing (EPA, 1979; Roy, et al., 2011).

Assuming adequate level of support to achieve this breakthrough, we expect that it would take less than five years to be market ready. A major deployment challenge is the lack of demand within the current market structure.

Some level of policy incentive must be created to encourage vehicle owners to install such a device. The difficulty of deployment in this case would be CHALLENGING.

Breakthrough 48: Difficulty of deployment



49 Small-scale waste incinerators with efficient combustion and clean emissions

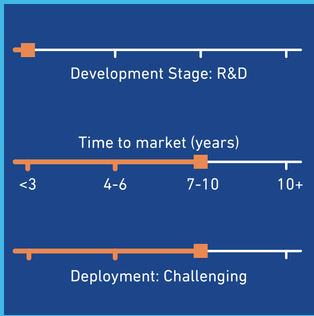
The challenge of urban waste management remains unmet in many cities in low-income countries. Mounds of household rubbish often accumulate uncollected, spreading disease vectors and increasing health risks to community residents. Fast-growing cities lack adequate truck fleets for waste collection and haulage, and existing landfills are often poorly operated and filling rapidly.

Facing the lack of centralized waste management, households and communities typically burn their garbage in uncontrolled open-air fires. This leads to the emission of particulate matter, volatile organic compounds and toxins such as dioxin, with serious adverse health impacts on residents. Refuse burning is responsible for 10 percent of all PM2.5 particulate emissions in all of India, 12 percent in the city of Delhi, and 14 percent in the state of Uttar Pradesh (Sharma, et al., 2016).

An important lever to solve the solid waste problem in low-income cities is well-engineered, appropriately-sized, incineration plants that safely combust waste materials (Silva & Lopes, 2017).

Breakthrough designs will be needed to ensure consistently safe air emission levels, even with diverse feedstock. Existing guidelines on small-scale incineration, for example of medical waste (MMIS, 2010), are unlikely to meet the necessary high standards for air emission quality. Siting of multiple small-scale incineration plants will facilitate collection of waste at local disposal centers. Mobile incinerators moved between collection points may allow higher capacity utilization and improved economics.

Current State



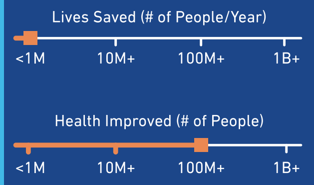
Associated 50BT Chapters

Global Health

Global Change

SDG Alignment

Impact



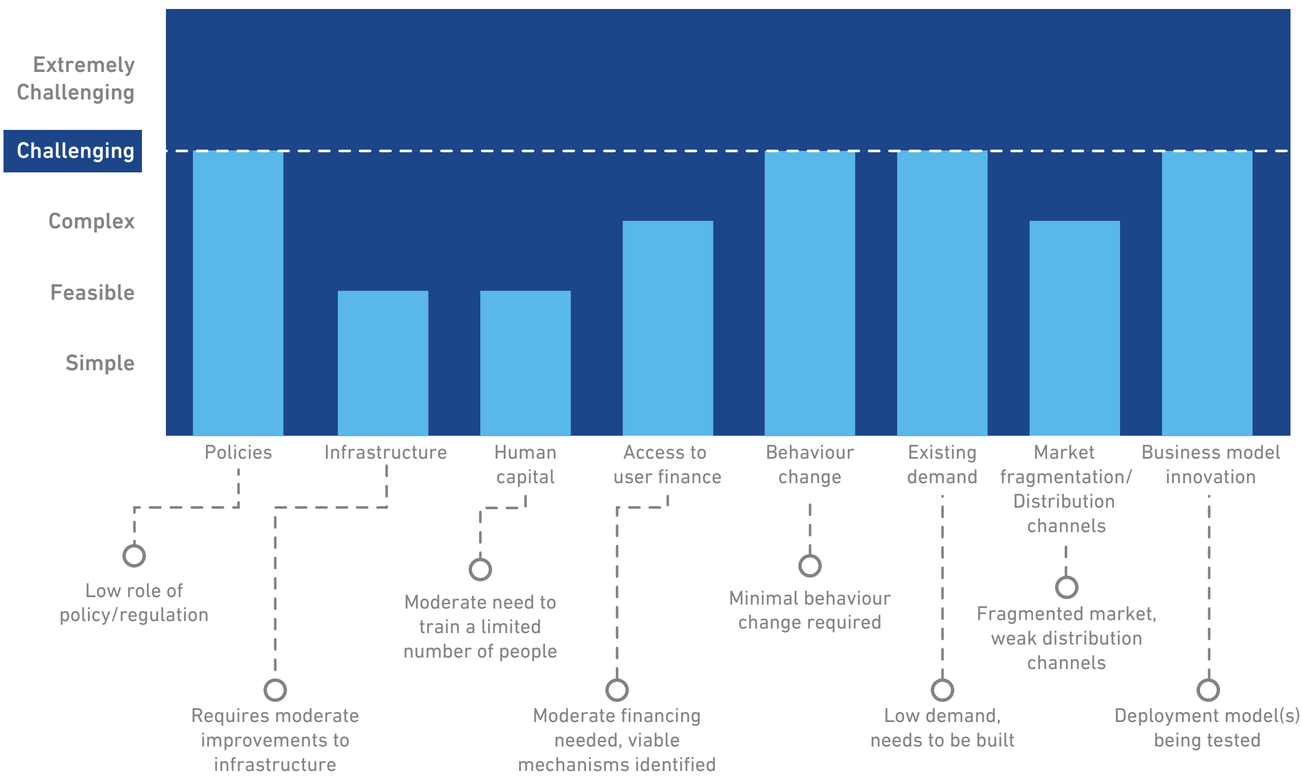
Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

With resources and dedication, this breakthrough could be market-ready in three to five years.

However, it faces strong challenges in terms of political and regulatory acceptance, and lack of demand, and business model innovation. Widespread deployment of this breakthrough is therefore CHALLENGING.

Breakthrough 49: Difficulty of deployment



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DIARRHEAL DISEASES

INTRODUCTION

Diarrheal diseases are responsible for the death of 526,000 children under 5 years of age (IHME GBD, 2017) while soil-transmitted helminths (STH) affect roughly 1.5 billion people globally (WHO, 2018).

In addition to mortality, the indirect burden of diarrheal disease and STHs is significant; they are a major contributor to malnutrition, which in turn is believed to underlie 45 percent of all childhood deaths (IHME GBD, 2017).

Diarrheal disease is transmitted through the fecal-oral pathway, traditionally addressed through interventions targeting water quality, water supply, sanitation, and hand and food hygiene. Diarrheal disease burden can also be reduced through vaccination, nutritional interventions and oral rehydration therapy.

Mortality from diarrheal disease has decreased dramatically over the past two decades. In the same time period, access to improved water, improved sanitation, vaccines and oral rehydration therapy all increased, while malnutrition decreased. However, the extent to which reduction in mortality can be attributed to specific interventions or demographic trends is a subject of debate.

Despite these gains, factors such as high population growth and constrained water supplies are expected to exacerbate diarrheal disease in the future.

Sustainability of interventions and adherence of beneficiaries (such as people consistently washing their hands) have remained major challenges in diarrheal disease prevention. Behaviors around practices like eating and defecation have deep cultural roots and can be hard to influence.

There is no shortage of failed interventions and technologies in addressing this issue. While there have been demonstrated reductions in diarrheal disease from small-scale interventions, there has been limited success in bringing these interventions to scale.

We have identified three technological breakthroughs with high potential for reducing mortality and morbidity from diarrheal disease.

- Breakthrough 3. Network of low-cost distributed monitoring sensors to measure and map air and water quality
- Breakthrough 4. Sustainable, affordable, household-level fecal waste management system
- Breakthrough 5. Medium to large-scale sewage treatment process with recovery of water (and ideally nutrients and energy)

Diarrheal disease is the third leading cause of childhood mortality worldwide, behind only neonatal conditions and lower respiratory infections. It is responsible for 526,000 childhood deaths, almost all in developing countries (IHME GBD, 2017) (Exhibit 1).

CORE FACTS AND ANALYSIS

Defined as passage of three or more loose or watery stools per day, diarrhea is usually a result of an intestinal tract infection, which can be caused by many different pathogens including bacteria, viruses and protozoa. These are generally spread through contaminated food, drinking water or person-to-person contact (WHO, 2013).

Soil-transmitted helminths (STHs) are parasitic nematodes (worms) that feed on the host tissue or compete with the host for nutrition. Many STHs are contracted when children ingest eggs that were excreted in fecal matter of infected individuals. STHs are estimated to infect some 1.5 billion people globally (WHO, 2013).

The most common and important STHs are roundworm, whipworm and hookworm. While these infections are rarely fatal, STHs can cause intestinal distress, malaise or weakness, and impaired cognitive and physical development. The severity of symptoms is directly related to the number of worms an individual harbors.

Both diarrheal disease and STHs lead to malnutrition in the host (**Table 1**). Diarrheal disease can reduce an individual's ability to absorb nutrients in the intestines and the effects of the disease last well beyond the diarrheal episode. STHs feed on host tissue, including blood, or compete with the host for nutrients. This leads to a loss of iron and protein and, similar to diarrheal disease, also causes malabsorption of nutrients.

Recently, a condition known as environmental enteropathy has been proposed to explain, in part, malnutrition that results from sustained exposure to fecal pathogens, even in the absence of diarrheal episodes. A 2008 WHO study concluded that as much as 50 percent of childhood underweight and malnutrition could be associated with repeated diarrhea or knitted helminth infections (Prüss-Üstün, et al., 2008).

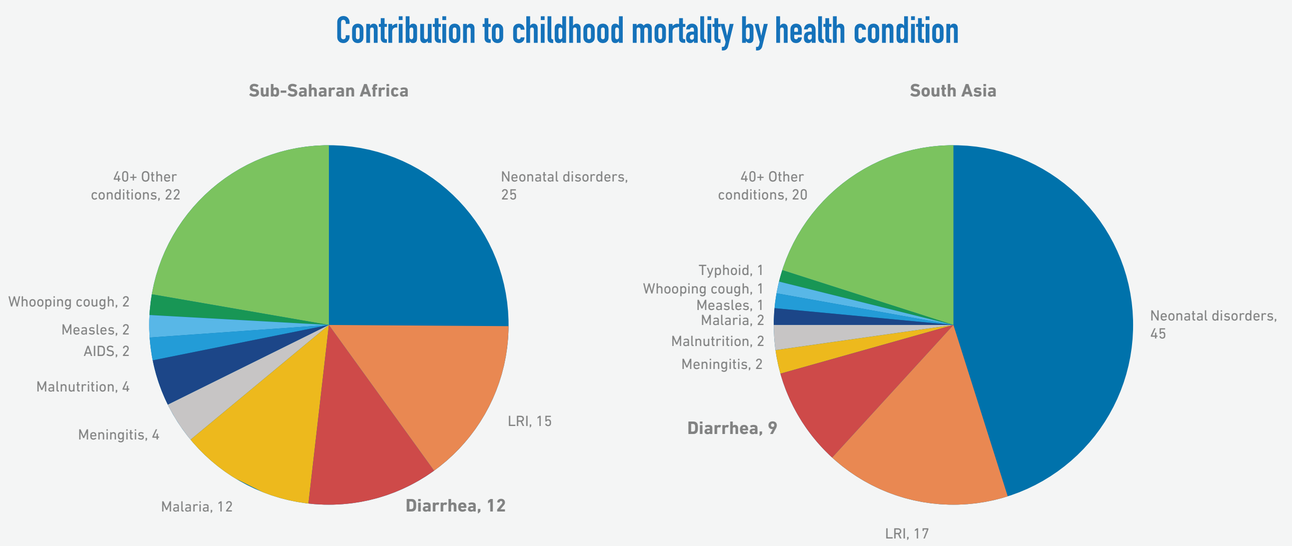


Exhibit 1: Diarrheal disease is the third leading cause of childhood mortality in sub-Saharan Africa and South Asia. (Source: IHME GBD, 2017)

Key diarrheal pathogens and soil-transmitted helminths

Pathogen Class	Important Pathogens	Effect
Diarrheal pathogen	Globally important pathogens: ***Rotavirus, Cryptosporidium parvum, Shigella, ST-enterotoxigenic E. coli (ST-ETEC)*** Additional pathogens important in some specific regions: ***Aeromonas, V. cholera, C. jejuni***	• Diarrhea, which causes dehydration and can lead to mortality • Reduction in ability to absorb nutrients (lasting beyond the diarrheal episode) • Environmental enteropathy (prolonged reduction in ability to absorb nutrients, can occur without diarrhea
Soil-transmitted Helminths	**Roundworm *(Ascaris lumbricoides)*, whipworm *(Trichuris trichiura)*, hookworm *(Necator americanus and Ancylostoma duodenale)*** and certain types of **tapeworm *(Taenia)***	• Enteric inflammation, general malaise and weakness, and impaired cognitive and physical development • Anemia (hookworm only) • Increased malabsorbtion of nutrients • Loss of appetite

Table 1: A handful of pathogens are responsible for the majority of severe diarrhea and STH infections. Rotavirus, *Cryptosporidium parvum*, *Shigella* and ST-ETEC are the four most important diarrheal pathogens globally. (Source: Kotloff, et al., 2013)

1. Diarrheal disease and malnutrition share a complex link

The relationship between diarrheal disease, soil-transmitted helminths and malnutrition is recognized but not entirely understood. Focusing specifically on diarrheal pathogens, the common belief for decades was that diarrhea itself caused a reduced ability for the body, specifically the small intestine, to absorb nutrients and that this effect could last significantly longer than the diarrheal episode itself.

One meta-analysis found that probability of stunting at age 2 increased by 2.5 percent per diarrheal episode, and 25 percent of all stunting was attributable to having five or more episodes of diarrhea (Checkley, et al., 2008).

Recently, the scientific community has begun to propose a more complex explanation, which is not related to diarrhea per se, but exposure to high levels of fecal pathogens. This condition is often referred to as 'environmental enteropathy' or 'environmental enteric dysfunction'.

Environmental enteropathy is a poorly defined condition and the underlying causal mechanisms have not yet been clearly determined (Humphrey, 2009).

One proposed model is that high enteric pathogenic bacterial exposure in the small intestines creates an immune response, which in turn causes the common characteristics of enteropathy such as atrophy of intestinal villi (small finger-like structures on the inner surface of the intestines that increase surface area for absorption of nutrients).

The effects are twofold. First, as a result of reduced surface area in the intestine, the small intestines have a reduced ability to absorb nutrients. Second, nutrients are repartitioned away from growth to support the immune system. This is an ongoing area of research.

Enteropathy could help explain why sanitation has stronger associations with achieving gains in infant and child growth, rather than reduction in diarrhea (Brown, et al., 2013). For example, a study in Peru found that diarrhea could explain 16 percent of stunting, while access to sanitation and water services could explain 40 percent (Brown, et al., 2013)[1].

[1]While many experts have come to take these positive associations between WASH interventions and health as conventional knowledge, some skeptics have noted the risk of confounding in this type of analysis, and a recent review (Dangour, et al., 2013a) did not include this particular study due to questionable methodological quality.

STHs do not trigger the same immune response as diarrheal disease. It is believed that they affect nutrition by feeding directly on intestinal contents or blood, leading to nutrient loss and anemia (WHO, 2013). STHs and their effects on nutrition and growth have increasingly become a debated topic. In 2007 and 2012,

The Cochrane Collaboration reviewed evidence for mass deworming initiatives and found that the evidence linking deworming programs to gains in nutrition and growth indicators was weak. Leaders from evaluation groups including Innovations for Poverty Action (IPA), the Center for Effective Global Action (CEGA) and the Abdul Latif Jameel Poverty Action Lab (J-PAL) have criticized these studies for excluding important randomized trials and ignoring the effect of deworming on improvements in education outcomes.

2. Diarrheal disease is primarily a childhood disease

Children under 5 represent 43 percent of the diarrheal disease burden (IHME GBD, 2017). Children are generally more susceptible to diarrheal disease, due to their developing immune systems and a high rate of malnutrition or other immune-suppressive risk factors.

Children are also at higher risk for life-threatening diarrheal disease due to the higher composition of water in a child's body relative to adults, relatively higher metabolic rates and lower capacity of their kidneys to conserve water (WHO-UNICEF, 2009).

In the past two decades there has been a large drop in childhood mortality caused by diarrheal disease (**Exhibit 2**). The WHO and UNICEF estimate that in 1990 mortality was as high as 5 million (WHO-UNICEF, 2009). Since 2000, childhood mortality from diarrhea diseases has dropped 55 percent from 1.1 million to about 0.5 million deaths per year in 2017 (IHME GBD, 2017).

While it is widely accepted that the global burden has dropped significantly over the past two decades, the specific reasons for this decline are not well understood. The primary drivers are believed to be improvements in nutrition, improved case management, particularly the widespread use of oral rehydration therapy, increased coverage of immunization for measles and rotavirus, and increased access to clean water and sanitation.

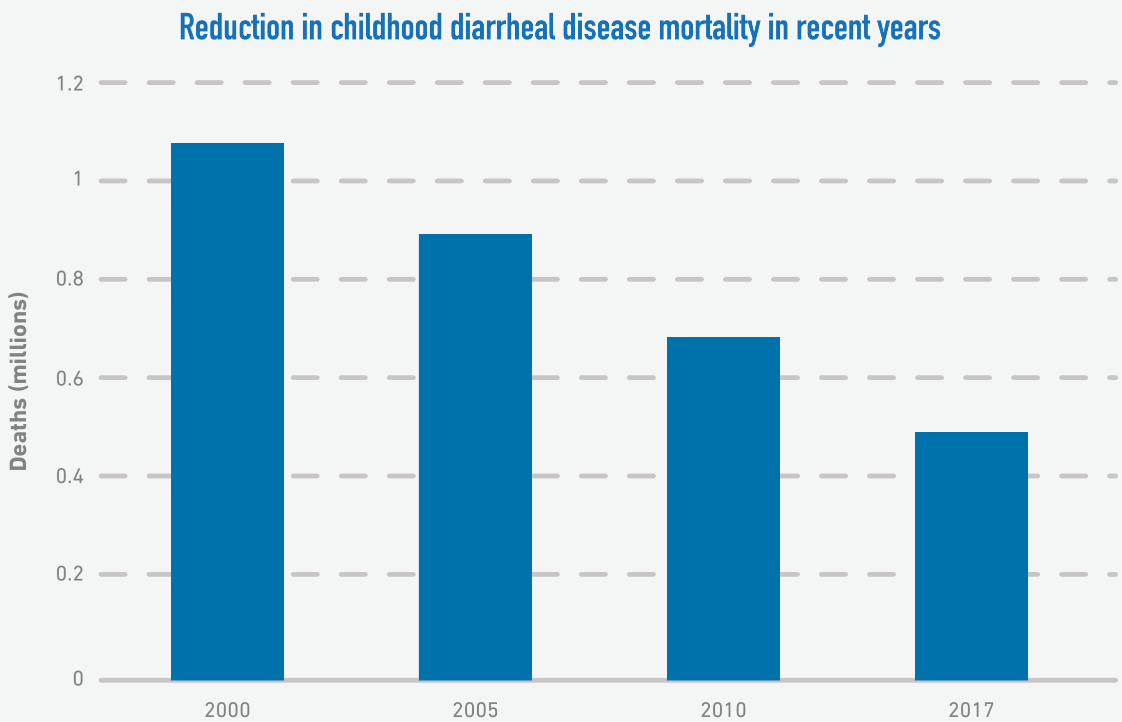


Exhibit 2: Since 2000, global mortality from diarrheal disease has decreased from nearly 1.1 million to about 0.5 million per year. The specific causes of this reduction, however, remain unclear. (Source: Liu, et al., 2012; IHME GBD, 2017)

While mortality from diarrheal disease has decreased, morbidity has remained more or less constant (Kosek, et al., 2003)[2]. This implies that the global health community has made major strides in case management and control of at least some pathogens that are responsible for moderate to severe diarrhea, but they have made relatively little progress in controlling the general transmission of diarrheal pathogens.

Diarrheal disease burden is highly concentrated in a small number of countries (**Exhibit 3**), with 10 countries representing 58 percent of deaths. Even within these countries, variability in the rate of diarrheal disease mortality is high (**Exhibit 4**).

Contribution to childhood diarrheal mortality by country

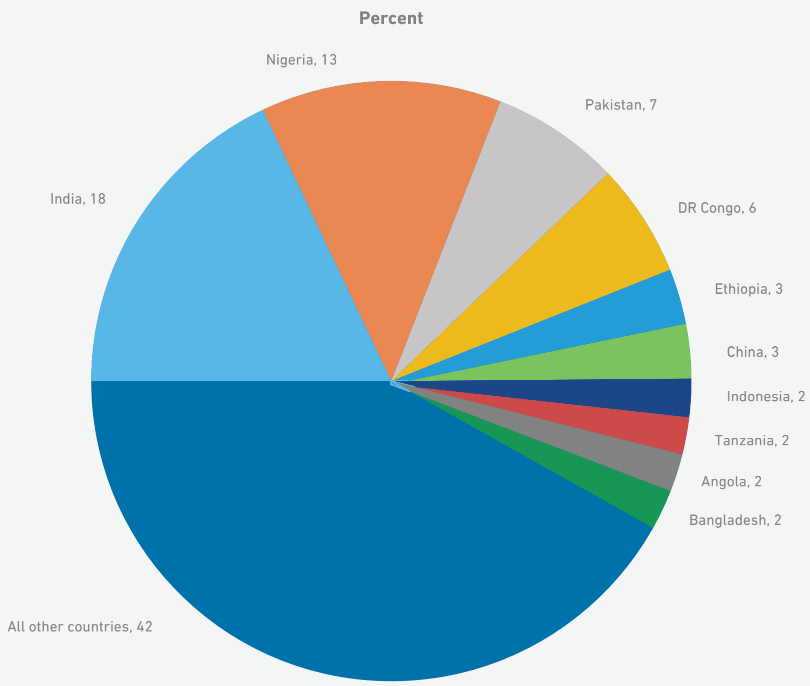


Exhibit 3: 10 countries account for 58 percent of childhood deaths from diarrheal disease. (Source: UNICEF, 2017)

Diarrhea mortality rates among children across high burden countries

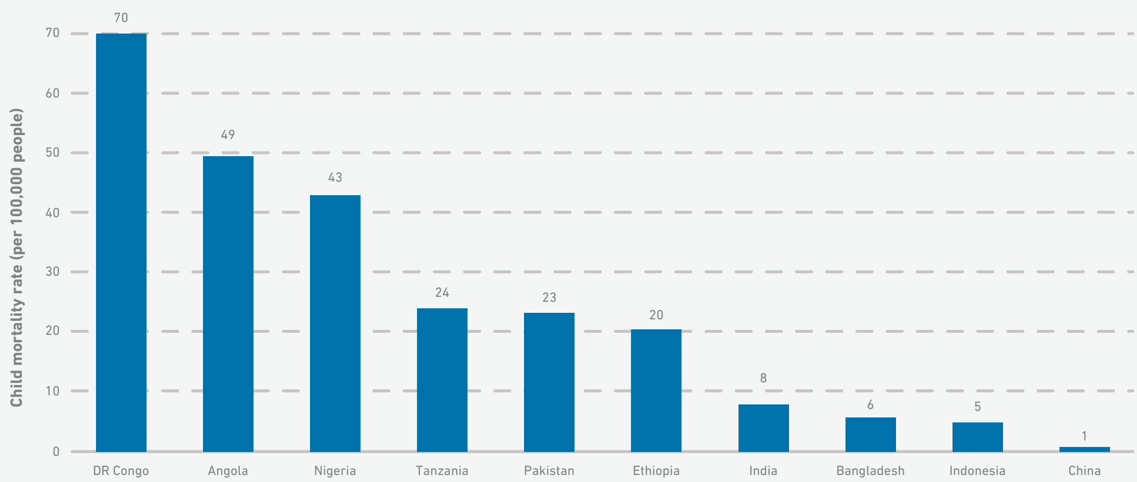


Exhibit 4: Mortality per 100,000 people varies greatly, even across high burden countries. (Source: UNICEF, 2017)

[2]This opinion is not universally held, and some experts note that cross-sectional surveys used to gather this data are unreliable (Luby, 2011).

3. Diarrheal disease and intestinal nematodes are caused by four types of pathogens

The various pathogens causing diarrheal disease and intestinal nematodes behave in different ways. Some bacteria, for example, are believed to be seasonal. There are major spikes in bacterial infections during the wet seasons, which highlights the importance of water as a transmission pathway.

In contrast, viruses, particularly rotavirus, show seasonal spikes in the drier, colder seasons. This indicates that person-to-person transmission is an equally or more important transmission pathway (Levy, et al., 2009).

Unlike viruses, bacteria can also reproduce outside of the human body (such as on food left at room temperature), thus becoming more likely to produce disease after ingestion.

STHs on the other hand must mature in soil, eliminating person-to-person transmission as a major pathway. Further description of the different types of pathogens can be found in **Table 2**.

The Global Enteric Multicenter Study (GEMS) identified four important specific pathogens that represent a disproportionate percentage of disease burden in developing countries: Rotavirus, Shigella, ST-ETEC and Cryptosporidium (Kotloff, et al., 2013).

Major classes of pathogens and their characteristics

Pathogen type	Important pathogens	Characteristics
Viruses	Rotavirus	Viruses are infectious pathogens that can only replicate after infecting other living cells. Rotavirus is the single most important pathogen associated with diarrheal disease.
Bacteria	*ST-Enterotoxigenic E. coli, Shigella, Aeromonas, V. cholera, C. jejuni*	Bacteria can grow on food and in water and sewage under the right conditions. Some bacteria are seasonal, with major spikes in the wet season.
Protozoa	*Cryptosporidium Parvum*	Protozoa are advanced organisms that are transmitted through cysts that are extremely robust, able to survive for long periods outside of the body and resistant to chlorine purification.
Soil-transmitted Helminths	Roundworm (*Ascaris lumbricoides*), whipworm (*Trichuris trichiura*), hookworm (*Necator americanus* and *Ancylostoma duodenale*) and certain types of tapeworm (*Taenia*)	Soil-transmitted helminths (STH) are parasites that do not cause diarrhea, but rather live in the body, generally the intestines, and cause enteric inflammation. Eggs must mature in soil before becoming infectious to humans, however, they are extremely persistent and can survive for weeks to months on crops and soil, and years in fecal matter.

Table 2: Each of the different types of pathogens travels along the fecal-oral pathway, but have different characteristics affecting their transmission and susceptibility to different interventions.

4. Traditionally, the flow of pathogens has been described through the F-diagram

Diarrheal disease and STHs are transmitted from person-to-person along the fecal-oral pathway, in which individuals ingest pathogens that have been excreted in fecal waste by other infected individuals and sometimes animals.

The pathway is complex and can follow many routes, which vary in importance from location to location. This pathway has historically been represented with the F-diagram that describes the flow of pathogens from fecal matter to new hosts (**Exhibit 5**).

The F-Diagram representing the Fecal-Oral Pathway

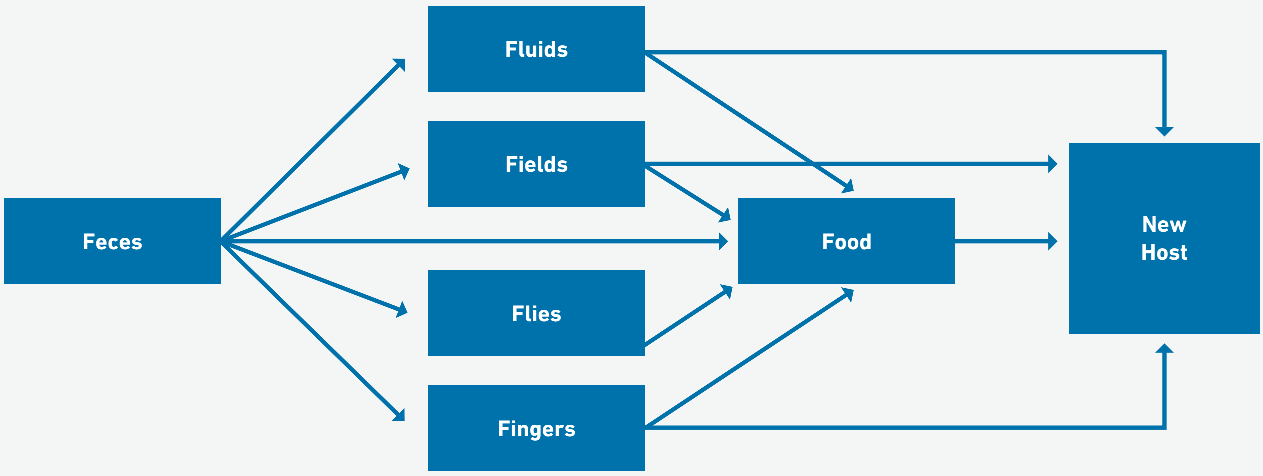


Exhibit 5: The F-diagram has historically been used to describe the fecal-oral pathway. (Brown, et al., 2013)

While this diagram is useful as a descriptive tool, it is limited in its usefulness for informing interventions. Drinking water or fluids, for example, can be contaminated in a number of ways including contamination at the source, either from flooding or direct runoff from inadequate sanitation systems, contamination in transit through water pipes with intermittent supply, or contamination in the household from poor storage practices.

5. A more nuanced fecal-oral pathogen flow model

In order to provide a more nuanced conceptual framework for problem and intervention analysis, we have developed the Pathogen Flow Model (**Exhibit 6**).

This five-stage model maps major transmission pathways, allows identification of major breakpoints and provides a view of which challenges must be solved in unison. Each stage of a pathway presents unique challenges that are responsive to different types of interventions.

Stage 1 - Pathogen hosting

The transmission of fecal pathogens begins with individuals who are carrying diarrheal disease causing pathogens in their gut. These individuals may be suffering from diarrheal disease or be asymptomatic carriers. In both cases, but particularly for individuals suffering from diarrheal disease, the disease-causing pathogens grow and replicate.

This can also occur with asymptomatic carriers of potentially disease-causing organisms who do not suffer from diarrhea. While humans can be infected by pathogens that come from animal hosts, the majority of infections responsible for the overall diarrheal and STH disease burden in children are likely acquired from other human hosts[3].

Fecal-Oral Pathogen Flow Model

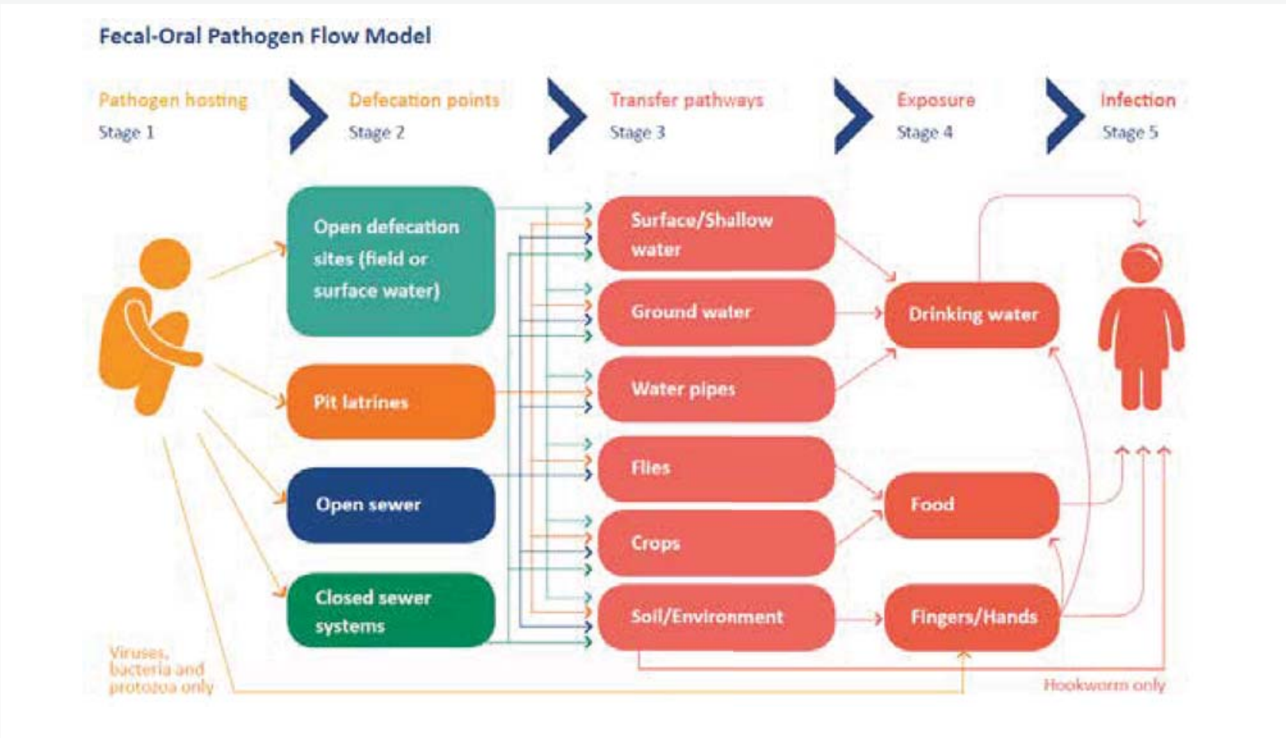


Exhibit 6: This five-stage model maps major transmission pathways for diarrheal disease and soil-transmitted helminths. It is important to note that different pathways are applicable in different contexts, for example in rural versus urban settings. (Source: ITT analysis)

[3]One notable exception is *Taenia*, which is often carried in cows or pigs.

Stage 2 - Defecation points

Following infection and the replication of pathogens in the body, pathogens are excreted into the environment at defecation points. These defecation points, such as open fields, sewers and pit latrines represent high-density sources of persistent diarrheal pathogens.

The challenges associated with defecation points vary from urban to rural locations but generally revolve around the lack of sustainable and scalable sanitation systems. It is often taken as common knowledge that sanitation interventions are positively correlated with reduction in diarrheal disease and childhood growth.

A meta analysis of sanitation interventions found an average relative risk reduction in diarrheal disease of 37 percent (Waddington, et al., 2009). A recent review, however, found there was insufficient evidence to link sanitation interventions to childhood growth (Dangour, et al., 2013b).

Stage 3 - Transmission pathways

When there are insufficient sanitation systems, diarrheal pathogens spread through transmission pathways like crops and water sources. There are many possible transmission pathways, and targeting any single pathway in isolation is unlikely to create major improvements in health.

Interventions at this stage have generally displayed less effectiveness than interventions at earlier or later points in the pathway. For example, water quality interventions at the source—a transfer point—are associated with an 11 percent reduction in diarrheal disease, while interventions at the household lead to a 35 percent reduction (Fewtrell, et al., 2005).

Stage 4 - Exposure

Pathogens enter the body in three ways: through drinking water, through food and directly from hands.

Drinking water
Drinking water is generally contaminated at three main points–at the source, in transit (such as through pipes) or in the home (through improper storage). Major interventions focusing on drinking water are generally source protection (prior to the exposure stage), water purification and safe household storage.

Food
Food can be contaminated in fields when farmers use wastewater for irrigation, when feces are deposited in fields due to open defecation or as fertilizer, in markets due to unhygienic conditions, or in the home through a mother's hands while preparing food, a child's hands while eating, or by flies that land on food and deposit pathogens.

The ability of bacteria to reproduce rapidly on food has led to food, and particularly complementary (weaning) food, gaining increased importance in reduction of diarrheal disease. Food hygiene generally focuses on hand washing before preparing food and eating, appropriate food preparation practices including washing or disinfecting and then properly cooking food, appropriate storage of leftover food and reheating food that had been previously prepared.

Hands and fingers
Hands and fingers can be contaminated during defecation, caring for an infant and through contact with the soil and environment. Hand hygiene is focused primarily on hand washing with soap. Interventions at the exposure stage tend to be moderately effective. Studies have found a 31 percent reduction in diarrheal disease from hygiene interventions and a 42 percent reduction from water quality interventions (Waddington, et al., 2009).

Stage 5 - Infection

Exposure does not necessarily lead to disease. Rather children who are malnourished, not optimally breastfed or are HIV positive are more likely to develop diarrhea after exposure to pathogens. Vaccination is also effective in reducing the risk of diarrhea following exposure to some pathogens.

KEY CHALLENGES

Diarrheal disease is a condition that is driven by some of the most fundamental human activities—eating, drinking, preparing food and defecating. In the absence of adequate sanitation systems, fecal pathogens contaminate the environment, food and water through environmental mechanisms and human activities.

Pathogens are then ingested, and in individuals who are susceptible, produce disease, at which point lack of adequate care becomes a major driver of mortality.

Key challenges in breaking the fecal-oral pathway, reducing susceptibility to disease through improved nutrition and health care, and improving care for those who fall sick are outlined below.

1. High rates of infection amongst the population lead to a constantly replenishing and growing supply of diarrheal pathogens and STHs in the environment

Rates of infection in many developing countries are extremely high. There are 1.7 billion cases of diarrhea globally per year, with an average of 2.9 episodes per child per year (Brown, et al., 2013). This indicates that diarrheal pathogens are constantly being excreted into the environment and in massive quantities.

2. Lack of adequate, sustainable sanitation systems enables wide-scale environmental contamination with fecal pathogens

There are a number of systemic, multifaceted problems which expose low-income populations to fecal pathogens. These include poor infrastructure, lack of public sanitation services and the absence of sustainable business models for private sanitation.

Lack of sanitation infrastructure

Sanitation infrastructure such as sewerage and treatment facilities, the most common approach to clean environments in developed countries, is severely underdeveloped in most developing countries. The gold standard of closed sewage systems where wastewater is treated before being returned to the environment is highly uncommon.

Sanitation systems generally only reach small portions of the population and are underdeveloped or in disrepair, leaving most individuals using alternative sanitation systems or practicing open defecation.

Lack of sustainable, scalable models for community or household sanitation systems

One of the key challenges with sanitation systems is maintenance—keeping the toilets at an acceptable level of cleanliness while removing waste—which is dependent on an effective business or public utility model. In most developing countries, government-funded sanitation systems have limited reach, often excluding the poor.

In the absence of public models, private or hybrid models are being developed, although none have yet been fully proven. In the absence of an effective model which generates revenue, either from usage of the toilet or through sale of the fecal sludge, sanitation systems inevitably become unsanitary and go into disuse.

Existing urban and rural systems have major shortcomings, which lead to environmental contamination

In urban areas, particularly for the poor, sanitation systems are generally pit latrines and open sewers, which have several major shortcomings. First, both are prone to flooding, which leads to widespread contamination. Second, open sewers in particular are often located in areas with high population density where they cause extensive contamination. Third, pit latrines often fill up faster than the waste decomposes, which means that they must be emptied.

Often pit latrines are emptied by private parties who dispose of the fecal sludge improperly, usually very close to urban populations, where the diarrheal pathogens can contaminate water sources or soil and come in easy contact with children. In rural areas, sanitation options are generally pit latrines or open defecation (more common in rural India, in particular).

In both cases, rains and flooding can contaminate soil and water. As with urban pit latrines, rural pit latrines need to be emptied frequently and fecal sludge is rarely disposed of properly.

3. Environmental conditions are conducive to the persistence and spread of pathogens

Bacterial pathogens can survive in water for 10 to 60 days and for many months in soil. STH eggs can survive in soil for 27 to 35 days in summers and up to six months during the winter season in temperate zones (Ensink & Fletcher, 2009). Both bacterial pathogens and STH eggs can survive significantly longer than their average lifespan in fecal waste.

4. In the absence of sanitation systems, there are a large number of ways in which food and water can become contaminated or children can be directly exposed to pathogens

When there are insufficient sanitation systems, diarrheal pathogens flow through multiple transmission pathways, which brings them in direct contact with potential human hosts. There are many possible transmission points, and therefore many breakpoints in the transmission pathway to consider.

Distributed water sources including surface water, shallow wells and boreholes

Surface and shallow water sources, especially in rural areas, can be contaminated through flooding and runoff of fecal matter and pathogens. Deeper groundwater, in both urban and rural areas, can be similarly contaminated through episodic flooding, particularly when boreholes are constructed poorly (without a concrete block at the surface to prevent fecal matter from reaching the aquifer through and around the pipe).

Centralized water sources (water pipes)

In urban settings, water distribution pipes and sewage pipes or ditches are often constructed near each other. Pipes are inherently leaky, with even well-maintained western systems losing roughly 15 percent of system water. Piping systems in developing countries are dramatically worse and often have only intermittent water supply. When the water supply is shut off, it creates reverse pressure, and if there is fecal matter around the pipes it can leach into the water pipes. This re-contaminates water even if it has already been purified.

Crops

An estimated 10 percent of the world's food supply is irrigated with wastewater (Jimenez, 2006). Use of untreated wastewater for irrigation deposits pathogens, particularly on vegetables, which can then be ingested if the produce is not cleaned and cooked properly before eating.

Flies

Some flies are born and breed in fecal matter and carry pathogens on their exoskeleton or through their gastrointestinal system. Flies also tend to proliferate in hot and humid conditions, especially during the rainy season, when there are more pathogens in the ecosystem.

Soil and environment

Soil and the broader environment are contaminated from open defecation, disposal of fecal sludge, runoff from inadequate sanitation systems, wastewater that is used for irrigation, and episodic flooding.

Diminishing water availability leads to utilization of lower quality water sources

As water sources become over-abstracted or are replenished at slower rates due to changes in hydrological patterns, water quality tends to degrade. Individuals then have to use lower quality water sources. This exacerbates existing challenges with nearly all water sources in water-poor areas, including most of South Asia and sub-Saharan Africa. This is also expected to become increasingly critical as the global population grows and hydrological patterns continue to change.

5. Children are exposed to diarrheal pathogens, either directly from pathogens on their hands or through consumption of contaminated food or water

Exposure to diarrheal pathogens is enabled by food and personal hygiene habits as well as insufficient water purification systems.

Hand hygiene

Mothers and children do not wash hands with soap after contact with fecal matter, either through defecation or care for a child or infant who has defecated.

Food hygiene

Mothers often do not wash their hands with soap before preparing food and children do not wash their hands prior to eating. Weaning foods are prepared under unhygienic conditions and stored at room temperature. Several studies have found that the second 6 months of life are the period with the highest rate of diarrheal disease (Motarjemi, et al., 1993).

According to one study, 41 percent of weaning food items were contaminated with E. coli (Black, et al., 1982). Due to storage of foods at high ambient temperatures, weaning foods have been found to be more contaminated than food prepared for adults, (Black, et al., 1982). Apart from weaning food, previously cooked food is often not reheated before consumption later. Storage at room temperature can lead to exponential bacterial growth in cooked food. Studies have found that bacterial contamination on food greatly exceeds that found in drinking water (Black, et al., 1982).

Water quality and supply

There are several challenges in providing safe water to children. First, water delivery infrastructure is often poorly developed and in some cases absent in developing countries, particularly in rural areas. While most individuals in urban areas have access to water, access in rural areas, particularly in sub-Saharan Africa and India remains low.

In both regions, only about half of the population has access to an improved water source. When there is no national level water infrastructure, community level systems are often employed; however, these systems need ongoing maintenance models and require an adequate service model to be sustainable.

However, studies have found significant heterogeneity in results from point-of-use water treatment systems, which is likely related to compliance (Clasen, et al., 2007). In one study of the poor in urban Bangladesh, even with bi-monthly visits to educate families about the dangers of untreated drinking water, only 30 percent of families used the most popular treatment system they tested, with lower rates of compliance for other systems (Luoto, et al., 2011).

The low rate of adequate water treatment is also greatest among the poor. In Africa, the richest quintile was more than three times as likely to use adequate water treatment relative to the poorest, highlighting the fact that people who are most at risk have the least access to appropriate water treatment (Rosa & Clasen, 2010). This indicates that while there is opportunity at the household level, these technologies are unaffordable, complex and time consuming, and require daily and continuous use.

Finally, even when water is treated, recontamination of water in the household is common. A study in urban India found that 40 percent of water stores at the houses of families who boiled their water were contaminated, with 25 percent of stores exceeding the WHO threshold for safe drinking water (Clasen, et al., 2008).

This is generally believed to be due to recontamination because of unhygienic practices in storing and retrieving water (meaning, water stores are re-contaminated from placing hands in water during retrieval).

6. Lack of adequate nutrition, low access to healthcare and low coverage of vaccines

Together, these factors increase a child's susceptibility to disease after exposure.

Increased susceptibility due to poor nutrition

Diarrheal pathogens are opportunistic. Development of active infection following exposure, like with many diseases, is driven by the strength of an individual's immune system. Malnourished children, in particular, have higher susceptibility.

Children who are stunted are 1.6 times more likely to die from diarrheal disease than those who are not stunted (Black, et al., 2008); Vitamin A deficiency causes a 60 to 70 percent increase in diarrhea prevalence (el Bushra, et al., 1992), and zinc deficiency has been found to increase diarrhea prevalence by 15 to 24 percent (Bhutta, et al., 2008).

Suboptimal breastfeeding also contributes to childhood susceptibility to diarrheal pathogens. Infants under the age of 6 months who are not breastfed are more than 10 times as likely to die from a diarrheal infection as those who are breastfed (Lamberti, et al., 2011).

Low vaccine coverage for rotavirus

An effective vaccine exists for rotavirus, which is the most common cause of moderate-to-severe diarrhea in children under 2, and makes up more than 40 percent of all incidences of moderate-to-severe diarrhea in children under 1—more than double the next highest cause (Kotloff, et al., 2013).

However, childhood coverage for this vaccine is still low due to the vaccine's fairly recent introduction as a global priority and its high cost relative to other vaccines.

Lack of vaccines for Shigella, ST-ETEC, Cryptosporidium and soil-transmitted helminths

With the exception of rotavirus, there is no effective vaccine for any of the other major pathogens that cause diarrheal disease, and there are major scientific challenges to many of these pathogens (Jones, et al., 2003). There are many strains of ST-ETEC and an effective vaccine would have to produce immunity against an array of antigens.

Developing vaccines for parasitic diseases is challenging due to the increased complexity of antigen analysis of higher life forms, as is the case with cryptosporidium and helminths. The challenge of developing a vaccine against STHs is compounded by the diversity of helminth organisms (Harris, 2011). Many experts believe that the development of additional vaccines is likely a high-cost, time-consuming opportunity relative to existing interventions.

7. Children do not receive adequate care during a diarrheal episode due to the low coverage of oral rehydration therapy

ORT is a proven intervention and can reduce mortality by 69 percent but coverage remains low (Bhutta, et al., 2013). Only 39 percent of children in developing countries with diarrhea receive ORT, and there has been little improvement in this rate since 2000 (WHO-UNICEF, 2009).

This is driven by a number of factors including the misconception that diarrhea is considered a normal part of growing up, the fact that often both parents work and have limited time to pay attention to their children, weak healthcare systems and the lack of awareness that diarrhea can be a major risk to a child's life.

8. There are many fundamental scientific questions that remain unanswered

Experts noted many key scientific questions, highlighted below, that require further research to help reduce the burden of diarrheal disease and STHs.

- What is the relative importance of various pathways of transmission?
- What is the relationship between gastrointestinal pathogens and malnutrition?
- What is the burden of disease, other than mortality, that is attributable to gastrointestinal pathogens? (For example, the loss of cognitive development associated with both intestinal parasites as well as growth faltering which may be mediated through environmental enteropathy).
- What is the role of the microbiome in increasing or decreasing the susceptibility of the child to exposure to gastrointestinal pathogens? And what interventions might contribute to a healthier more protective microbiome?
- How clean does the environment need to be for thriving children and thriving communities?
- What is the underlying cause of environmental enteropathy?
- What are the pathways through which environmental contamination and malnutrition contribute to growth faltering?
- How do we scale up successful pilot projects to better protect large vulnerable populations?
- What are easier, lower cost methods for detecting and measuring the concentration and viability of pathogens in the environment?
- What are better dose-response curves to use for modeling exposure (Quantitative Microbial Risk Assessment) that describe the susceptibility of children to different organisms? Most dose-response data are from studies on healthy adults.

In summary, systemic challenges require systemic solutions. The core challenge, breaking the fecal-oral pathway, is dealt with in developed countries through large government investments in public infrastructure including sewer systems, wastewater treatment plants, water purification facilitates and ubiquitous piping into households—all of which require constant service and maintenance. This is almost certainly not practical in most of the poorest regions of the world.

SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

There have been several successes in reducing diarrheal disease at a small to mid-level scale, usually in the range of thousands of households. Very few interventions, however, have been proven at a scale comparable to the problem itself—in the range of millions of households.

Amidst the successes are an abundance of failed interventions—broken water filters or toilets that were installed but never used or quickly broke, again highlighting the fact that diarrheal disease is not a challenge that can be solved just by technology, by building infrastructure or by influencing behavior or habits.

Rather, successful interventions must be holistic and consider the whole system and include business or public financing models to ensure sustainability.

Technology does, however, play an important role in a holistic solution, and there are three scientific and technological breakthroughs that can improve sanitary conditions and significantly reduce diarrheal diseases.

Breakthroughs:

1 2 3 4 5 6 7 8 9 10
11 12 13 14 15 16 17 18 19 20
21 22 23 24 25 26 27 28 29 30
31 32 33 34 35 36 37 38 39 40
41 42 43 44 45 46 47 48 49 50

3 Network of low-cost distributed monitoring sensors to measure and map air and water quality

Discharge of pollutants into the air and water is an undesirable side effect of conventional industrialization and development processes. Because many environmental pollutants are invisible, tasteless and odorless, severe cases of contamination often go undetected and unremedied. Detection of environmental pollutants currently requires costly equipment and elaborate sampling protocols, and provides only isolated snapshots of individual places, times and contaminants. To fully understand and solve the problem of environmental pollution of air and water, a more fine-grained knowledge of exposure is required.

There is an urgent need for the development and widespread deployment of sensors that detect the levels of the most significant pollutants affecting the air and water, and transmit that information to a platform where it is validated and publicly displayed. Sensors will need to identify and measure a broad range of pollutants. Key air contaminants to be measured include particulate matter, ozone and carbon monoxide, while essential water contaminants include E. coli, salinity and arsenic. Though challenging, there is an important and growing need to measure diverse chemical toxins from sources including industry, vehicles and agriculture.

Required technological innovations include integrated sensors for the most significant contaminants that are inexpensive enough for mass deployment, as well as a platform for data collection, validation, analysis and dissemination. The sensors may be hard-wired and provide continuous monitoring of particular locations, or may be portable to conduct mobile geolocated assessments of contamination.

Fixed sensors would likely form the basis of a sensor network, transmitting (continuous or periodic) data to a mapping platform to show changes in quality parameters over time. Issues of sensor performance degradation over time will need to be addressed, to enable robust long-term monitoring. A successful sensor technology will likely not test separately for each individual contaminant, but would scan a sample of air or water and determine quickly and inexpensively its multiple constituents.

For maximum effectiveness, this sensor technology would be integrated with a web-based platform to allow collection and comparison of environmental pollution risks over time and place.

The linking of improved sensor technology with mobile communications technology would lead to a system for real-time, spatially-explicit, multi-agent exposure monitoring that would create an unprecedented understanding of global air and water pollution, and pathways toward their reduction. Once identified, areas of high risk could be assessed in more detail, and critically contaminated locations in need of remediation can be flagged.

Current State

Development Stage: Engineering

Time to market (years): <3 | 4-6 | **7-10** | 10+

Deployment: Complex

Associated 50BT Chapters

Food Security

Global Change

SDG Alignment

3 GOOD HEALTH AND WELL-BEING

6 CLEAN WATER AND SANITATION

Impact

Lives Saved (# of People/Year): **<1M** | 10M+ | 100M+ | 1B+

Health Improved (# of People): <1M | 10M+ | 100M+ | **1B+**

Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- Emerging markets potential; requires derisking (sustainable)
- **Non-commercial (unprofitable)**

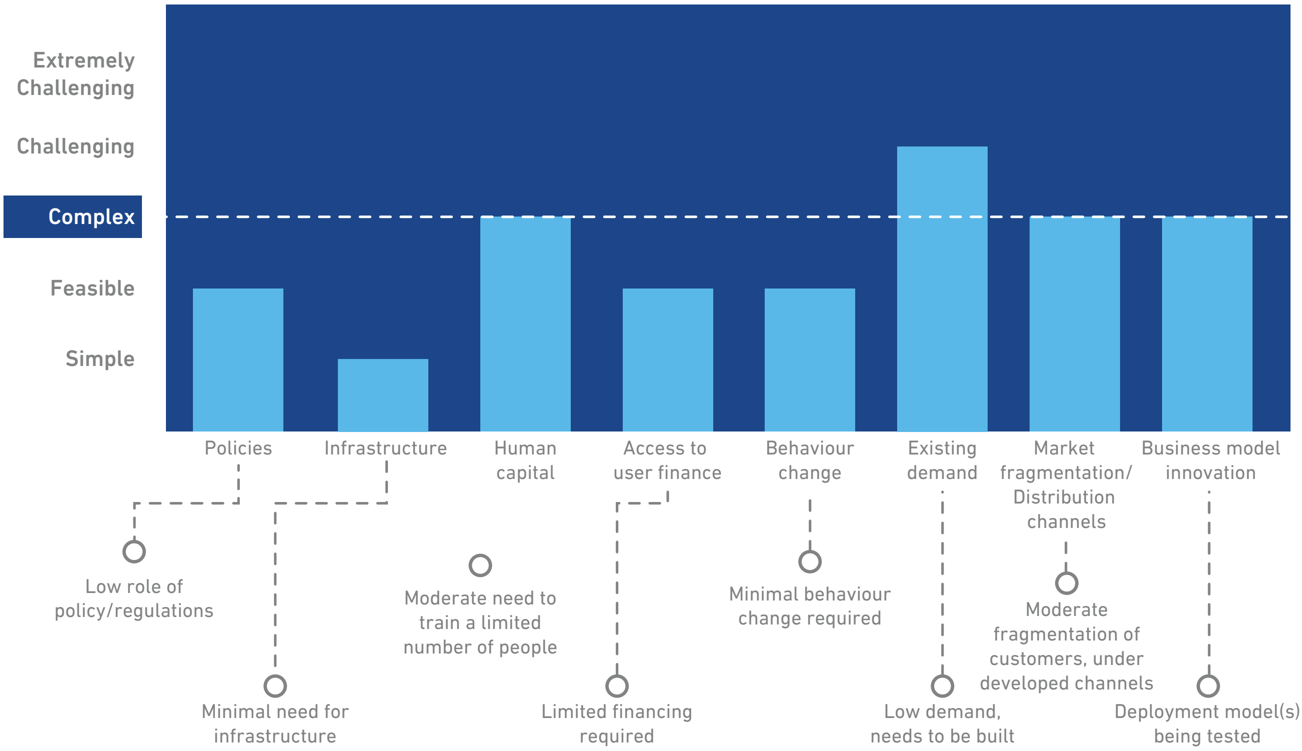
Portable sensing by trained staff using mobile devices with disposable one-time sensors could also be useful to increase the spatial density of measurements. Another approach to mobile sensing is community-based air and water quality monitoring, using low-cost portable sensors connected to smartphones that communicate results to the network.

This approach may face issues with data reliability due to incorrect sampling techniques or fraud, so would require additional validation. The initial cost of the hardware should be modest (less than $500), perhaps taking the form of a plug-in sensor that leverages the computing power of an existing mobile device. Cost of consumables should be low (less than $1 per test), allowing ubiquitous monitoring even in remote sites of low- and middle-income countries.

Progress is being made rapidly in the field of environmental monitoring, though there appears to be little focused effort towards the integrated technology we envision here. A basic form of air quality mapping using near real-time data from a global network of sensors can be found at http://aqicn.org/map/world/.

If sufficient resources were allocated to allow the necessary research and development efforts, we expect that it will take seven to ten years for this breakthrough to be ready for use. A significant deployment challenge is the lack of consumer demand for environmental monitoring. Therefore, deployment is likely to be COMPLEX.

Breakthrough 3: Difficulty of deployment



4 Sustainable, affordable, household-level fecal waste management system

A large share of the population in rural and peri-urban areas of many low-income countries lacks access to household toilets, and is habituated to open defecation. Many others have access to toilets, but of substandard type and capable of contaminating groundwater. This poses serious health risks in the form of diarrheal and other diseases. An effective household sanitation system must provide an initial hygienic separation of the fecal waste, as well as prevent opportunities for secondary exposure to the fecal pathogens such as surface and groundwater contamination. Ultimately, the fecal waste must be made harmless and definitively disposed of.

In rural and many peri-urban areas, the most appropriate sanitation system employs household-level collection and full on-site treatment of waste materials. Household-level sanitation is quite appropriate in rural areas, where extensive sewage networks would be prohibitively expensive due to low population density.

Household sanitation is also widely used in some higher density places such as peri-urban areas, where sewer networks have not reached. A wide range of on-site sanitation technologies have been developed, including pit latrines (single and twin pits), pour-flush pit toilets (with septic tanks, and single and twin leach pits), vermicomposting toilets, dry composting toilets, and anaerobic baffled reactor toilets.

However, existing on-site sanitation methods fall short is some regards. In some cases they do not safely contain fecal waste, instead letting it leak into groundwater aquifers. In other cases, the waste is safely contained in storage only temporarily, but eventually becomes full and must be emptied and can then cause broad contamination.

Despite our long experience accumulated with sanitation practices, there is a large gap for a sustainable, affordable, decentralized, on-site household sanitation solution for low-income households. Of the existing household sanitation technologies, vermicomposting toilets appear to provide relatively high performance at low cost, largely due to enhanced decomposition of fecal matter by earthworms, leading to less waste build-up and less frequent emptying and thus lower maintenance costs.

Current State

Development Stage: In-Market Small Scale

Deployment: Challenging

Associated 50BT Chapters

Water Security

Global Health

Gender Equity

SDG Alignment

3 Good Health and Well-Being

6 Clean Water and Sanitation

5 Gender Equality

Impact

Lives Saved (# of People/Year): <1M | 10M+ | 100M+ | 1B+

Health Improved (# of People): <1M | 10M+ | 100M+ | 1B+

Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

The development of improved on-site household sanitation systems should be viewed as a long-term solution to rural sanitation (and possibly peri-urban sanitation) rather than an interim fix, and should be given a high priority in resource allocation.

Sanitation facilities that are merely waste storage repositories, such as pit latrines, must be coupled with mechanisms for regular emptying of fecal sludge and transporting it to appropriate sites for processing or safe disposal. Facilities that include on-site treatment, such as vermi-filtration, generate smaller quantities of residue that must be disposed of.

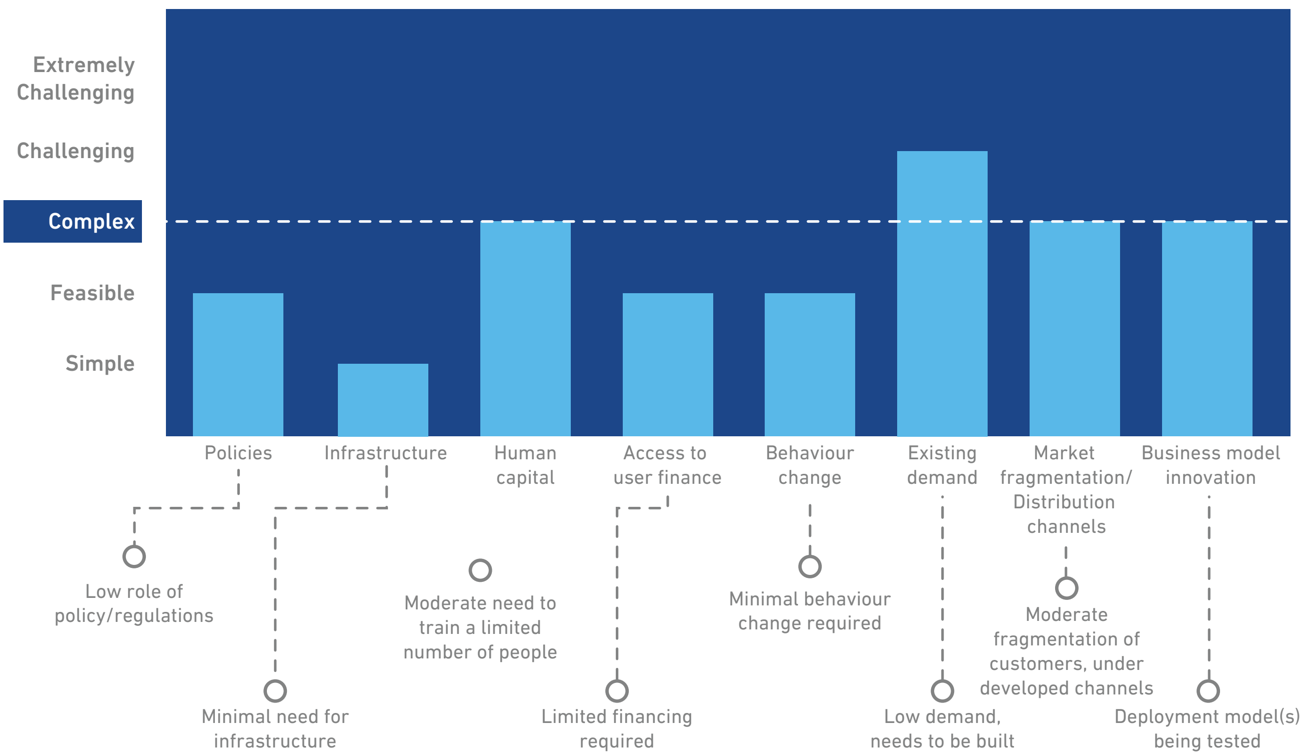
One potentially useful path may involve additives that facilitate the breakdown of fecal sludge, reducing the need to empty latrines. Researchers are currently developing and testing several options, including addition of higher organisms, microorganisms and hydrolytic enzymes.

In the longer term, opportunities could include use of fermenting organisms, development of new enzymes or facilitation of the current microorganisms involved in digestion. Regardless of the specific path, each step of the sanitation service chain is important to achieve effective waste management, from toilet siting and construction, to final treatment and disposal of waste.

Effective sanitation is challenging where there is no piped water or sewerage, as household toilets must be low-cost, have an effective method to control odor, a system for processing and disposing of waste, and occupy minimal space.

Significant experience has been gained on technical aspects of sanitation, but we lack full understanding of the important socio-cultural aspects. Initial technologies are already on the market, but the difficulty of deployment is CHALLENGING.

Breakthrough 4: Difficulty of deployment



5 Medium to large-scale sewage treatment process with recovery of water (and ideally nutrients and energy)

This imperative calls for the development and deployment of novel sewage treatment facilities that are net sources, rather than sinks, of resources. Primarily this applies to water resources, for treating and reusing the wastewater collected in sewer systems. Systems should enable reuse of the treated water for secondary purposes including industrial, recreational and agricultural applications.

A secondary focus is on energy resources, where sewage treatment facilities could operate with net zero energy inputs, and could even have the capability to produce energy for societal use. The recovery of nutrient resources from sewage, such as phosphorus or nitrogen, may also be a goal. Integrated sewage treatment can be viewed as a way to harvest clean, renewable sources of water, energy or nutrients while disposing of a waste product.

There is a great need for a low-cost, sustainable and scalable sewage management process for deployment in fast-growing cities in developing regions. In India, for example, less than 38 percent of the sewage that is generated is treated before being discharged into water bodies. The amount of resulting sewage in the environment is contributing to the country's health problems, including diarrheal outbreaks among children and lifelong stunting and wasting.

The massive organic and nutrient loading also has adverse environmental effects and leads to the destruction of ecological productivity of water bodies. Simultaneously, many growing cities have difficulty meeting the water needs of households and industries, due to physical constraints to water supply manifest as closed river basins and depleting groundwater stocks.

The quantities of wastewater generated in major cities are enormous, thus reusing this water for other purposes is a major lever for enhancing water security. For example, if 80 percent of the wastewater collected by urban sewage networks in India were reused, an additional water resource of 18 cubic kilometers per year would be obtained (ITT, 2018). What is lacking is an effective and affordable sewage treatment method that can rapidly scale up in developing regions.

Conventional wastewater treatment methods are a major resource sink, and should not be held as models for scalable sanitation methods for fast-growing cities in low-income countries. In the United States, for example, about 1.3 percent of all electricity is used for sewage treatment. This is a wasted opportunity, because raw sewage contains about six times more chemical energy than the amount of electrical energy required to treat it.

The most appropriate method of treatment for wastewater will depend largely on the intended use of the recycled wastewater and the scale of the treatment facility. Major reuse applications include agriculture (food and non-food crops), industry, and groundwater recharge, for which increasing effluent quality is required, respectively. For agricultural purposes, nutrient removal (or partial nitrogen removal) can be left out of the treatment process, whereas reuse in industrial applications or groundwater recharge requires nutrient and solids removal.

Current State

Development Stage: In-Market Small Scale

Deployment: Challenging

Associated 50BT Chapters

Water Security

Global Health

Global Change

SDG Alignment

3 GOOD HEALTH AND WELL-BEING

6 CLEAN WATER AND SANITATION

14 LIFE BELOW WATER

Impact

Lives Saved (# of People/Year)

<1M 10M+ 100M+ 1B+

Health Improved (# of People)

<1M 10M+ 100M+ 1B+

Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

Groundwater recharge applications may also require removal of micro-pollutants as well as organic carbon. In terms of costs, the higher the quality of treated effluent, the higher the total capital and operational costs are. Generally, larger treatment plants have an increased efficiency, which lowers the lifecycle costs and environmental impacts per cubic meter of treated water.

Novel sewage treatment methods followed by wastewater reuse is a potentially important lever for enhancing water security. Reusing wastewater brings two important benefits: less pollution entering water bodies, and less need for freshwater withdrawals.

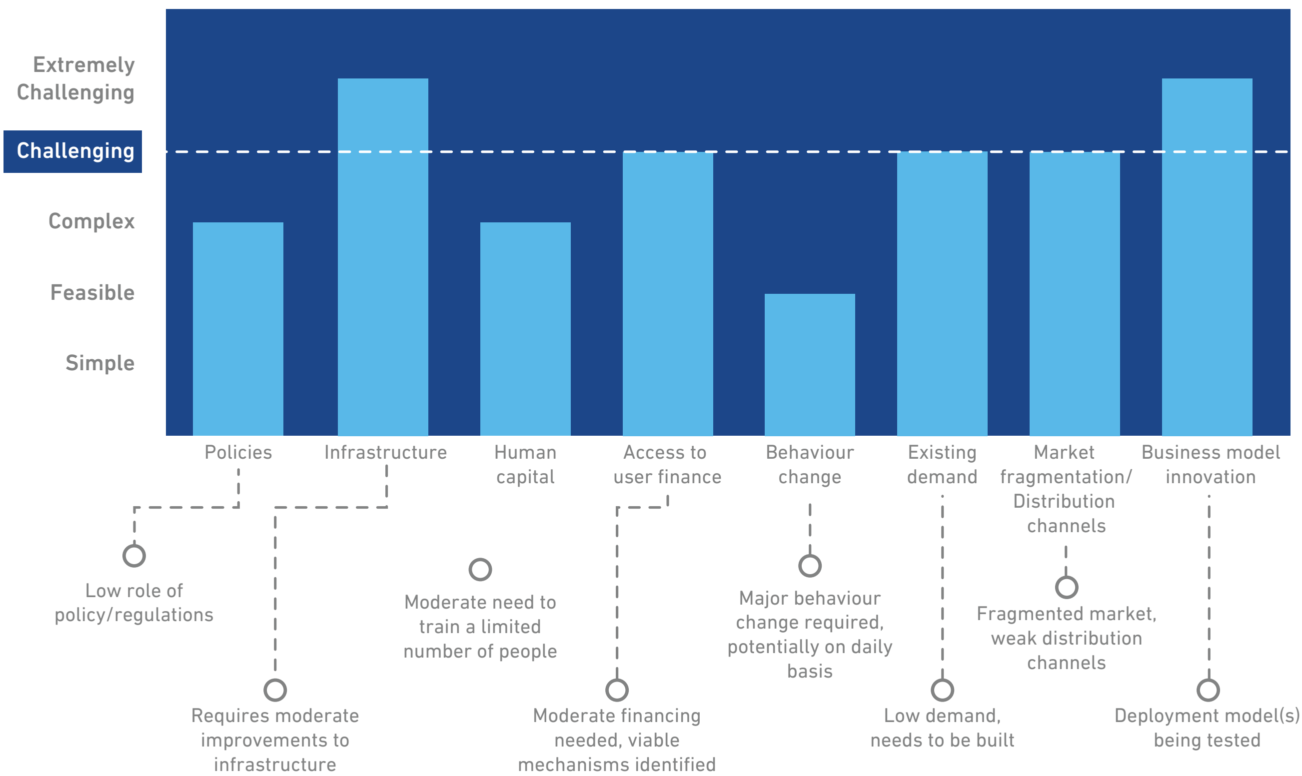
However, in the areas where it is currently practiced, wastewater reuse is typically considered as a temporary solution for acute needs, instead of implemented as a long-term solution to improve water security. Important criteria for successful treatment technologies include the extent of land area required, the economic resources needed for capital and O&M, and the quality requirements for the reused water.

Land area requirements, in particular, may be an impediment to scale-up of some technologies. Different technology solutions may be appropriate for different settings as the scale increases from household to neighborhood and metropolitan level.

There are many challenges to sanitation infrastructure deployment, and business models should not expect to extract high-value content from sewage. Sanitation systems tend to have fairly high up-front costs and require skilled labor to install and maintain. Distribution channels are also poorly defined. In addition, significant public investment is likely to be still required.

Some promising technologies have entered the market, and others should become market-ready in the coming years. Given the lack of proven models and the growing scale of the urban sanitation problem, the level of difficulty for deployment is CHALLENGING.

Breakthrough 5: Difficulty of deployment



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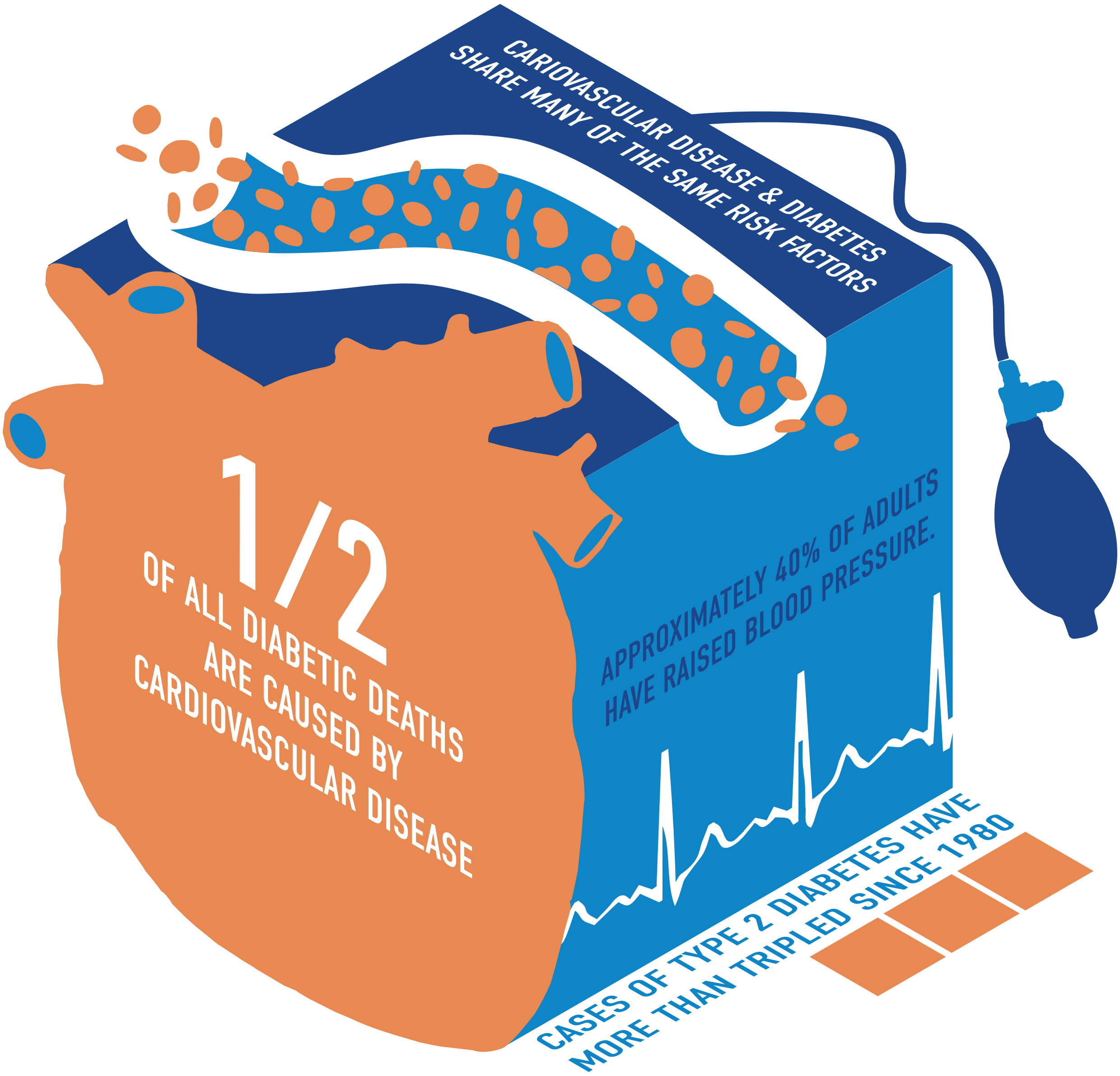


NON-COMMUNICABLE DISEASES

INTRODUCTION

In many low- and middle-income countries (LMICs), non-communicable diseases (NCDs) are becoming an increasingly important health concern, as the populations experience economic growth, increasing urbanization and declining disease burden from infectious disease.

According to WHO, out of 57 million global deaths in 2016, about 71 percent were due to noncommunicable diseases (NCDs), with cardiovascular diseases (17.9 million), cancers (9.0 million), diabetes (1.6 million) and chronic respiratory diseases (3.8 million) having the greatest burden. Earlier considered as primarily a problem of high-income countries, NCDs today disproportionately affect LMICs, with more than three quarters of NCD deaths occurring in these countries (WHO, 2016).

The leading cause of mortality amongst NCDs is cardiovascular disease (CVD), which represents 43 percent and 34 percent of NCD mortalities in South Asia and sub-Saharan Africa, respectively (IHME GBD, 2017). Contributing to this figure, and driven by many of the same risk factors, is diabetes, often considered a parallel epidemic.

Diabetes is a key risk factor for CVD; half of all diabetic deaths are caused by CVD. Other key risk factors for CVD include hypertension, smoking, raised cholesterol and being overweight. Of these, hypertension is considered the most crucial. It is estimated that between 10 and 20 million people out of the approximately 650 million people living in sub-Saharan Africa may have hypertension (Opie & Seedat, 2005).

It is estimated that 60 percent of the world's new cases of cancer are diagnosed in LMICs (Sukhun, et al., 2017), with 70 percent of cancer deaths occurring in these countries (WHO, 2018). While cancer incidence and mortality rates, in particular breast and cervical cancers, have remained stable and even lowering in many high-income countries, they are increasing rapidly in LMICs. More concerning is the particularly high age-standardized mortality rates in Africa with respect to incidence rates (Azubuike, et al., 2018).

Key drivers of NCD mortality and risk factors include demographic trends, such as increasing life expectancy, increased urbanization and inactivity, poor diets and high rates of smoking, along with genetic risk factors like predisposition to diabetes and hypertension.

In addition to these are challenges in the delivery of care. Medical systems in most developing countries were designed to treat infectious diseases rather than NCDs, and most developing countries are still early in the development of their national NCD programs. Diagnostics and treatments, in particular for cancers, are expensive and inaccessible in most LMICs.

In 2015, India became the first country to develop specific national targets and indicators aimed at reducing the number of global premature deaths from NCDs by 25 percent by 2025 in line with the WHO's global action plan for the prevention and control of NCDs.

Two technological advances show potential for tackling the growing burden of NCDs:

- Breakthrough 36. Affordable, home-use point-of-care diagnostics suite (blood, urine, vitals) for the common NCDs
- Breakthrough 37. Affordable wearable technology with broader functionality for patient adherence and monitoring of health status

Non-communicable diseases (NCDs) are becoming increasingly prevalent in low- and middle-income regions. Over the past few decades, life expectancy and incomes in developing countries have increased substantially, allowing for more prosperous and older populations.

CORE FACTS AND ANALYSIS

1. Non-communicable diseases (NCDs) are a growing health risk in developing countries

NCDs in 2017 accounted for 62 percent of total DALYs worldwide, 55 percent of DALYs in South Asia and 30 percent of DALYs in sub-Saharan Africa (IHME GBD, 2017).

NCD mortality attribution is shown in **Exhibit 1**, and demonstrates an increase in the NCD burden of disease in low-income countries and LMICs over the last decade.

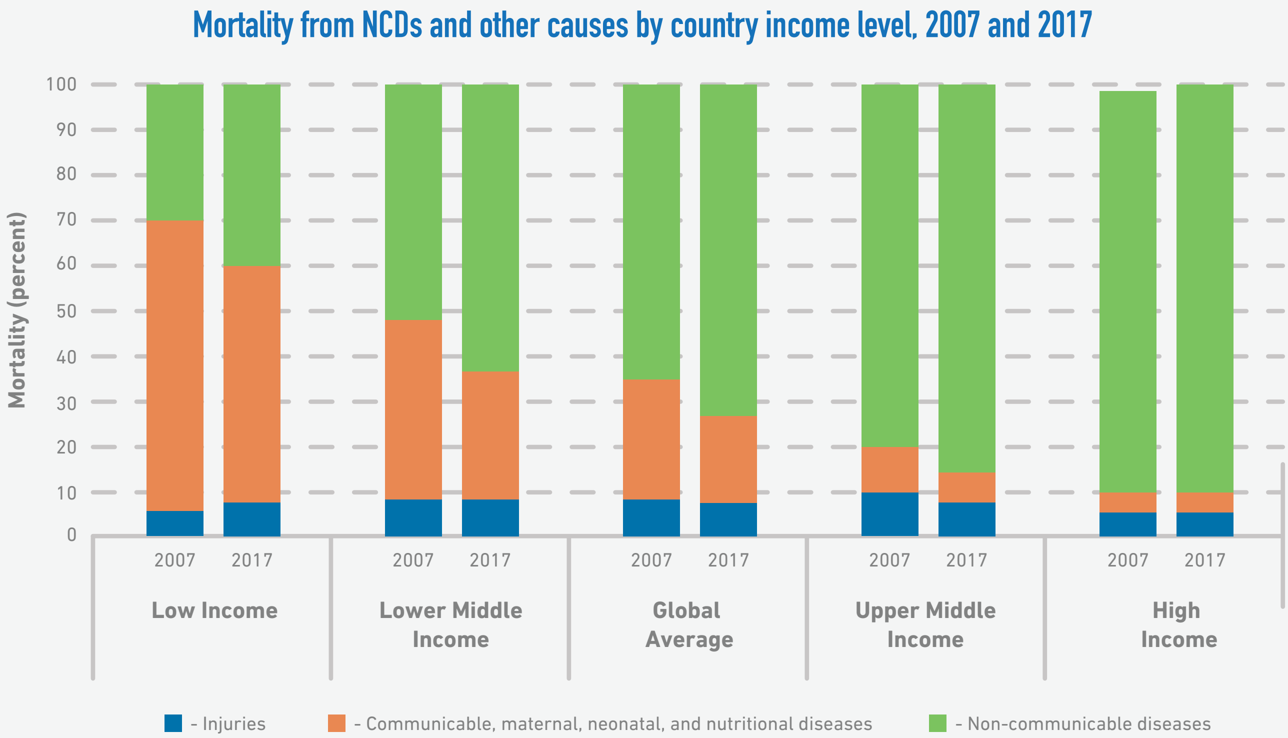


Exhibit 1: : As countries become wealthier, NCDs contribute increasingly to overall deaths. While communicable disease burden has decreased, the burden of disease from NCDs in low-income and lower-middle-income countries has increased over the past decade. (Source: IHME GBD, 2007 & 2017)

As life expectancies and incomes increase in South Asia and sub-Saharan Africa, so too has the relative importance of NCDs in public health (**Exhibit 2** and **Exhibit 3**).

As is the case with the rest of this study, this section also focuses primarily on sub-Saharan Africa and South Asia.

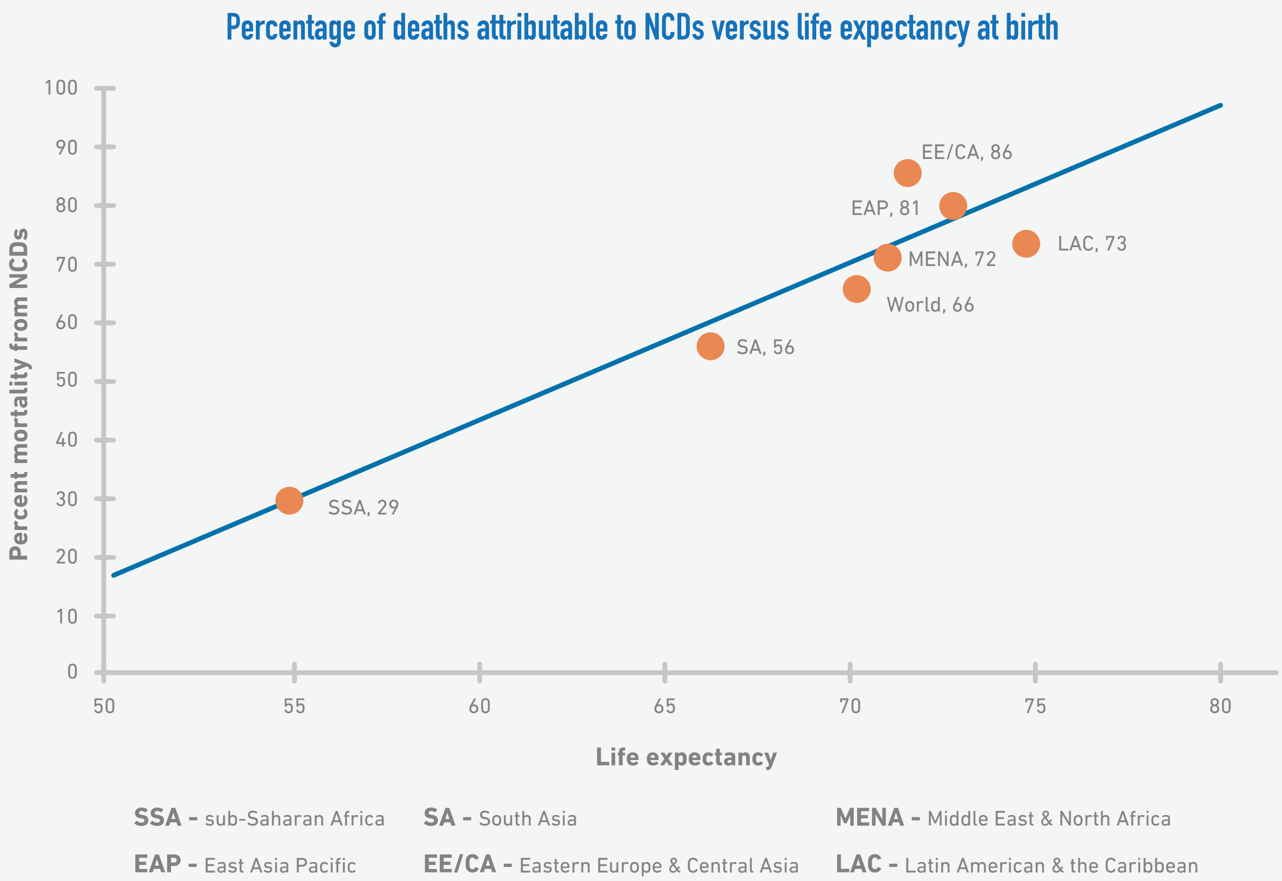


Exhibit 2: As life expectancy increases, the attributable share of mortality due to NCDs rises. Sub-Saharan Africa and South Asia's low life expectancies and young populations explain in part why NCDs are not as significant a source of mortality in these regions as in the rest of the world. As the populations in these regions age, NCDs are expected to occupy a greater share of causes of mortality. (Source: WHO, 2013; UNDP, 2013)

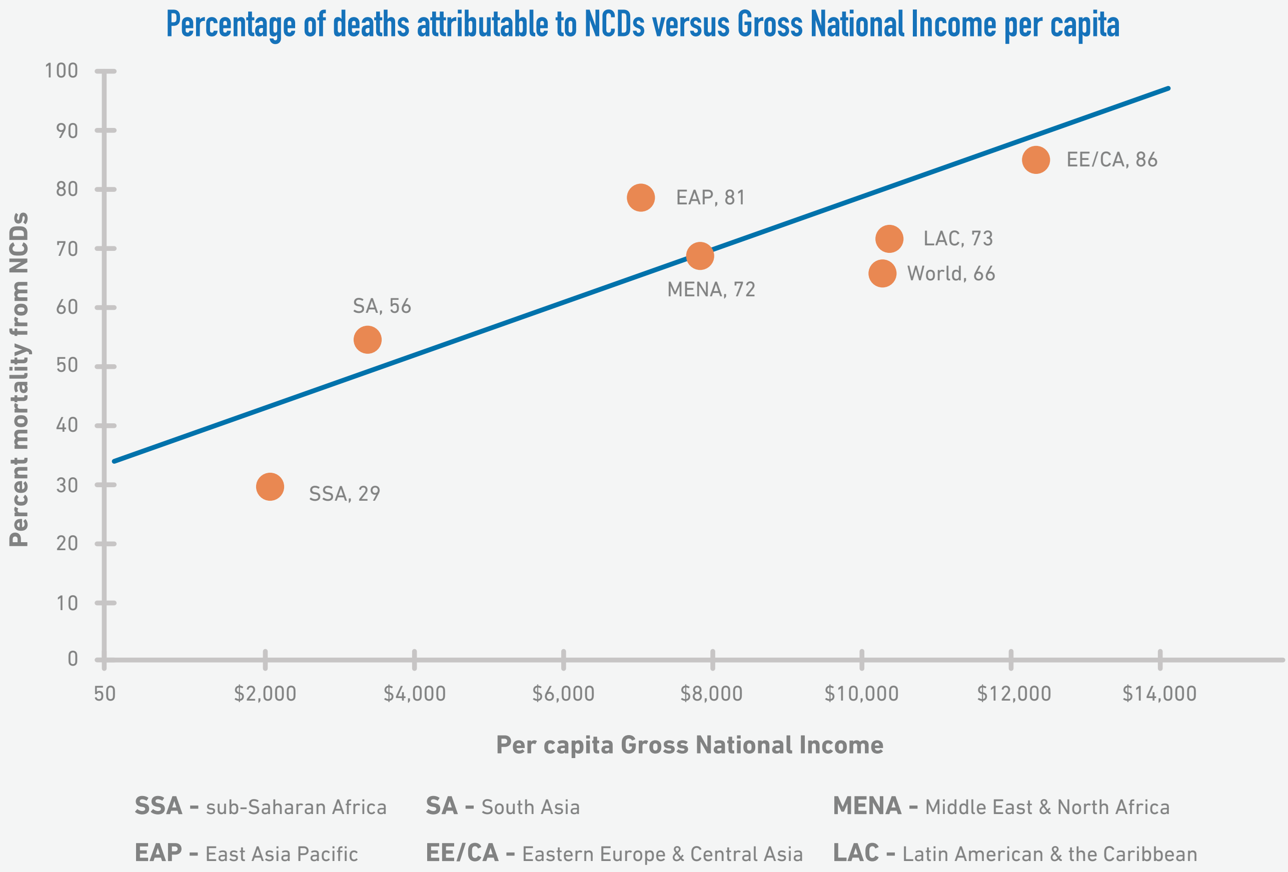


Exhibit 3: As incomes rise, the attributable share of mortality due to NCDs rises. Higher incomes accompany urbanization, richer diets and sedentary lifestyles. In addition, higher incomes enable governments to provide more resources to controlling communicable diseases, feeding into the longer life expectancies seen in Exhibit 2. (Source: WHO, 2013; UNDP, 2013)

2. Cardiovascular disease: the leading NCD killer

Among NCDs, cardiovascular disease (CVD) is the single largest cause of death (**Exhibit 4**). CVD causes nearly one-third of all NCD deaths in South Asia and sub-Saharan Africa and is more than twice as prevalent as cancers—the next largest NCD category in these regions.

While CVD prevalence rates in developing regions are low due to young populations, age-standardized mortality rates are among the highest in the world. As mentioned above, hypertension is one of the most crucial risk factors for CVD. An estimated 15 to 30 percent of people in sub-Saharan Africa have hypertension. Of greater concern, however, is the low percentage of hypertension awareness, treatment and control (Ataklte, et al., 2015).

Higher age-standardized prevalence and lack of treatment options in low-income countries indicate that the combination of younger populations, higher communicable disease burdens, and low awareness and diagnosis of key risk factors are masking a CVD problem that will manifest itself more acutely as countries successfully address other public health burdens.

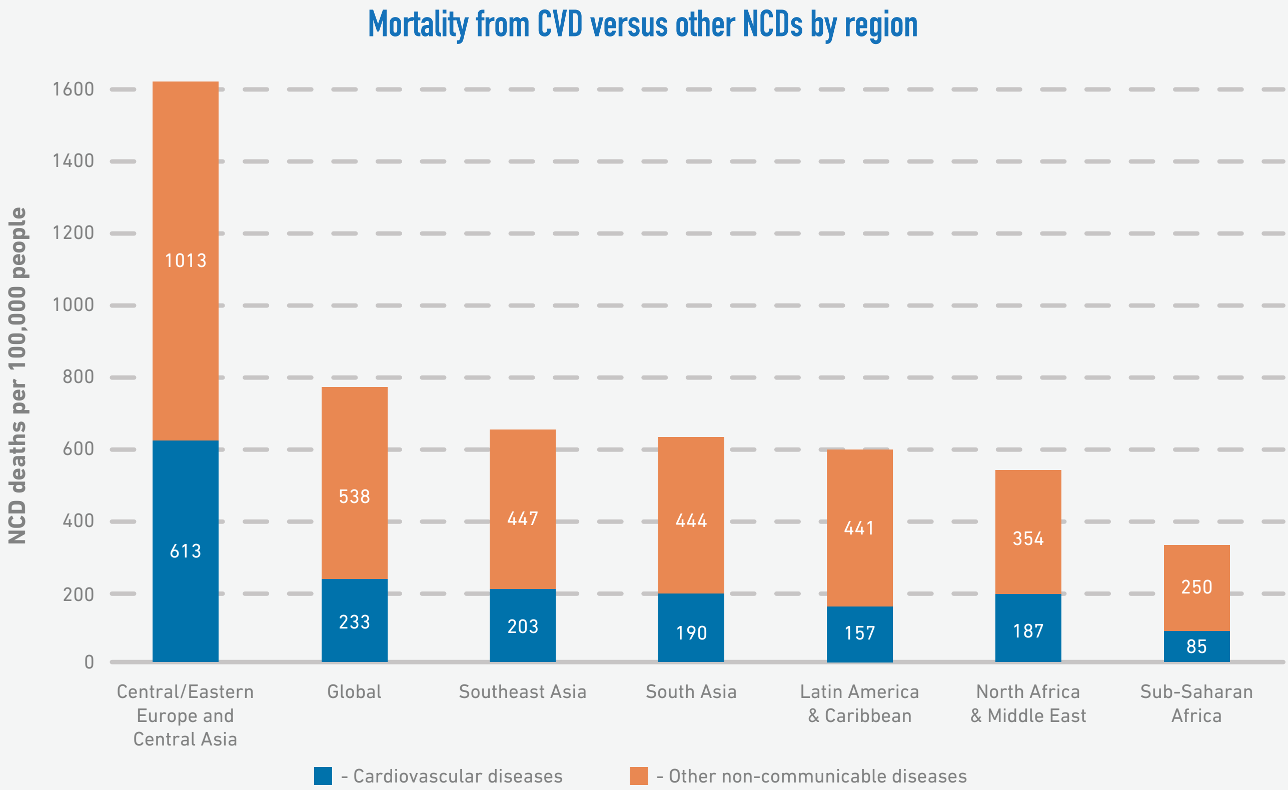


Exhibit 4: In most regions, CVD represents about a third of all deaths from NCDs. (Source: IHME GBD, 2017)

CVD encompasses a range of conditions afflicting the heart and circulatory system. Notably, two conditions in this category account for 80 percent of all NCD mortality.

Ischemic heart disease

Also known as coronary heart disease, ischemic heart disease is characterized by the reduction of blood flow to the heart, usually due to atherosclerotic build-up in arteries. This disease is the leading cause of acute myocardial infarctions (AMI) commonly referred to as 'heart attacks.'

An AMI can rapidly cause permanent heart damage or death. In 2017, ischemic heart disease was responsible for 50 percent of CVD deaths worldwide, and 57 and 42 percent of CVD deaths in South Asia and sub-Saharan Africa respectively (IHME GBD, 2017). Ischemic heart disease is the leading cause of death in South Asia, accounting for 15 percent of all deaths in the region (IHME GBD, 2017).

Cerebrovascular disease

More commonly known as a 'stroke,' cerebrovascular disease results from a disturbance in blood flow to the brain, usually either through lack of blood flow or a blockage. More than one-third of CVD victims are killed, and another third are permanently disabled, by strokes.

In 2017, strokes accounted for 30 percent and 36 percent of all CVD fatalities in South Asia and sub-Saharan Africa, respectively (IHME GBD, 2017). Cerebrovascular disease is the second most significant cause of NCD death and the fifth highest overall cause of death in sub-Saharan Africa (WHO, 2016).

3. Diabetes: a parallel epidemic

While diabetes is a separate disease, it shares many risk factors with CVD, particularly poor diet and not enough exercise. Diabetes is also one of the leading risk factors for CVD, the latter being a leading cause of death for diabetics. Half of diabetic deaths are caused by CVD. This is due both to the co-occurring risk factors with CVD as well as additional risk factors unique to diabetes, such as high fasting blood sugar. Given the close relationship between the two, including common risk factors, we consider these diseases in tandem.

Diabetes mellitus, known simply as diabetes, refers to a group of diseases in which the body is unable to metabolize sugar. In Type 1 diabetes, also known as juvenile diabetes because it disproportionally affects children, the pancreas does not produce adequate insulin to break down the sugar. In Type 2 diabetes, also known as adult-onset diabetes because it occurs later in life, the body still produces insulin, but cells lose their ability to use the insulin to metabolize sugar. The third type of the disease, gestational diabetes, occurs when pregnant women suffer from very high glucose levels because their insulin receptors are disrupted.

Of the three types of diabetes, the overwhelming share of the disease burden in developing countries (90 percent) is due to Type 2 (IDF, 2013), which is the focus of this section. Type 2 diabetes doubles the risk of CVD and can cause retinopathy and blindness, reduced blood circulation to limbs (which can lead to severe complications such as gangrene), long-term nerve damage and kidney failure.

Diabetes has grown rapidly in the past two decades. The number of people with diabetes globally has more than doubled between 1990 and 2017, from 211 million to 476 million (IHME GBD, 2017). This number is expected to increase to 592 million in 2035 (IDF, 2013).

In developing countries, 70 percent of this increase can be attributed to population growth and aging, while the remaining 30 percent is considered to be due to increasing prevalence (Danaei, et al., 2011). Prevalence of Type 2 diabetes in sub-Saharan Africa between 1960 and 1980 was lower than 1 percent but now stands at 4.8 percent and is expected to grow to 5.3 percent by 2035 (Mbanya, et al., 2010; IDF, 2013). Prevalence in South Asia is predicted to increase from 8.2 percent currently to 10.1 percent by 2035 (IDF, 2013).

4. Metabolic syndrome and key risk factors

Increase in both CVD and diabetes has been linked to growth in metabolic syndrome and the risk factors associated with it. Metabolic syndrome is a cluster of five risk factors for CVD: central (abdominal) obesity, raised triglycerides, reduced HDL cholesterol, raised blood pressure and raised fasting plasma glucose.

Individuals are considered to have metabolic syndrome when they have central obesity and at least two of the remaining four risk factors. People with metabolic syndrome are twice as likely to die from CVD, and three times as likely to have a heart attack or stroke, as people without the syndrome. They are also five times more likely to develop Type 2 diabetes (IDF, 2006).

It is estimated that 20 to 25 percent of the world's adult population has metabolic syndrome. While each of these factors independently increases the risk of CVD, the clustering that indicates metabolic syndrome appears to confer an additional cardiovascular risk beyond the sum of the individual risk factors (IDF, 2006).

The underlying causes of metabolic syndrome are still not fully understood, but insulin resistance and central obesity are believed to play key roles, in addition to genetics, physical inactivity, aging, a pro-inflammatory state and hormonal changes (IDF, 2006).

Cardiovascular disease has several additional risk factors beyond metabolic syndrome and its contributing risk factors. The Interheart and Interstroke studies focused on CVD specifically and identified nine major risk factors, which are believed to drive 90 percent of the cerebrovascular and AMI burden. These risk factors and the odds an individual will have CVD relative to those without the risk factors are shown in **Table 1** (O'Donnell, et al., 2010; Yusuf, et al., 2004).

Addressing CVD involves tackling the risk factors that drive it (**Table 1**). The most important and broad reaching risk factor is hypertension, which contributes to 45 percent of ischemic heart disease deaths and 51 percent of cerebrovascular disease deaths worldwide (WHO, 2013).

The prevalence rate of hypertension in Africa is 67 percent—the highest in the world (IHME GBD, 2017). Hypertension is primarily driven by age, genetics and certain behavioral factors like poor diet, lack of exercise, obesity, alcohol abuse and psychosocial stress.

Odds ratios[1] of various risk factors and AMI or Stroke (odds ratio greater than one indicates positive association)

Risk Factors	AMI	Stroke
Hypertension	1.9	2.6
Smoking	2.8	2.1
High cholesterol	3.3	1.9
Diabetes	2.4	1.4
Overweight	1.1	1.7
Diet*	0.7 (healthy diet)	1.4 (unhealthy diet)
Excercise*	0.9	0.7
Moderate alcohol*	0.9	0.9
Psychosocial stress	2.7	1.3

Table 1: Various risk factors increase the likelihood of a serious CVD incident. These risk factors are responsible for 90 percent of the CVD burden worldwide. (Source: O'Donnell, et al., 2010; Yusuf, et al., 2004) *These are protective factors, which protect against CVD. Diet was defined as healthy diet for the Interheart study and unhealthy diet in the Interstroke study.

[1]Odds ratio is the likelihood that someone with a particular risk factor (for example, hypertension) will have a particular outcome (such as AMI) relative to the likelihood that someone without that risk factor will have the same outcome.

5. Cancer

Cancer is the second leading cause of death globally. While the rate of new cancer cases in 2018 found in LMICs stands at 60 percent, it is estimated that this figure will increase to 75 percent by 2030 (Globocan, 2012). Much of the increasing rate comes from cancer-causing infections, such as hepatitis and human papilloma virus (HPV). These two infections are already responsible for up to 25 percent of cancer cases in LMICs (Plummer, et al., 2016).

Many cancers are now less deadly, and some are treated almost like a chronic disease. But while less than 50 percent of people diagnosed with cancer in high-income countries die from their disease, 66 percent of their counterparts in LMICs do (Al Sukhun, et al., 2017).

WHO estimates that 70 percent of all deaths from cancer occur in LMICs (WHO, 2018). Two of the biggest killers are cervical and breast cancer, with two out of three breast cancer deaths, and nine out of ten cervical cancer deaths occurring in these countries.

These two types of cancer kill almost three times as many women every year as the complications of pregnancy and childbirth, yet currently receive much less attention (The Lancet, 2016).

Around one third of deaths from cancer are due to the five leading behavioral and dietary risks: high body mass index, low fruit and vegetable intake, lack of physical activity, tobacco use, and alcohol use.

Many cases of cancers, between 30 to 50 percent, are shown to be preventable by avoiding these risk factors and using tried and tested prevention strategies. There are also cost-effective strategies, such as routine human papillomavirus (HPV) vaccination of girls and cervical screening with treatment of pre-cancers that are highly effective in preventing cervical cancer (The Lancet, 2016).

The low survival rates in less developed countries can be explained mainly by the lack of early detection programs, resulting in a high proportion of people presenting with late-stage disease, as well as by the lack of adequate or affordable diagnosis and treatment facilities.

KEY CHALLENGES

In South Asia and sub-Saharan Africa, the drivers of NCD mortality can broadly be classified into two groups (WHO, 2013):

1. Demographic, behavioral and genetic risk factors

2. Challenges in delivery of medical care

1. Demographic, behavioral and genetic risk factors

People are living longer

As mentioned earlier, life expectancy in developing countries has increased substantially over the past several decades through a combination of economic development, successes in combating infectious diseases and improved access to basic healthcare and nutrition.

These gains in life expectancy have resulted in the populations of these countries getting older. By 2025, the number of Africans over the age of 60 years is expected to double (Mbewu, 2009). Older populations are more vulnerable to NCDs like CVD and Type 2 diabetes, as shown in **Exhibit 5**.

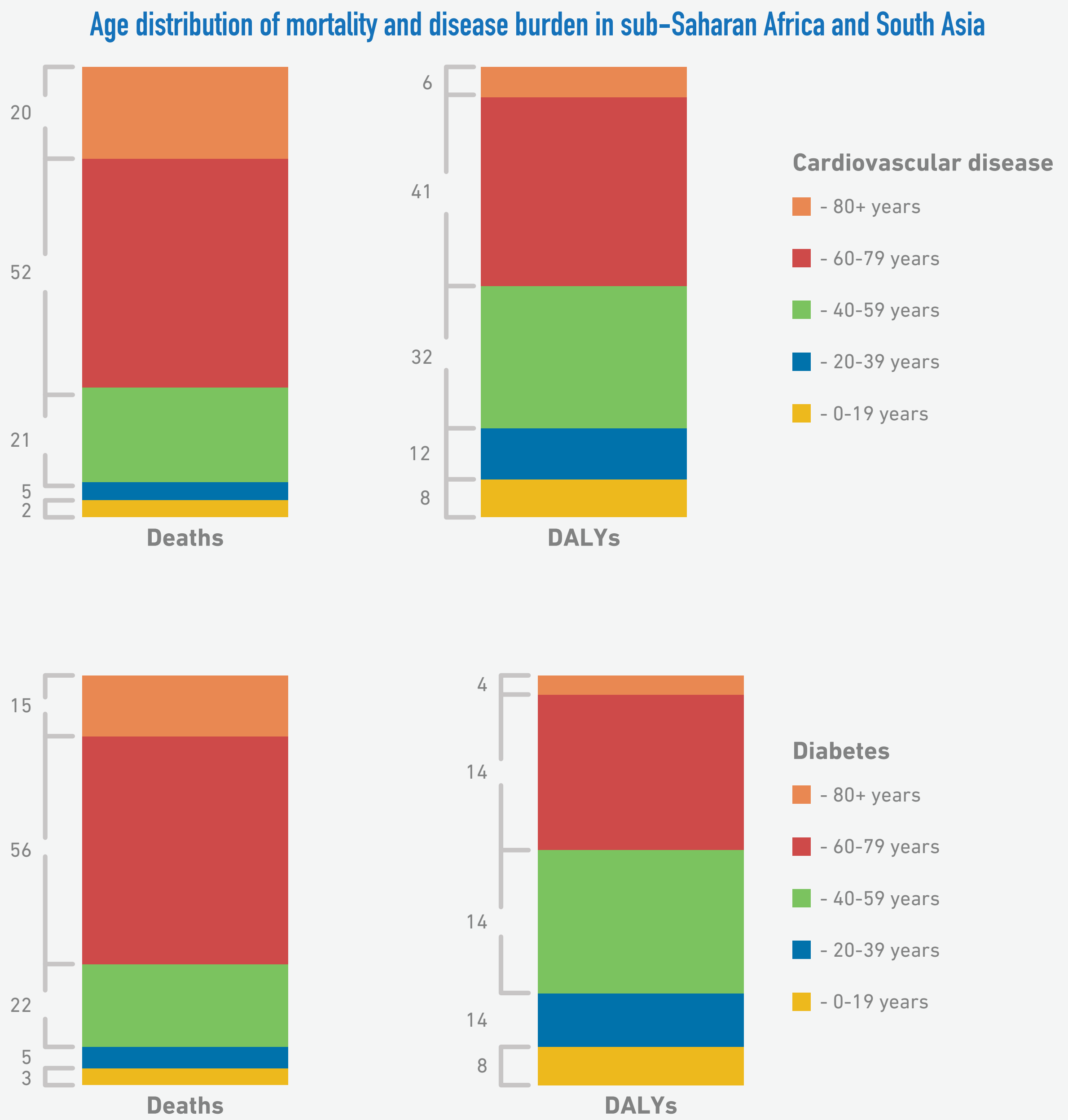


Exhibit 5: As life expectancy increases in developing countries, the population becomes susceptible to a different class of diseases, such as CVD and diabetes, which disproportionately affect older people. (Source: IHME, 2012)

Urbanization and inactivity

There has also been an increase in the rate of urbanization in developing countries, which is linked to an increase in NCDs due to reduced physical activity and less healthy diets. As **Exhibit 6** shows, urban populations tend to have higher rates of diabetes than their rural counterparts. The lower levels of physical activity are also contributing to higher rates of systolic blood pressure, a significant risk factor for CVDs in African countries.

The bulk of the increase in CVD in India occurred in urban settings (Gupta, et al., 2008) and obesity has nearly doubled in urban areas of India between 1991 and 2006 (Cecchini, et al. 2010). In Africa, the highest rates of diabetes are among urban and peri-urban communities in South Africa (Mbanya, et al., 2010).

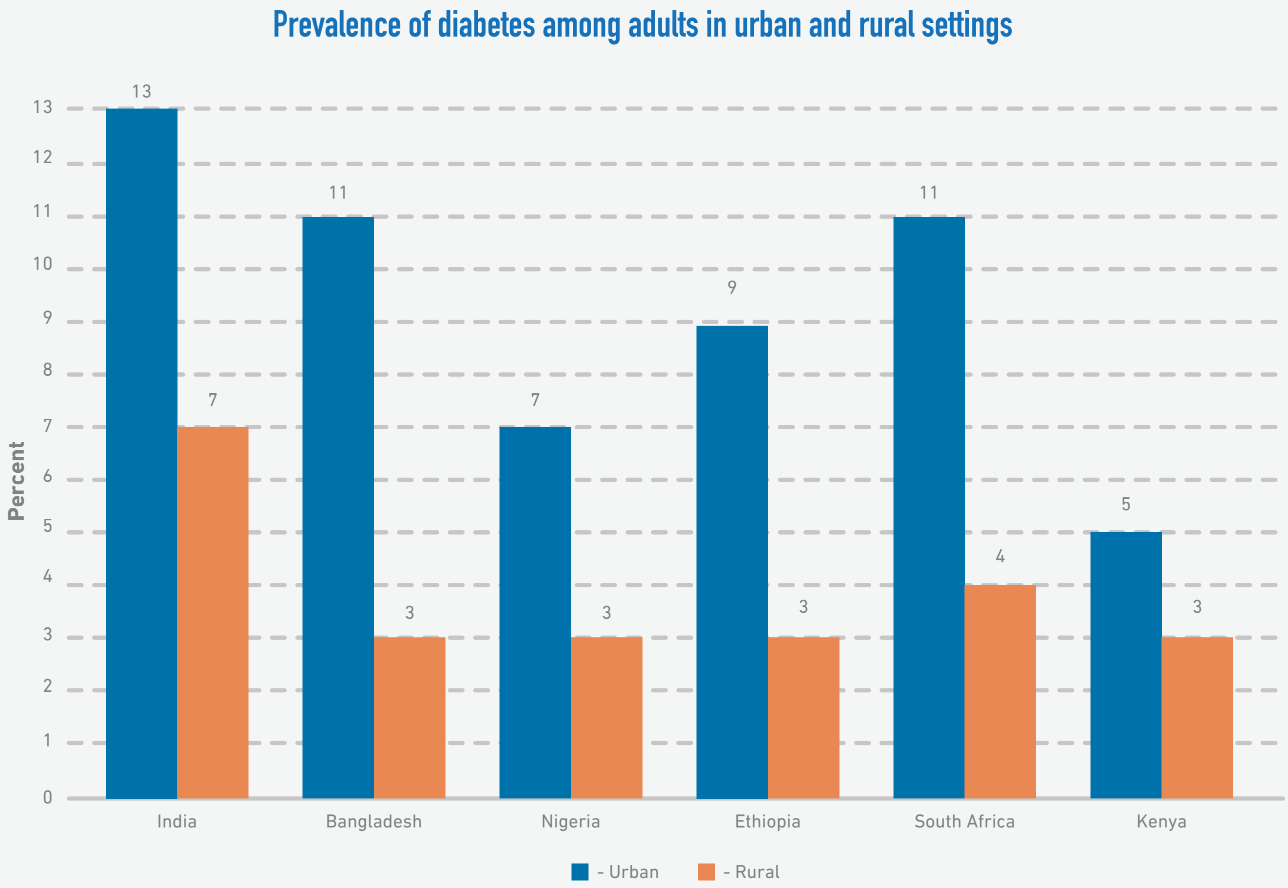


Exhibit 6: Urban populations suffer substantially higher rates of diabetes, likely due to factors such as lower levels of physical activity and higher consumption of processed foods. (Source: IDF, 2013)

Poor diets, high in processed foods

Dietary patterns in developing countries have also been changing (Pingali, 2004). Diets in low-income countries often fail to meet the criteria for healthy eating (classified by the Alternative Healthy Eating Index).

In some countries, such as in India, traditional foods have always been high in refined carbohydrates (for example, white rice), sugar, salt and tropical oils (Gupta, et al., 2011; Hu, 2011) and have been a major contributor to diabetes. Unhealthy diets also contribute to hypertension (Institute of Medicine, 2010; Hu, 2011).

High rates of smoking

Tobacco use is a significant risk factor for heart disease, diabetes and cancer. It is associated with a three-fold increase in the risk of non-fatal AMI (Teo, et al., 2006) and a 45 percent increased risk of diabetes (Hu, 2011). Tobacco use is also found to be responsible for approximately 22 percent of cancer deaths (WHO, 2018). It is estimated that 82 percent of the world's tobacco smokers live in developing countries (Teo, et al., 2006).

High blood pressure

Hypertension is caused by the previously mentioned risk factors, as well as genetics and a high intake of salt.

Globally, it is estimated than 40 percent of adults have raised blood pressure. In Africa, 46 percent of adults have raised blood pressure, higher than any other region in the world (WHO, 2013), which is particularly high considering that the demographic risk factors that generally influence hypertension are less pronounced in sub-Saharan Africa relative to other regions (meaning sub-Saharan Africa has a small middle class, is still largely rural and has lower rates of obesity).

Hypertension is diagnosed easily either through an electronic blood pressure cuff or through an inflatable pressure cuff and a stethoscope. Hypertension is treated with two inexpensive and generic drugs—captopril and nifedipine—which are generally available, although they must be taken on a daily basis.

Diabetes

As mentioned earlier, while diabetes is a condition on its own, it is also a critical risk factor for CVD, with half of all deaths of diabetic individuals being caused by CVD.

Diabetes is diagnosed using a glucometer—a blood glucose measurement device—which costs $10 to $20, although it requires single-use enzymatic strips. These strips are inexpensive to manufacture but are proprietary, which means specific strips work with specific glucometers.

This limits the availability of low-cost strips in developing countries with small existing markets. Treatment of diabetes is challenging relative to high blood pressure. Early stage Type 2 diabetes can often be managed using only oral medication. Once the disease becomes more advanced, however, injectable insulin is required, which is more expensive, challenging to administer, requires a constant supply and has some sensitivity to temperature.

Moreover, patients being treated for both early stage and late stage diabetes need access to a glucometer to monitor their blood glucose on a daily basis.

2. Challenges in diagnosis and delivery of care

Healthcare systems in developing countries were built to primarily treat infectious diseases, where treatment occurs over a fixed period of time or care is focused on certain, distinct life events like birth, early childhood or pregnancy.

Chronic diseases like CVD and diabetes require different approaches to care, particularly mechanisms for broad screening and systems that facilitate disease management and patient compliance with treatment over the course of years, rather than weeks or months. The lack of appropriate delivery systems is compounded by patients' approach to medicine in developing countries, where the concept of lifelong medication is unfamiliar.

Even in the United States, it is estimated that only about a third of individuals with hypertension are managing it effectively. For cancer, challenges range from the lack of oncology specialists, to unavailable and unaffordable diagnostics and treatment. Access to cancer prevention and screening programs and modern treatment facilities, including surgery, radiation therapy, imaging and pathology, is limited. In 2017, only 26 percent of low-income countries reported having pathology services generally available in the public sector (Al Sukhun, et al., 2017). Radiation therapy, the most common way to treat cancer, exists in less than 50 percent of African countries.

Numerous studies have concluded that the main challenge to decreasing cancer mortality has been the lack of will, effort and investment to implement cost-effective interventions.

Many common cancers, for example cervical cancer, are preventable with high-impact interventions that do not require specialist equipment or expertise. Screening programs can increase early detection and diagnosis, which can greatly improve survival rates. Moreover, only one in five LMICs have the necessary data to drive effective cancer policy (WHO, 2018).

Important emerging trends in point-of-care diagnostics involve the development of biosensors, lateral flow tests, and integrated or lab-on-a-chip technologies. A growing number of such devices for diagnosis of cancers and cardiac disease are becoming commercially available (**Table 2**), but have had limited adoption in developing economies.

Data analytics and artificial intelligence, such as image detection methods, are also showing promise in enhancing and reducing the complexity of robust diagnostic methods such as the pap smear (Lehigh University, 2017).

Diagnostics for cancer and cardiac disease

	Company	Product Name	Disease	Analyte/Antigen (Ag)	Required sample	Detection Time (Min)	Sensitivity	Specificity
Cancer	CTK Biotech	On Site PSA Rapid Test	Prostate cancer	Prostate specific antigen (PSA)	60-90 uL of S/P	10	Relative: 100%	Relative: 99%
	Alere	Alere NMP22 BladderChek	Bladder cancer	Nuclear matrix protein (NMP22)	4 drops of Urine	30	99% when combined with cystoscopy	99% NPV along with cystoscopy
	Alere	Clearview iFOBT	Colon cancer	Faecal Occult Blood	Faeces	5	93.60%	99.10%
	Arbor Vita Corp.	OncoE6 Cervical Test	Cervical cancer	E6 oncoproteins	Cervical swab	150	84.6%	98.5%
	Quicking Biotech Co. Ltd	CA125 rapid test kit	Ovarian cancer	CA125 Ag	100 uL of S	10	-	-
	Innovation Biotech	AFP Test	Hepatocellular Cancer	Alpha fetoprotein Ag	S/P	10	25 ng/mL	99%
Cardiac Diseases	LifeSign	StatusFirst CHF NT-proBNP	Congestive Heart Failure	NT-proBNP	3 drops of P	15	20 pg/mL	-
	BTNX Inc.	Rapid Response CK-MB Test	Myocardial infarction (MI)	Creatine kinase MB (CKMB)	WB/S/P	10	5 ng/mL	99.80%
	Boditech Med Inc.	ichroma™ CK-MB Test	Myocardial infarction (MI)	Creatine kinase MB (CKMB)	75 uL of WB/S/P	12	3 ng/mL	-
	Response Biomedical Corp.	RAMP MYOGLOBIN TEST	Acute myocardial infarction (AMI)	Myoglobin	WB	10	2.36 ng/mL	-
	Trinity Biotech	Meritas® Troponin I	Myocardial infarction (MI)	Troponin I	200 uL of WB/P	15	0.036 ng/mL	-
	BRNX Inc.	RAPID RESPONSE D-DIMER TEST	Venous Thromboembolism (VTE)	D-Dimer	WB/P	10	500 ng/mL	-
	American Screening Corp.	Instant-View Troponin I	Acute myocardial infarction (AMI)	Troponin I	2-- uL of WB/S	10-20	-	-

WB - Whole Blood S - Serum P - Plasma CSG - Cerebrospinal fluid

Table 2: Overview of commercially available lateral flow test strips for diagnosis of cancers and cardiac disease. (Source: Sharma, et al., 2015)

SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

CVD, diabetes and cancer are major public health challenges that require systemic interventions, such as policy and healthcare system strengthening. While technology can support this, lack of technology is not the key bottleneck preventing a reduction in NCD mortality.

The decrease in CVD mortality in developed countries can be linked with three pivotal aspects: increased awareness of CVD and its risk factors, timely diagnosis and access to treatment. Reducing risk factors requires nutritional awareness and access to healthy foods, environments that enable physical activity, and actively discouraging the use of harmful substances like tobacco.

Such national level behavior change interventions rely largely on government policy and implicitly demand economic development. Developing the medical system to provide more appropriate diagnosis and care for patients is also critical. Similarly, increased awareness of risk factors, plus many cost-effective, non-technology dependent interventions, can increase early detection and diagnosis of common cancers.

Implementing these changes in developing countries will require national level awareness campaigns about the risk factors and signs of CVD and diabetes, inclusion of blood pressure and glucose level screening in routine medical care, and increased distribution of medication to treat hypertension.

Additional interventions could include increased distribution of oral medication for those with early stage diabetes and development of simple tracking systems to ensure compliance with treatment. In the longer term, insulin should be available to all diabetics who require it, although the logistical and cost challenges around daily use of insulin make this unlikely to be a wide-scale possibility in the near future.

A few technologies can help with behavior change in areas like exercise and diet, and with the treatment of diabetes-related complications such as foot ulcers and eye disease. Treatment for foot ulcers leading to amputation is an area that appears to have some opportunity for technological innovation, particularly in devices that can help treat peripheral vascular disease.

Over the past decade, numerous scientific advancements have improved our capacity for identification, diagnosis and treatment of non-communicable diseases.

These include improved biochemical assays for rapid diagnosis, non-invasive testing methods, improved clinical hardware and software, and artificial intelligence-based therapeutics. We have identified two critical breakthroughs that build on these advances, to significantly reduce NCD burden if implemented at scale.

Breakthroughs:

1 2 3 4 5 6 7 8 9 10
11 12 13 14 15 16 17 18 19 20
21 22 23 24 25 26 27 28 29 30
31 32 33 34 35 36 37 38 39 40
41 42 43 44 45 46 47 48 49 50

36 Affordable, home-use point-of-care diagnostics suite (blood, urine, vitals) for the common NCDs

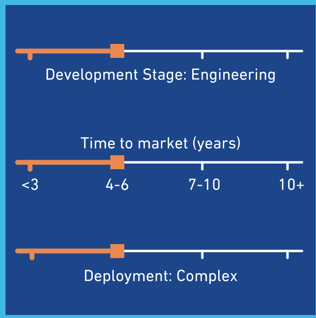
Point-of-care testing is essential for the rapid detection of diseases at the point of care, which facilitates faster disease diagnosis, reduces costs and improves outcomes. Moreover, home-use tests are increasingly designed to be simple to administer and interpret, thus overcoming the challenge of paucity of trained personnel. In the last few years, there has been a move towards integrating tests with mobile applications due to ease of data capture, better user experience and widespread adoption of smartphones. These include both standalone mobile health applications and more integrated testing applications.

The latest improvements in point-of-care diagnostics are a result of continuous developments in biosensors, lateral flow tests, as well as integrated or lab-on-a-chip technologies. These include tests for diabetes, cardiac conditions and cancer. Many of these technologies have already been developed and commercialized in developed economies but are yet to find adoption and successful commercial models for widespread adoption in developing economics.

For example, testing of EG Antigen for cervical cancer, developed by Arbor Vita is currently available only in the United States. In 2018, the US Food and Drug Administration approved the use of in-home genetic tests for breast cancer developed by genetic testing company 23andMe. Molecular diagnostics offer great promise but are less available in low-resource settings.

Data analytics and artificial intelligence, such as image detection methods, are also showing promise in enhancing and reducing the complexity of robust diagnostic methods such as the pap smear, and can help scale up proven diagnosis methods into low-resource setting. Such technologies can increasingly be deployed in home-based and point-of-care settings, due to growing capacity for data networking.

Current State



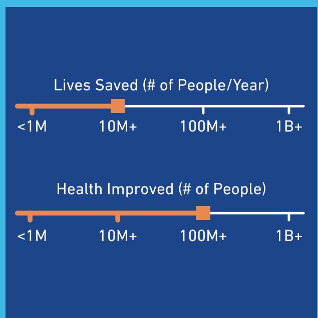
Associated 50BT Chapters

Global Health

SDG Alignment

3 GOOD HEALTH AND WELL-BEING

Impact



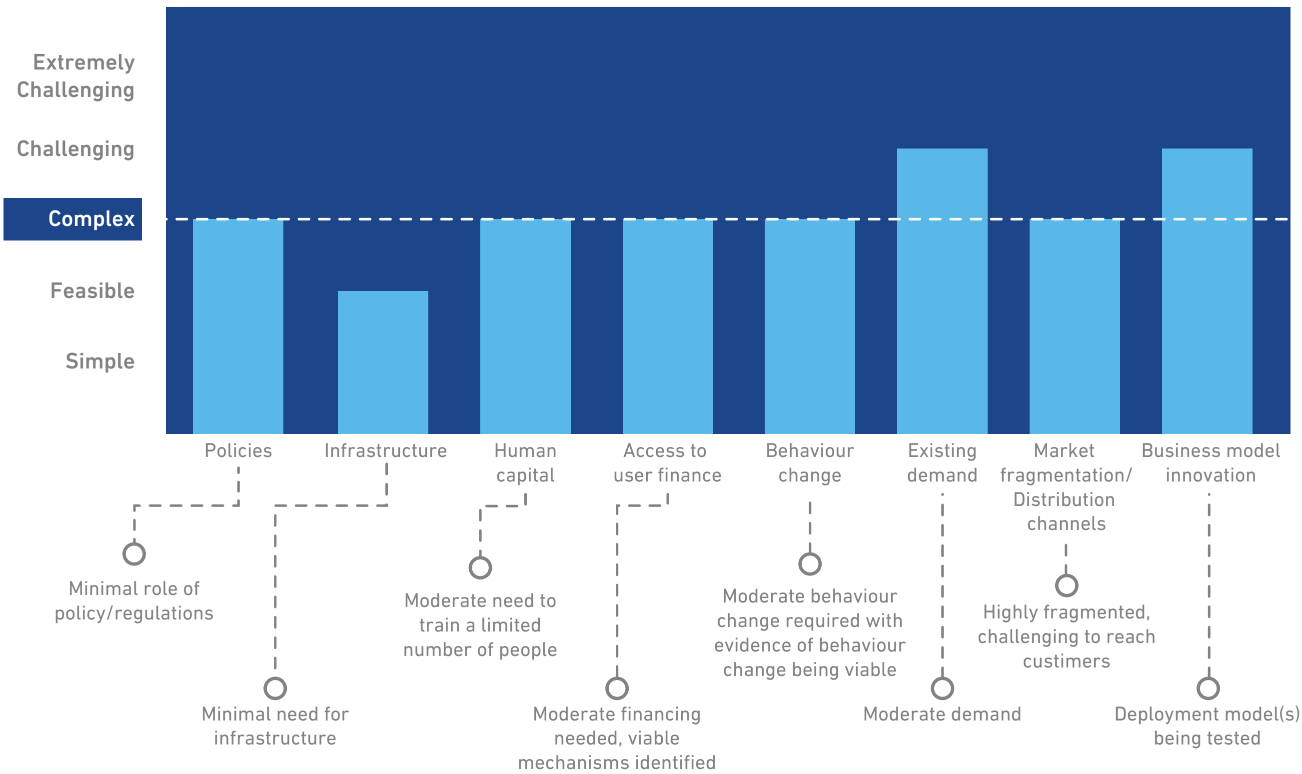
Commercial Attractiveness

- **Attractive for industrialized markets (high profits)**
- Attractive for emerging markets (lower profits)
- Emerging markets potential; requires derisking (sustainable)
- Non-commercial (unprofitable)

Widespread deployment of home-use point-of-care diagnostics devices for common NCDs will depend particularly on consumer demand for such service. Business models will need to focus on enhancing demand for the product through motivating customer self-interest.

Initial products with limited capabilities are currently on the market, and more sophisticated devices with improved performance will likely appear in the next 5 years. The difficulty of deployment is estimated to be COMPLEX.

Breakthrough 36: Difficulty of deployment



37 Affordable wearable technology with broader functionality for patient adherence and monitoring of health status

Wearable technology (or simply, wearables) refers to a broad category of devices that can be integrated into day-to-day clothing or other accessories to capture health data and provide information on the user's personal fitness and activity. While a typical wearable is a fitness tracker that can be worn on the wrist, today there is a much wider array of devices, including implantable devices and an ingestible pill (recently approved by the US FDA) that can track specific markers of physical and mental health and adherence to drug regimens.

Today's common wearables (such as the Fitbit) track heart rate, blood pressure, breathing patterns, physical activity and sleep levels. However, the next generation of devices (still in prototype stage) aim to collect data on blood glucose, indicators of cardiovascular disease, and even cancer. For example, Apple recently released the KardiaBand, an Apple Watch accessory with an inbuilt EKG to detect irregular heartbeat and share the information with caregivers.

Current State

Development Stage: Engineering

Time to market (years): <3 | 4-6 | 7-10 | 10+

Deployment: Complex

Associated 50BT Chapters

Global Health

SDG Alignment

Impact

Lives Saved (# of People/Year): <1M | 10M+ | 100M+ | 1B+

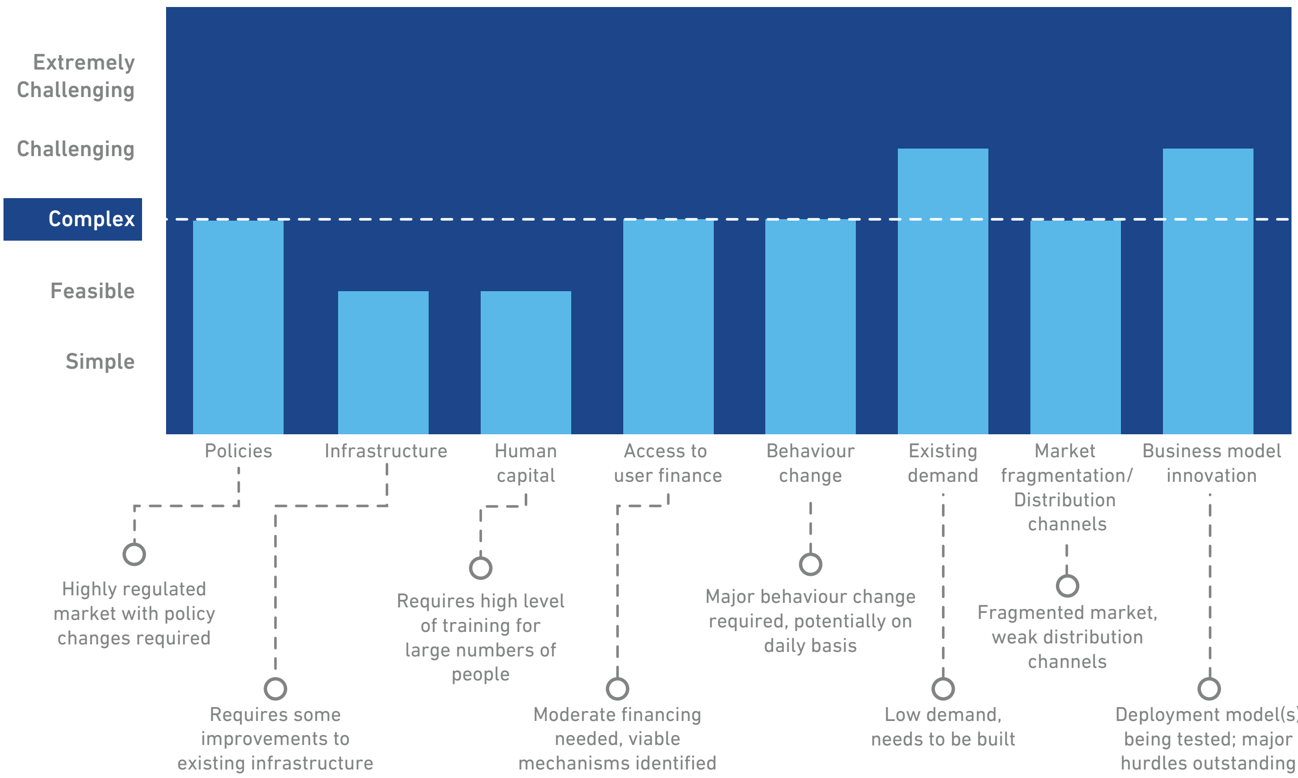
Health Improved (# of People): <1M | 10M+ | 100M+ | 1B+

Commercial Attractiveness

- **Attractive for industrialized markets (high profits)**
- Attractive for emerging markets (lower profits)
- Emerging markets potential; requires derisking (sustainable)
- Non-commercial (unprofitable)

Early indications are that such wearables, especially if combined with game-based incentives, can increase positive health-improving behaviors (Shmerling, 2017). While it is too early to understand the long-term impact of such technologies, an increasing number of health insurance companies and employers who provide health insurance are encouraging their use.

Breakthrough 37: Difficulty of deployment



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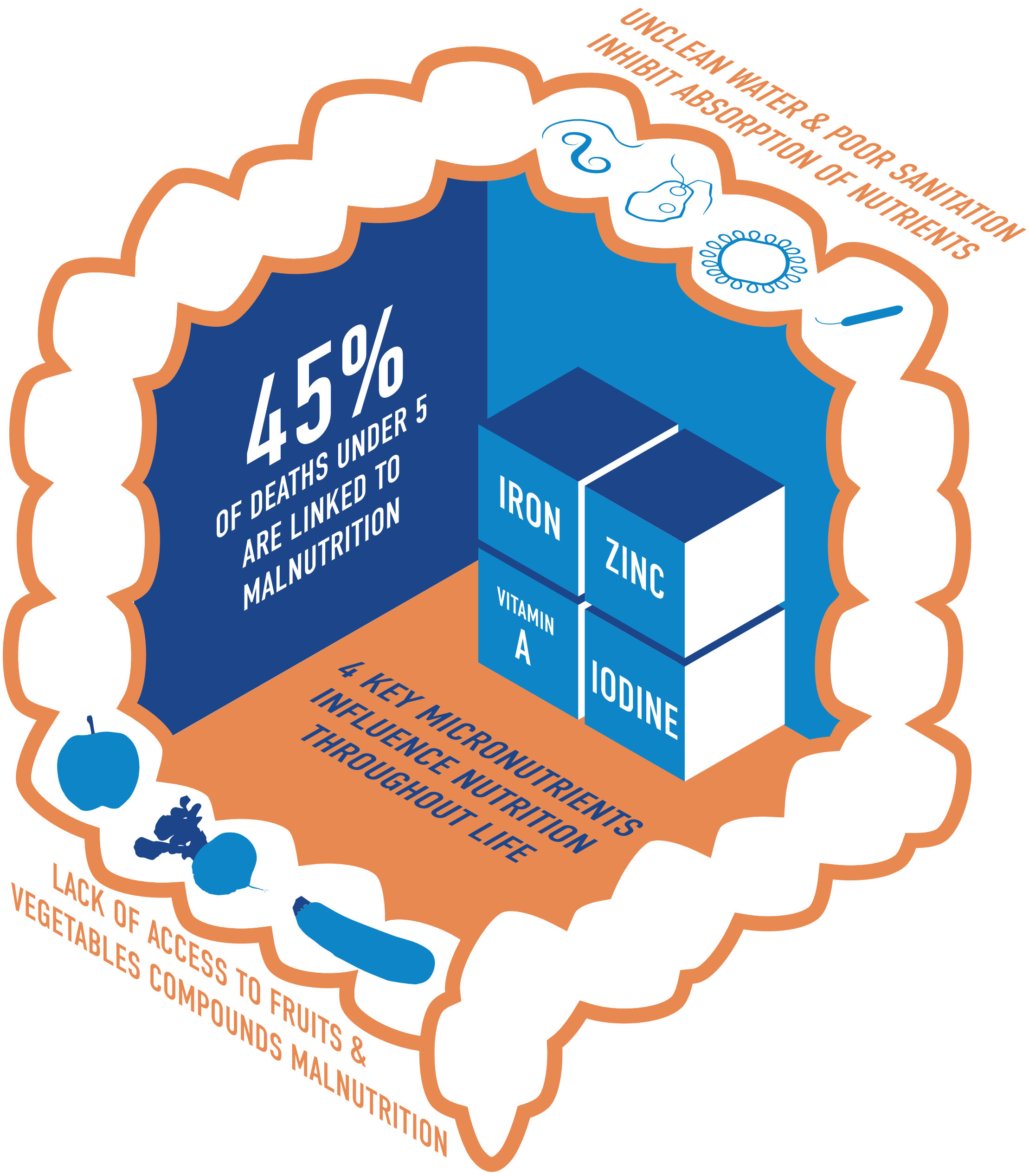


NUTRITIONAL DEFICIENCIES

INTRODUCTION

Malnutrition is linked to 45 percent of deaths among children under age 5, and is responsible for the stunting of 155 million children across the world (WHO, 2018).

Factors influencing nutrition, especially for children and women, are often complex, rooted in systemic and social issues and extend well beyond simply satisfying caloric needs.

There are two primary lenses through which nutrition is viewed. The first is physical growth in early life, specifically in the first 1,000 days, stretching from conception to a child's second birthday. Growth during this crucial period is a strong predictor of adult height, as well as learning and earning potential.

Children who are undernourished (and become stunted) are significantly more likely to experience disease. Linear growth requires a diverse diet including sufficient caloric intake, proteins, fats and micronutrients, absence of infectious disease (particularly from diarrheal pathogens) and appropriate feeding and care.

The second lens for viewing nutrition is deficiency of key micronutrients, particularly iron, vitamin A, zinc and iodine. These critical micronutrients are linked closely to cognitive development, anemia and the ability of a child to fight off infections. Micronutrients also play an important role in overall health throughout life.

We have identified two breakthrough technologies, focusing on the preservation of food, that can significantly improve nutritional outcomes for both children and adults.

- Breakthrough 12. Affordable (less than $50) off-grid refrigeration for smallholder farmers and small agribusinesses
- Breakthrough 13. Commercial scale, affordable and energy efficient refrigeration/cold-chain systems for agribusinesses and transport of food

In addition, three other supply chain innovations will also be helpful:

- Improved processing technologies to preserve food life and reduce degradation of nutritional content
- Improved storage technologies for grains and pulses to reduce development of mycotoxins
- Diagnostics to determine nutritional content and bioavailability of nutrients in foods

Nutritional deficiencies due to suboptimal intake of carbohydrates, fats, proteins and micronutrients like iron, zinc, folic acid, vitamin A and iodine, are among the most significant risk factors for death and disability in children in developing countries. Beyond supporting just health, good nutrition is vital for cognitive development and correlates with educational performance. Nutritional deficiencies underlie 45 percent of all deaths in children under 5 years of age, resulting in 2.4 million deaths annually (WHO, 2018).

CORE FACTS AND ANALYSIS

Nutrition is a broad area but is generally considered from the perspective of anthropometry or physical growth in early life, focusing on the nutritional needs to support normal and healthy growth in children. Growth is measured using physical metrics including weight for age, height for age and weight for height at birth and throughout early childhood. In the past, the global burden of undernutrition was principally measured by tracking the prevalence of underweight, which refers to children with a weight-for-age two standard deviations below a population median.

More recently, with the rapid emergence of overweight and obesity as global health concerns, the nutrition community has begun tracking prevalence of stunting—low height for age—as a superior indicator of nutrition and health. Whereas weight for age can be optimized through the provision of energy alone, through carbohydrates and fats, linear growth requires a high-quality diet with protein and growth promoting nutrients, as well as absence of inflammation, infection and disease.

In addition to supporting growth, nutrition influences susceptibility to infection in children; 57 percent of the disease burden from LRIs and 55 percent of the disease burden from diarrheal disease are attributable to malnutrition. Other infections where malnutrition is a major underlying factor include measles and neonatal disorders (Global Burden of Disease, 2017).

1. Nutrition and growth in early life

Growth in early childhood, including height attained by the age of 24 to 36 months, is a strong predictor of adult height as well as future learning and earning potential. This has led to a focus on the first 1,000 days stretching from conception to a child's second birthday. Children who are stunted at the age of 2 often remain stunted throughout life.

Globally, 155 million children under age 5 suffer from stunting and 52 million suffer from wasting (WHO, 2018). Wasting is an acute condition that requires medical intervention and is a challenge particularly in areas affected by drought, disaster and conflict. Preventing stunting in the first 1,000 days of life is considered critical for a child's health and survival.

Maternal health and nutrition during and before pregnancy

The first factor driving a child's development is the health of the mother entering, and during, pregnancy. The mother's nutrition is important for assuring healthy fetal growth, a term delivery, and for providing adequate nutrition during the even more nutritionally demanding process of lactation. Mothers who are undernourished are more likely to give birth to low birthweight and small for gestational age infants.

These infants are at higher risk of illness, poor growth or future stunting and early mortality. Furthermore, while undernourished mothers are physiologically capable of producing a sufficient quantity of milk to feed their infants (breast milk quantity is a function of suckling frequency), the nutritional quality of milk, including fat content and nutrients like vitamin A, depends on diet.

The health and nutrition of the mother before pregnancy are also important, in part because adequate nutrition is needed for early first trimester cell proliferation and brain and organ development of the fetus. Pre-conception health, however, particularly among adolescent girls, is considered challenging to address.

As a result, it has seen little focus compared with maternal health during pregnancy. That said, there are a number of straightforward interventions that can address pre-conception nutrition, especially among adolescent girls, such as screening and treatment for anemia.

Maternal health and nutrition during breastfeeding
The quality and energy density of breast milk is directly linked to a mother's diet during the breastfeeding period. When a mother's milk is low in fat (energy), the newborn must suckle more to receive sufficient nutrients to support optimal growth. This can be physically difficult for low birthweight babies, further contributing to faltering growth.

Childhood nutrition and health during breastfeeding and weaning

Exclusive breastfeeding is recommended for infants for the first six months of life. Past six months, babies should be given a combination of breast milk and complementary foods.

The caloric and nutrient density and diversity of these foods are major factors contributing to adequate early growth. Having sufficient energy is important to maintain basal metabolic function as well as to support healthy growth, but energy (calories) alone is not sufficient to ensure that bone and muscles develop and grow properly.

Healthy growth, in height and lean body mass, requires a diverse and nutritious diet and absence of disease. Any infection or inflammation either diverts nutrients away from growth to mount an immune response, or wastes them due to poor absorption and inefficient utilization.

Hygiene and sanitation are important for preventing diarrhea and subclinical inflammatory processes. There is also evidence that other environmental conditions, including stress, can interfere with nutrient use and healthy growth.

2. Four key micronutrients influence nutrition throughout life

The second lens for characterizing nutrition is 'hidden hunger' or micronutrient deficiencies. In this context, four micronutrients are particularly critical.

Iron

Anemia is a condition when the body does not have sufficient red blood cells. While it can be caused by many conditions, such as blood loss or hereditary conditions, the primary driver in developing countries is iron deficiency.

Iron is required to produce hemoglobin, the protein that carries oxygen in red blood cells. When there is insufficient intake of iron, usually found in red meat and leafy green vegetables, the body cannot produce enough red blood cells.

Globally, anemia affects 2.6 billion people and iron deficiency is the leading cause (Lopez, et al., 2015). Anemia affects 43 percent of children, 29 percent of non-pregnant women and 38 percent of pregnant women (Stevens, et al., 2013).

Vitamin A and zinc

Found in a mix of meats, fruits and vegetables, vitamin A and zinc serve a range of critical needs like fighting infections, healing wounds and tissue repair. Without an adequate intake of these nutrients, children are more susceptible to infectious diseases.

Around the world, 33 percent of preschool age children— 190 million—and 15 percent of all pregnant or lactating women suffer from vitamin A deficiency (UNICEF, 2017). One study found that Vitamin A supplementation in infants caused a 14 percent reduction in mortality within the first six months of life (Haider & Bhutta, 2011). A similar analysis showed that zinc supplementation reduced incidence of diarrhea by 13 percent and reduced pneumonia morbidity by 19 percent (Yakoob, et al., 2011).

Iodine

Almost 2 billion individuals around the world suffer from insufficient iodine intake, and 19 countries are still classified with insufficient iodine intake (Global Nutrition Report, 2018). This leads to cretinism and other forms of cognitive developmental delays. Iodine deficiency is considered the single largest preventable cause of mental retardation (UNICEF, 2008).

The Global Burden of Disease models show that iron-deficiency anemia and protein-energy malnutrition (or underweight, as it is more commonly known) together account for 85 percent of the direct disease burden from nutritional deficiencies, as well as almost 100 percent of fatalities caused by nutritional deficiency (**Exhibit 1**) (IHME GBD, 2017). **Exhibit 2** shows that malnutrition prevalence in rural communities is higher than that in urban areas in South Asia, Africa and Latin America & the Caribbean.

Between 1990 and 2010, the disease burden from being underweight has decreased significantly, but the same is not true for anemia. However, data from the 2017 Global Burden of Disease shows significant decrease in all forms of nutritional deficiencies since 2010 (**Exhibit 3**). Geospatial analysis shows that the prevalence of stunting in Africa has decreased moderately from 2000 to 2015 (Global Nutrition Report, 2018). Although the DALYs rate of anemia has decreased by 25 percent, the increase in population has kept overall DALYs essentially constant (IHME GBD, 2012).

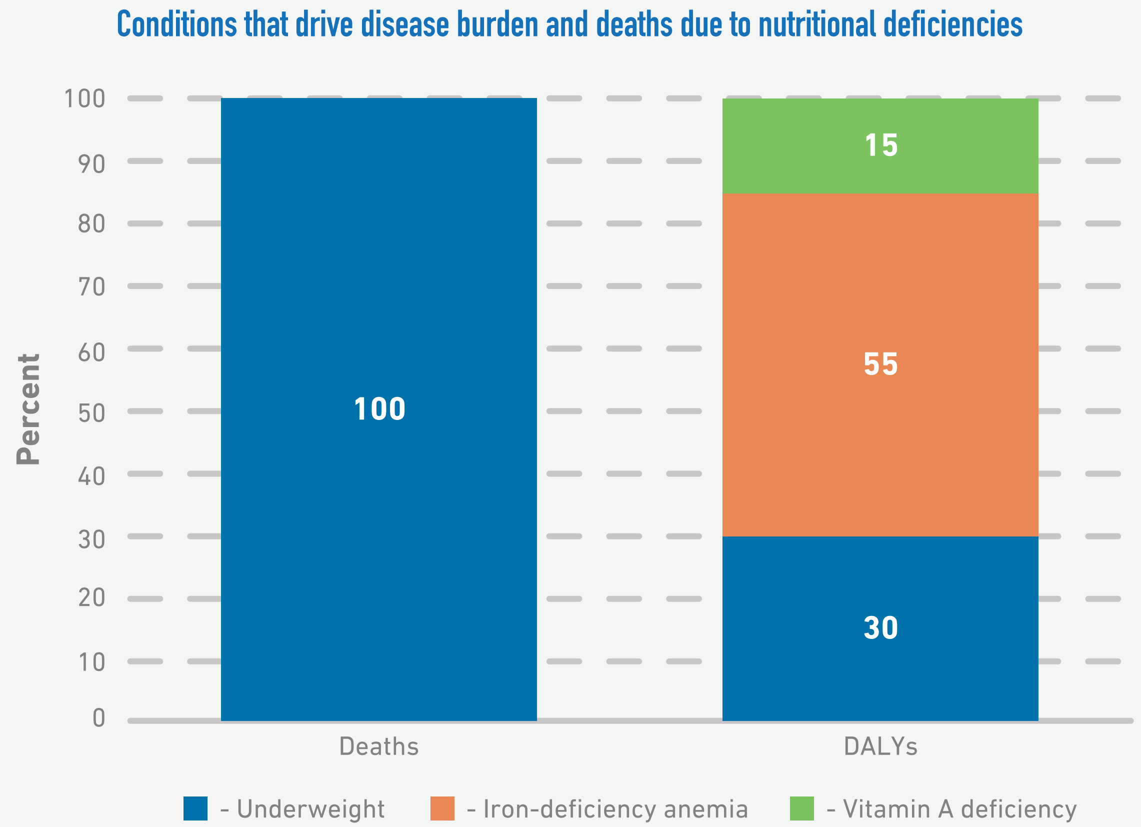


Exhibit 1: Two nutritional conditions—iron-deficiency anemia and underweight—account for the vast majority of DALYs and deaths caused by nutritional deficiency. (Source: IHME GBD, 2017)

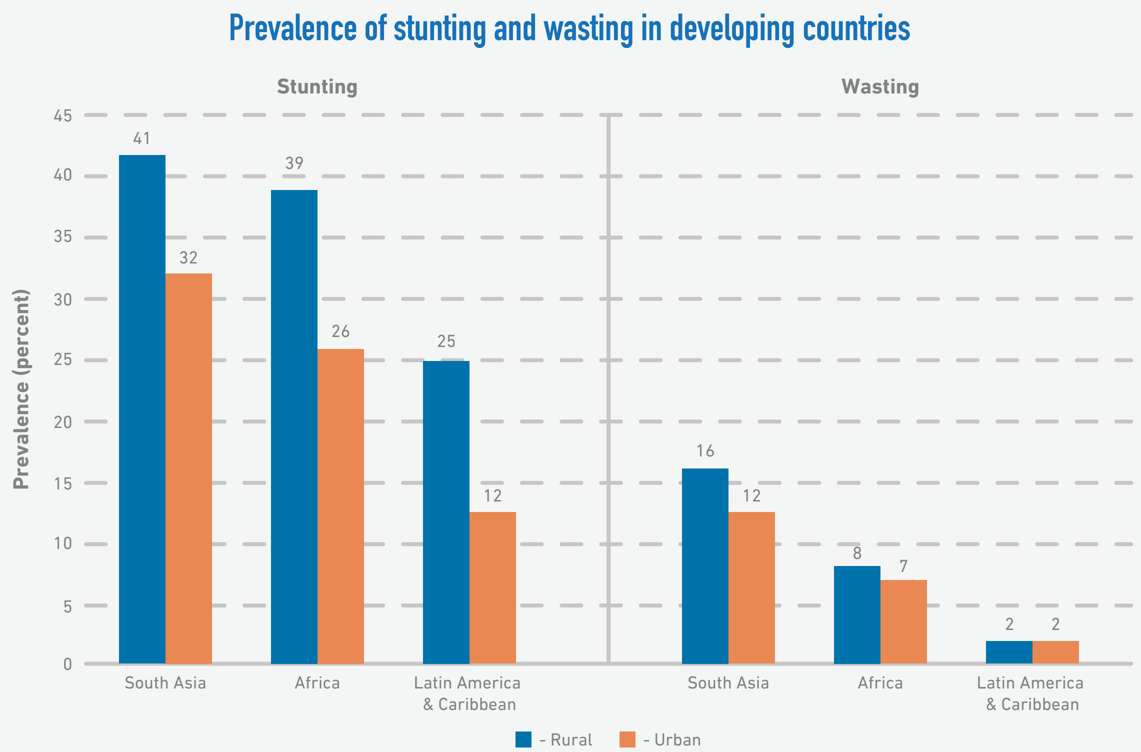


Exhibit 2: Childhood malnutrition is somewhat more prevalent in rural areas of developing countries, compared to urban areas. (Source: 2013 data from Global Nutrition Report, 2018)

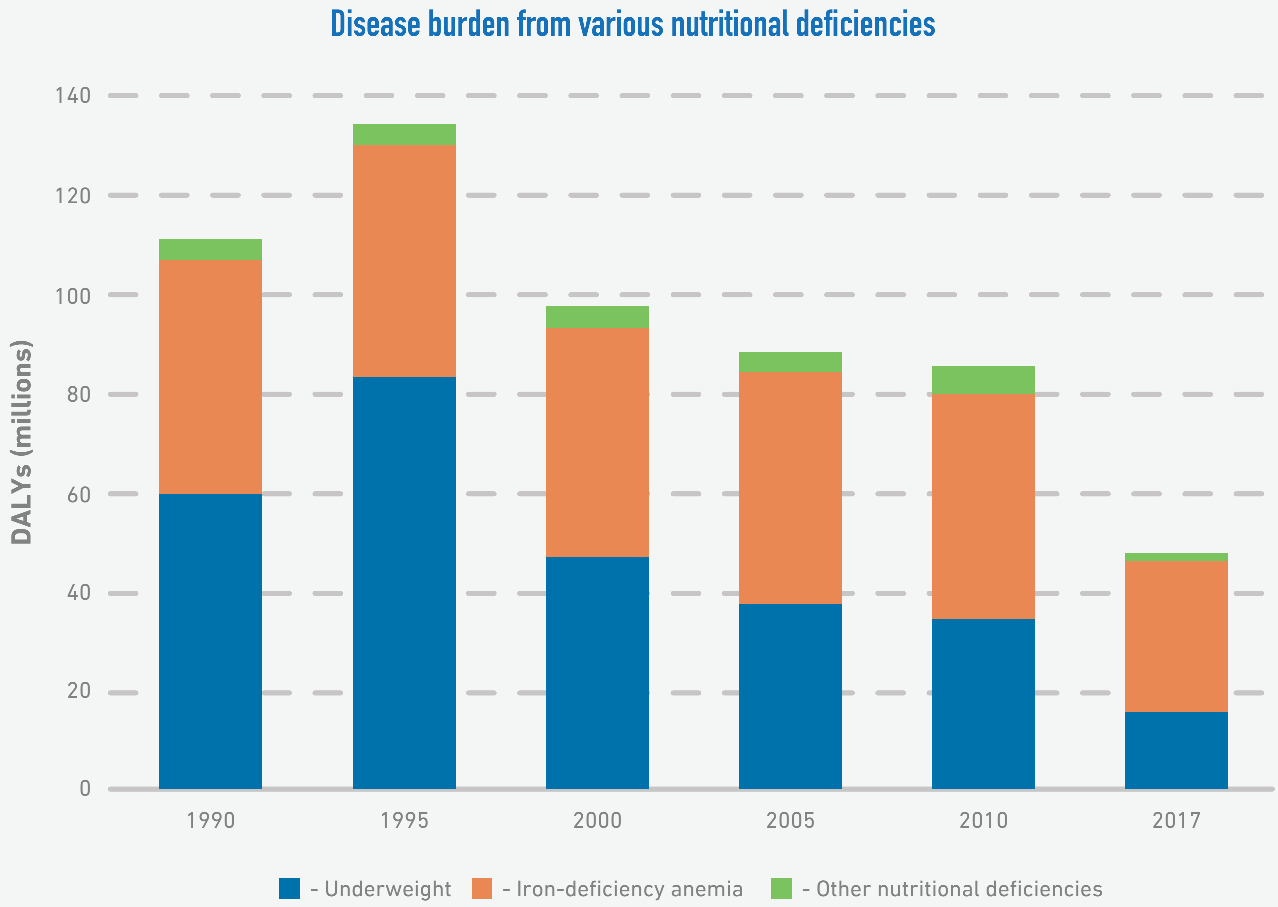


Exhibit 3: The disease burden of being underweight has decreased significantly in recent decades, while iron-deficiency anemia has been more persistent. (Source: IHME 2012; IHME GBD, 2017)

In addition to the effects of nutritional deficiencies, the risk of over-nutrition, which leads to obesity and related non-communicable diseases (NCDs) has garnered increasing attention in the last few years. Unhealthy diets comprising an excess of sugar or fat, and too few fruits and vegetables, combined with inactive lifestyles are leading to a dramatic increase in diabetes, cardiovascular disease and obesity.

These NCDs currently account for 41 million deaths globally and 32 million deaths in low- and middle-income countries (WHO, 2018; Global Nutrition Report, 2018). These figures are expected to grow. We address nutrition-related NCDs in a separate section on cardiovascular disease and diabetes, rather than this one on core nutritional deficiencies.

KEY CHALLENGES

There are four broad challenges in addressing nutritional deficiencies, three of which relate directly to early childhood growth while one pertains specifically to the problem of iron-deficiency anemia.

These challenges extend well beyond simple dietary intake (although diet is a crucial challenge), to also include the heath and care of young children.

1. Lack of rich, diverse diets, early in life

Newborns in developing countries often receive poor diets beginning with suboptimal breastfeeding and continuing through the first two years of life.

Breastfeeding

The WHO recommends, "immediate breastfeeding within the first hour of life, exclusive breastfeeding up to six months of age, with continued breastfeeding along with appropriate complementary foods up to two years of age or beyond." Breast milk provides key nutrients for infants, as well as antibodies that protect against infections like diarrhea and pneumonia (Fleming & de Silva, 2009).

On the other hand, substitutes like infant formula and other foods do not contain the antibodies found in breast milk, are expensive, and can lead to diarrheal disease when such food is prepared with unsafe water or in unsterilized feeding bottles.

Still, due to cultural factors, lack of knowledge and support, and other impediments, globally less than 40 percent of infants under the age of six months are exclusively breastfed, with only 36 percent of infants in the United States breastfed at 12 months (WHO, 2013; CDC, 2018).

Furthermore, the nutritional quality of breast milk is linked to the nutritional intake of the mother, and mothers who are undernourished or are not eating a diverse and nutritious diet produce lower nutritional quality breast milk for their babies.

Weaning

The nutritional content of complementary foods is critical as the infant weans off breast milk. Due to an infant's small stomach, it is important that complementary foods be high in nutritional value to support growth. However, in many countries infants are given thin cereal-based porridges that lack nutritional diversity.

Childhood and beyond

Nutritional deficiencies continue as a health concern well past the first 1,000 days. There are several additional diet-related challenges that affect children, adolescents and adults of all ages in developing countries.

- Lack of access to fruits and vegetables, which provide critical nutrients that are not found in sufficient quantities in cereals. Fruits and vegetables are often more challenging to grow than cereals and available easily only during harvest times; they are more sensitive to stresses and water availability, and once harvested have a limited shelf life in the absence of appropriate cooling or refrigeration. These foods are also more expensive than cereals, thus reducing access for low-income families.
- Inadequate access to, or a tradition of not feeding young children, animal source foods like meat, poultry, eggs and dairy that are rich in easily-absorbed iron, is a major driver of iron deficiency.
- Lack of awareness about the importance of dietary diversity—and what it entails—leads to infants and young children primarily being fed grain-based foods.
- The absence of agricultural cold chains and in-home refrigeration limits access to horticulture products and the ability to store perishables.
- Increasing abundance of low-priced, highly processed foods that are high in fat and sugar particularly in urban settings.
- Increasing abundance, and in turn consumption, of low priced, highly processed foods (high in fat and sugar) in place of healthier alternatives, particularly in urban areas, can lead to conditions like obesity.

2. Unclean water, poor sanitation and hygiene conditions inhibit absorption of nutrients

Diarrheal disease and intestinal nematode infections lead to reduced nutrient absorption and can cause long-term intestinal damage, inhibiting nutrient absorption long after the infection has cleared (Brown, et al., 2011).

Diarrheal disease significantly increases the risk of stunting, especially before the age of 24 months (Checkler, et al., 2008). Fecal pathogens also cause environmental enteropathy, which can lead to long-term reduction in nutrient absorption even in the absence of frequent diarrheal episodes (Brown, et al., 2013).

Young children are extremely vulnerable to diarrheal disease and gut enteropathy. Other infections and inflammation can also affect nutrition by diverting nutrients away from growth or immune response. These concerns have been discussed in greater detail in the chapter on diarrheal disease.

3. Improper care of infants

Core to the health of a child is the care he or she receives from the mother. Key behaviors related to nutrition include feeding practices and care seeking practices. The former entails knowledge of what comprises a rich and diverse diet and how to prepare and store complementary foods while the latter entails recognizing signs of sickness and seeking care when necessary.

Often, cultural practices can be at odds with what is best for the child. For instance, taboos exist in some cultures against bringing an infant out of the house and this limits access to care if the infant is sick. Proper care of the infant is increasingly being linked to a mother's education, her own self-efficacy, self-confidence and control over the family's resources. Many of these issues are believed to be more severe in urban settings where support networks are often weaker.

4. Intestinal nematode infections, and to a lesser extent, malaria infections (for anemia specifically)

Chronic blood loss resulting from parasitic infections, primarily hookworm, trematodes and whipworm are a major cause of anemia in children. Although anemia caused by blood loss is not iron-deficiency anemia explicitly, it exacerbates the effects of iron deficiency.

Both conditions, nematode infection and iron-deficiency anemia, are very common and tend to occur together. Smaller-scale studies have found that, particularly in areas with a high hookworm burden, deworming can lead to reduced anemia (Smith & Brooker, 2010).

However, the effectiveness of large-scale deworming programs is a controversial topic and the subject of significant debate. Malaria too can contribute to iron-deficiency anemia (Verhoef & West, 2003).

SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

As the above discussion suggests, nutritional deficiency is driven by systemic issues tied to broader food production and food infrastructure, economic development, education, gender dynamics and the extent to which women have control over a family's resources and food.

Programs like deworming, free school lunches for low-income students and conditional cash transfers can serve as effective safety nets for vulnerable populations, but these are likely not a sustainable substitute for deeper systemic change.

We have identified two breakthrough technologies, focusing on the preservation of food, that can significantly improve nutritional outcomes for both children and adults. In addition, three other supply chain innovations will also be helpful.

Breakthroughs:

1 2 3 4 5 6 7 8 9 10
11 12 13 14 15 16 17 18 19 20
21 22 23 24 25 26 27 28 29 30
31 32 33 34 35 36 37 38 39 40
41 42 43 44 45 46 47 48 49 50

12 Affordable (less than $50) off-grid refrigeration for smallholder farmers and small agribusinesses

The absence of affordable refrigeration and electricity severely limits the ability of smallholder farmers to produce, preserve and sell perishable commodities like vegetables, fruits, meat and dairy. Such products are highly sensitive to temperature, and the lack of refrigeration dramatically reduces their shelf life, especially in tropical climates.

While there are some inexpensive refrigerators available in emerging markets like India and China, they still cost more than $100, need reliable electricity and are difficult to repair once damaged. A new kind of refrigerator that costs less than $50 and can run on solar power will help smallholder farmers provide better nutrition for their families, and take high-value commodities to market, thereby increasing their incomes.

There is a recent resurgence of interest of very affordable age-old traditional cooling technologies (like clay pots). While this showcases the potential demand for an affordable and durable solution, traditional options like clay are subject to biological contamination and difficult to clean.

Moreover, as agricultural systems advance, there will be greater need for commodity-specific temperature control. Furthermore, it is difficult to see traditional cooling solutions leading to modern and profitable agricultural value chains.

To serve the needs of rural, low-income farmers, refrigerators need to be operable off-grid (like solar-powered), considerably less expensive than the current $100 range and easy to repair. Such technologies appear to be on the horizon.

Current State

Development Stage: Engineering

Time to market (years)

<3 | 4-6 | 7-10 | 10+

Deployment: Challenging

Associated 50BT Chapters

Food Security

SDG Alignment

Impact

Increased Access to Food (# of People)

<1M | 10M+ | 100M+ | 1B+

New Income Generated (# of People)

<1M | 10M+ | 100M+ | 1B+

Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- **Attractive for emerging markets (lower profits)**
- Emerging markets potential; requires derisking (sustainable)
- Non-commercial (unprofitable)

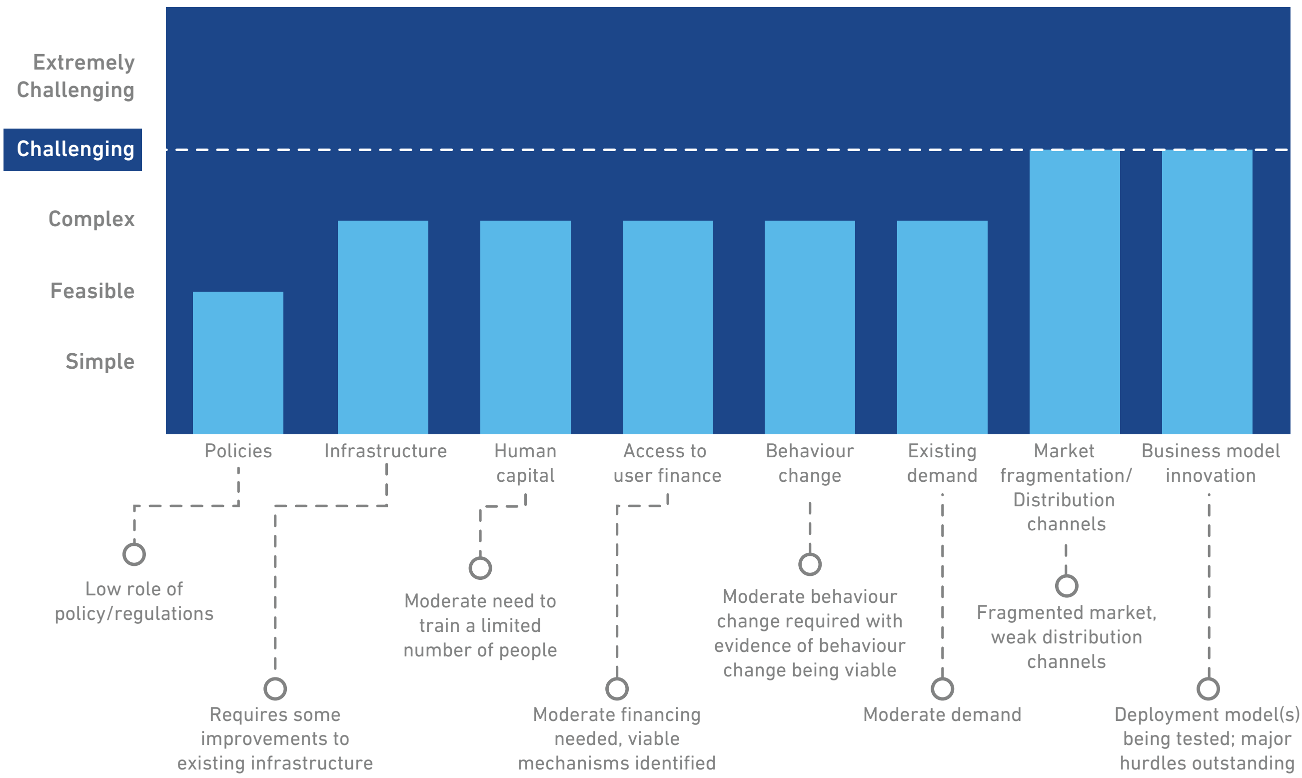
A new generation of refrigerators using thermoelectric technology is beginning to reach the market, supplementing existing vapor-compression models.

Given the broad demand for refrigeration there is reason to believe that an affordable product will gradually reach a critical mass of smallholder farmers—notwithstanding the usual problems of market fragmentation and distribution.

Based on the above, it is likely only a matter of four to six years before low cost refrigerators become practical for rural farmers.

Despite the need and expected demand, such a technology will face considerable barriers to deployment due to the fragmented nature of the market, the absence of a value chain for distribution and maintenance and the need for financing for farmers. Hence, deployment will be CHALLENGING.

Breakthrough 12: Difficulty of deployment



13 Commercial scale, affordable and energy efficient refrigeration/ cold-chain systems for agribusinesses and transport of food

The ability to transport food to markets while preserving freshness will not only reduce post-harvest losses, but also create new value propositions for smallholder farmers.

The absence of such cold chain infrastructure is one of the factors limiting access to market for higher-value produce (for example, horticulture; and as the Livestock section discusses, meat and dairy). The lack of refrigeration also reduces everyday access to a diverse base of nutrients for children and the population in general.

Refrigerated trucks available on the market today cost tens of thousands of dollars, require diesel and are built for smooth roads. To be useful to dealers and agribusiness entrepreneurs who serve smallholder farmers in remote areas, refrigerated storage chambers and transport vehicles will have to be robust and cost significantly less than $5,000.

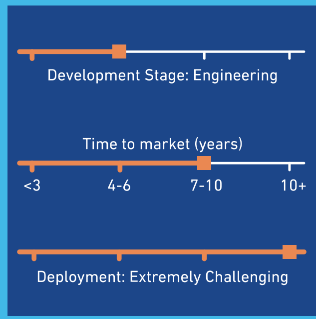
While advances in stationary refrigeration technologies can also help advance mobile refrigeration, there are a number of significant differences.

First, stationary refrigerators normally operate indoors, whereas transport refrigerators will have to operate outdoors, under much warmer ambient temperatures and harsher conditions.

Second, while a major challenge for stationary refrigeration is the absence of reliable electricity, transport refrigerators can use the fuel used to power the vehicles.

Third, refrigerated vehicles will become affordable only after general-purpose vehicles become affordable. Based on the above analysis, the projected time to market for such technologies is seven to ten years.

Current State

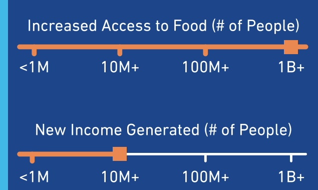


Associated 50BT Chapters

Food Security

SDG Alignment

Impact



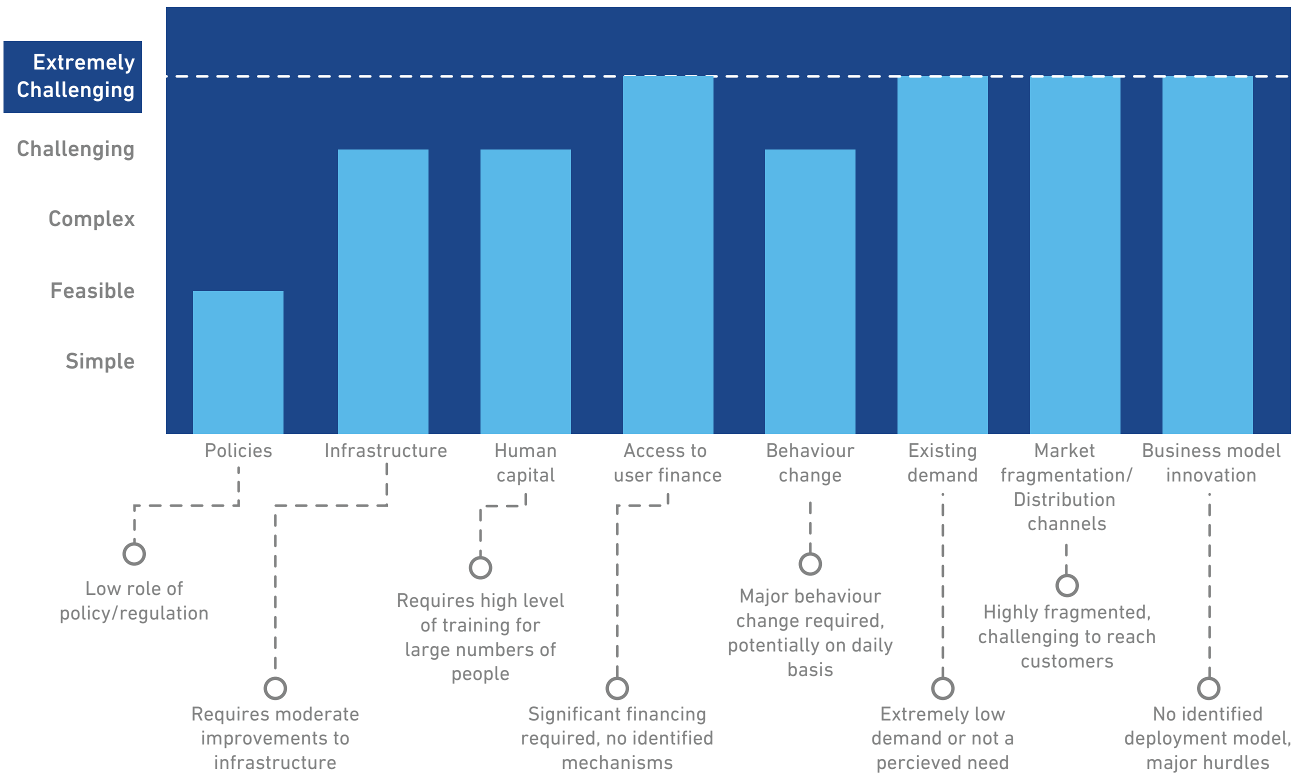
Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- **Attractive for emerging markets (lower profits)**
- Emerging markets potential; requires derisking (sustainable)
- Non-commercial (unprofitable)

Even when such a technology is developed, deployment will be difficult. The market is extremely fragmented and adoption will depend on the growth of the broader market for the relevant agricultural commodities. In addition, poor road infrastructure and the sparse presence of fueling stations will be a major hurdle in the usability of refrigerated transport.

Finally, a maintenance and repair infrastructure (currently absent) will be necessary to keep these refrigeration facilities functioning. We estimate that deployment will be EXTREMELY CHALLENGING.

Breakthrough 13: Difficulty of deployment



In addition to these two breakthroughs, three further innovations may also help in the fight against nutritional deficiencies:

Innovation: Improved processing and storage technologies to preserve food life and reduce degradation of nutritional content

Due to the seasonal nature of agriculture, farmers experience major swings in the availability of different foods. This is often most acute with fruits and vegetables, which spoil fairly rapidly after harvesting, leading to limited availability. Drying and processing preserves the life of food and often its nutritional content, thereby reducing the seasonal nature of hunger.

Specific technological needs vary depending on the food items (for example grains versus vegetables). In general, however, drying, processing and storage technologies need to be less capital intensive and should preserve as much of the nutritional content of the crop as possible. This is an area of emerging research. Milling rice, for example, often strips away nutritional content in the germ, although it also removes phytates, which bind nutrients and can prevent their absorption. The full impact of processing on nutrition requires continued research for improved understanding.

In most cases there is no fundamental technological issue to overcome. Rather, these are technologies that have traditionally received minimal attention. While there are some technologies capable of, for example, hermetic or air tight storage, none are at a cost low enough to enable large-scale deployment. When it comes to drying and processing technologies, the primary constraint is developing a technology with a low enough cost to enable a sustainable deployment model.

The projected time to market readiness varies widely. Some new products may enter the market within one to two years, while other products have received such little attention that they will likely not be introduced for seven to 10 years. The difficulty of deployment is similarly varied, but due to low margins and the need to target remote and rural areas the expected difficulty of deployment is challenging.

Innovation: Improved storage technologies for grains and pulses to reduce development of mycotoxins

Mycotoxins are poisonous compounds that are created primarily by fungi that accumulate during harvest and post-harvest storage and processing. The FAO has estimated that as much as a quarter of the world's crops could be contaminated with mycotoxins. The problem is believed to be most acute and least understood in sub-Saharan Africa, followed by South Asia.

In particular, aflatoxins are known to build up in maize and groundnuts, when crops are improperly dried and/or stored in cool, damp places in the household. Chronic exposure to mycotoxins has been linked to malnutrition, impaired immunity and various forms of cancer.

There are multiple approaches to preventing contamination from mycotoxins. Storage technologies have focused on prevention of insect infestation, which can cause exposure to fungal spores, and technologies to reduce condensation. Biological strategies include development of fungi or bacteria that can outcompete the fungi that produce mycotoxin. Chemical strategies have generally focused either on compounds that prevent insect infestation or those that prevent the growth of fungi.

Different approaches are at various stages of development. Several compounds are being tested and some are nearly market ready. However, any successful technology will face major deployment challenges. Mycotoxin poisoning is poorly understood by most smallholder farmers.

Moreover, there are few distribution channels that address smallholder farmers, where most contamination occurs. While market readiness varies by technology, some technologies could be ready within two to four years. The difficulty of deployment for any technology is extremely challenging.

Innovation: Diagnostics to determine nutritional content and bioavailability of nutrients in foods

Many nutrition interventions rely on provision of fortified foods to address nutrient gaps. While there are multiple processes to fortify staple foods, it is challenging to assure quality and control safety due to the difficulty of assessing nutritional content in food.

Assessments are usually made in laboratories, which are rarely sufficiently resourced to either accurately assess nutritional content of food or handle the sheer number of samples that need testing. Due to this lack of quality assurance, a major nutrition agency has estimated that as much as half of fortified food staples do not actually contain enough supplemental nutrients to create desired health benefits.

In order to address this issue, better diagnostics are needed that can assess the nutritional content and bioavailability of nutrients in food. The ideal device would produce rapid results and be usable in a field rather than lab setting.

Little applied research is underway in this area. Only a small number of universities or companies are developing rapid micronutrient testing devices, with at least one nearing market release. Further work related to precision, validation and local reagent production need continued research. Detecting vitamin B9, iodine and zinc deficiencies, in particular, require rapid diagnostic technologies.

The current market for such devices is concentrated. Only a small number of entities have an existing need for such a device. These institutions could benefit greatly from such a diagnostic and may be somewhat price insensitive, although cost is still expected to be a major barrier.

A dearth of commercial demand for diagnostics and a lack of willingness within local governments to enforce micronutrient testing in food remain significant hurdles. The projected time to market readiness is about one to three years, and the difficulty of deployment is complex.

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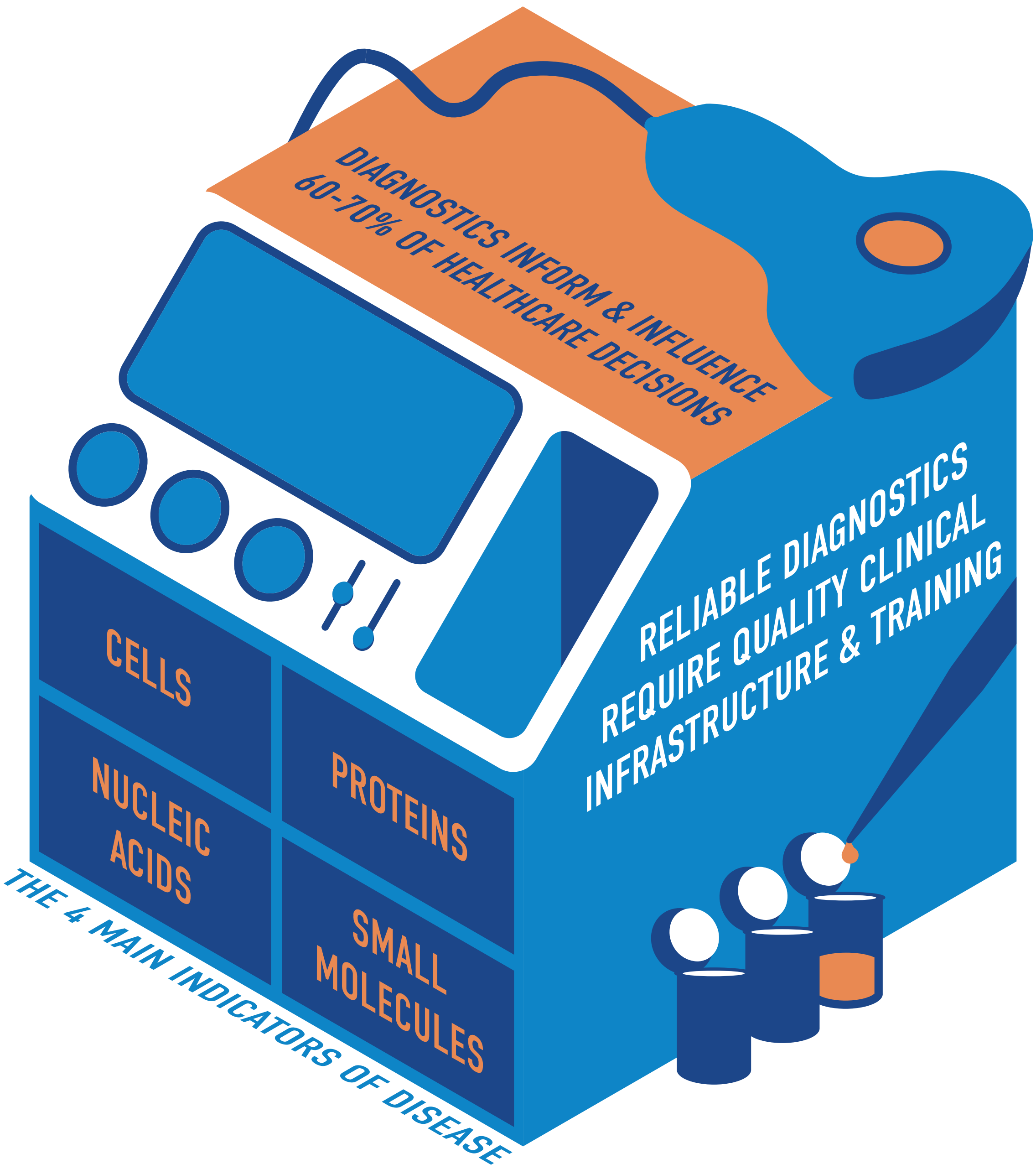


DIAGNOSTICS

INTRODUCTION

Accurate and timely diagnosis increases the likelihood of successful treatment.

Diagnostics play a particularly vital role in clinical scenarios where patients present non-specific symptoms that are common to multiple diseases, or in situations where the specific strain of the disease must be identified to determine the correct treatment regimen.

Since many infectious diseases are asymptomatic, diagnostics are necessary for screening asymptomatic patients. This helps prevent long-term complications from untreated infections and decreases the rate of disease transmission within communities. While early diagnosis and detection of communicable diseases like cervical cancer can greatly increase positive treatment outcomes, diagnostics are also essential for monitoring treatment effectiveness for chronic diseases like diabetes. Indeed, diagnostics inform and influence 60 to 70 percent of healthcare decisions.

Although simple rapid diagnostics are becoming more widely available, most are not completely reliable. Most reliable diagnostics require clinical infrastructure and need to be administered by highly trained healthcare workers. Though technologically reliable, centralized testing continue to face significant challenges in timely diagnosis and treatment due to delays from specimen transport and results reporting, among others. Accurate diagnosis and timely treatment are particularly important in the current era of drug resistance.

To meet the needs of these patients, a new generation of innovative diagnostics need to be developed. These tests must be portable and lightweight, capable of operating without grid electricity, tolerant to high ambient temperature and humidity, able to withstand physical shock while being transported, and simple enough to be used by minimally trained healthcare workers at the point-of-care. These technologies must also be built with actionable data management, effective consumables supply management and quality assurance processes. There are four technology breakthroughs that can make that possible:

- Breakthrough 32. Low cost, novel diagnostics for pneumonia
- Breakthrough 34. Automated multiplex immunoassays that can test for a broader range of diseases (compared to the current state) and are compatible with easily collected sample types
- Breakthrough 35. Point-of-care nucleic acid test (NAT) that is simple, robust, and compatible with easily collected sample types
- Breakthrough 36. Affordable, home-use point-of-care diagnostics suite (blood, urine, vitals) for the common NCDs

Around the world, clinical assessment is core to the diagnosis of disease. Diagnostic testing confirms or disproves clinical suspicion, enables early detection of disease, and allows clinicians to provide patients with the right treatment quickly, including triage to a higher level of care. Importantly, diagnostics inform and influence as much as 60 to 70 percent of healthcare decision-making (The Lewin Group, 2005) but must be used in conjunction with appropriate treatments and other interventions to have real impact on health outcomes.

CORE FACTS AND ANALYSIS

Diagnostic tests play a particularly crucial role when the patient's symptoms are non-specific (common to multiple diseases requiring different treatments) or when the treatment is sufficiently expensive that it is given only to those with confirmed cases of infection (Mabey, et al., 2004).

In such clinical scenarios, diagnostics increase the chances of successful therapy and decrease the chances of mis-treatment or over-treatment. This is critical for diseases like malaria where drug resistance threatens the long-term viability of existing treatments, or ones where different treatment protocols exist for different pathogen strains, as is the case with TB.

Even after treatment selection, diagnostics play an important role in monitoring treatment effectiveness for diseases like HIV, where treatment is long-term and its efficacy must be closely tracked.

Since many infectious diseases are asymptomatic, diagnostics also play a critical role in screening asymptomatic patients; this helps prevent long-term complications from untreated infections and decreases the rate of disease transmission within communities.

In this chapter, we focus on diagnostic challenges and needs in peripheral health centers and clinics ('Level 1' health facilities) in developing countries.

For about 60 percent of people in developing regions, point-of-care facilities are at peripheral health clinics, which are typically poorly resourced with little in the way of reliable electricity, clean running water, laboratories, laboratory equipment (like centrifuges and refrigerators) or well-trained clinicians (Nantulya, 2006; Girosi, et al., 2006).

Patients seeking care in such settings often do not have access to reliable diagnostics. The problem is particularly acute for diseases like TB, where existing diagnostic methods most commonly employed in such settings have proven lacking due to low sensitivity and specificity, and the inability to determine the drug susceptibility of the pathogen.

Diagnostic uncertainty today exacts an enormous toll in morbidity and mortality in developing countries by implicitly restricting the control of non-communicable diseases and the most fatal infectious diseases, particularly where HIV is prevalent (Perkins & Small, 2006)[1]. Innovative diagnostic tools need to be developed and deployed in low-resource settings, especially in developing countries.

[1]Convergence of infectious diseases, such as TB and HIV, exacerbates the negative impact of weak diagnostic tools. HIV in TB-endemic settings increases incidence and the population of symptomatic individuals, while co-infection decreases the sensitivity of microscopy for accurately diagnosing TB.

1. There are four main categories of analytes (indicators) of disease

Our focus is on in vitro diagnostics, the predominant method for testing for various diseases. In vitro diagnostics utilize a fluid or tissue sample from a patient to identify the presence, absence or changed quantity of specific analytes (molecular indicators of disease) through biological or chemical analysis.

The four main categories of analytes measured by in vitro diagnostic technologies are explained below.

Cells

Cell-based diagnostics are a mainstay of modern medicine and rely on the evaluation of whole cells to detect the presence of certain diseases and for hematological analysis. Information on full blood cell counts is required to diagnose and monitor conditions, such as HIV/AIDS, for which CD4+ T-lymphocyte counting (CD4 count) forms the basis of monitoring disease progression.

Most cell-based diagnostics, in their current form, are not practical for use in low-resource settings because they generally require sophisticated laboratory facilities, stable electricity and highly skilled personnel. Moreover, the success rate of these diagnostics is dependent on the skill level of the technician running the assay.

Proteins

Proteins found in patient samples, such as whole blood, serum/plasma, saliva and urine, are important for diagnosing a variety of diseases. At the point-of-care, protein detection is performed using both immunoassays and enzymatic assays. Tests are available for viral infections (anti-HIV antibodies, antibodies against influenza A/B virus, rotavirus antigens), bacterial infections (antibodies against Streptococcus A and B, Chlamydia trachomatis, Treponema pallidum), parasitic infections (histidine-rich protein 2 for P. falciparum, trichomonas antigens), and non-communicable diseases (PSA for prostate cancer, C-reactive protein for inflammation, HbA1c for plasma glucose concentration) (Chin, et al., 2013).

Nucleic acids

Nucleic acid detection is used in prenatal diagnosis of inherited disorders, diagnosis of genetic disease, identification of infection, disease staging, and measuring drug resistance. Nucleic acid testing (NAT) detects the presence of a pathogen either by directly detecting the pathogen's genetic material (DNA or RNA) in the host, or by first amplifying the pathogen DNA or RNA and then using probes that are specific to the pathogen of interest.

Advantages of NAT include high sensitivity due to amplification, and specificity because it targets unique sequences associated with the pathogen of interest. NAT can detect low-level infections when either the amount of the infecting agent is minimal or when the immune system hasn't had time to form antibodies against it.

This reduces the time between infection and diagnostic detectability of the disease (Chin, et al., 2013). This method can be used to accurately quantify the level of infection and to determine the type of strains and the drug resistance profiles, which are significant issues in diagnosing and treating diseases like TB and HIV.

Small molecules

Small molecules from a variety of bodily fluids can be used to measure health parameters. Examples include testing of iron levels to indicate anemia in pregnancy, blood glucose for diabetes monitoring, and lipid levels for cholesterol monitoring.

Such tests analyze a range of electrolytes like potassium ion and chloride, physiologically important molecules like urea, lactate, albumin and creatinine, and blood gases. These tests are based on electrochemical detection such as potentiometry, amperometry and conductance (Chin, et al., 2013).

2. Over the years, a number of point-of-care diagnostic tests and devices have been developed

In order to benefit the majority of patients in developing countries, diagnostic tests must be portable and lightweight, capable of operating without clean water or electricity, resilient to heat, humidity and transport, and simple enough to be used by minimally trained health care workers at the point-of-care. Diagnostic tests for the above analytes have not yet been fully optimized for use in low resource settings. Nevertheless, a number of relevant point-of-care diagnostic applications have been developed, which are profiled below.

Cell-based assays

Point-of-care cell-based diagnostics are becoming increasingly important in hematology, particularly for the quantification of white blood cells for diagnosing, monitoring and clinical staging of diseases like HIV/ AIDS. Such tests aim to replace resource-intensive laboratory technologies like flow cytometry, which are typically not viable in low-resource settings (Chin, et al., 2013). Most technologies being developed now are self-contained, portable, handheld, do not require extensive sample processing, and have the potential to meet the pressing need for a point-of-care CD4 count quantification method for the management of HIV/AIDS (Chin, et al., 2013).

Immunoassays

These assays utilize the binding of an antibody (naturally produced by the immune system to neutralize pathogens) to an antigen in order to diagnose a disease. Immunoassays make use of the binding interactions between antigens and antibodies to detect protein markers from either the pathogen or the host immune response. Immunoassays generally rely on either a visual read-out for the healthcare worker administering the test to show whether the antigen or antibody of interest is present, or on a fluorescent dye that can be quantified using a plate reader, microscope or other detection methods.

Immunoassays are considered the gold standard laboratory assays for diagnosing a variety of diseases that involve natural host immune responses, including infectious diseases like HIV/AIDS and a wide variety of autoimmune diseases such as multiple sclerosis. In the developing country context, immunoassays have led to simple, low cost rapid diagnostic tests (RDTs), based on simplified ELISA (Enzyme-linked immunosorbent assay) testing techniques for a small number of important conditions: malaria, HIV/AIDS, syphilis and hepatitis B (RDTInfo, 2013), as well as proteinuria and pregnancy.

These tests have yielded significant improvement in health outcomes in developing regions, and have overcome the challenges of traditional immunoassays (namely personnel training and equipment) by including all of the reagents as part of the test and producing a visual readout that is easy to interpret.

Critically, these tests are based on patient samples like nasal swabs, urine, saliva or whole blood that can be collected using minimally invasive techniques by healthcare personnel with limited training. Currently, most RDTs are strip tests or dipsticks and rely on low cost immunochromatography (ICS) technology to detect antigens or antibodies.

Nucleic-acid testing

Nucleic acid tests are high cost, complex and require trained laboratory technicians. They are therefore mainly used in hospitals and centralized laboratories (LaBarre, et al., 2011). The difficulty of developing a self-contained, simple, robust and cost-effective NAT system for use at the point-of-care has a lot to do with the technical difficulties of integrating the steps of sample preparation, nucleic acid amplification and detection, which will be explored in more detail later in this section.

Despite these difficulties, there is increasing emphasis on bringing NAT to the point-of-care. One commercial example is Cepheid's GeneXpert® test platform for TB, which is currently available in many developing countries. However, this system requires uninterrupted and stable electrical power supply and annual validation of the system to ensure test accuracy (Chin, et al., 2013), limiting its use in low resource healthcare settings.

GeneXpert® utilizes a real-time fluorescence-based technique for polymerase chain reaction (PCR) detection. Other detection approaches being explored for NAT at the point of care include electrochemical methods, magnetic resonance and lateral flow devices for end-point detection (Chin, et al., 2013).

Clinical chemistry assays

These assays measure a variety of blood parameters including gases, electrolytes, hemoglobin, pH, enzymes, metabolites, lipids, hormones, vitamins and trace factors, inflammatory markers and cytokines, coagulation proteins, therapeutic drugs and drugs of abuse (Chin, et al., 2013).

Point-of-care testing of these clinical chemistry markers is preferable as test accuracy can decline when samples are transported to central laboratories for testing. Very few peripheral healthcare facilities in developing regions today carry out clinical chemistry testing.

Some instruments that use an electrochemical detection method for measurement of electrolytes, general chemistries, blood gases and hematocrit are not widely available yet at the point-of-care. Others are still exploring optical detection methods that have the potential to reduce the cost of clinical chemistry assays at the point-of-care (Chin, et al., 2013).

Hematology

At the point-of-care, hematology tests are widely used for measurement of hemoglobin and hematocrit to test for anemia and to measure blood coagulation. Several companies have developed point-of-care technologies to measure such parameters, including Sphere Medical, Abbott Diagnostics, Roche Diagnostics and Alere (Chin, et al., 2013).

Detection technologies

Recent technology improvements in optical detection have shown promising results. The new focus on using readily available consumer electronics, such as webcams charge-coupled device cameras and LEDs, has resulted in developing low-cost medical diagnostics in resource-poor settings. These technologies have the potential to overcome the traditional challenges faced by older optical detection technologies, which had low sensitivity and specificity (Balsam et al., 2013). A few breakthrough technology examples are:

- A webcam-based multiwavelength fluorescence plate reader and a webcam-based fluorescence microscope demonstrated for colonic mucosa tissue pathology analysis
- A lens-free optical detector used for the detection of Botulinum A neurotoxin activity
- A lab-on-a-chip, which enables the performance of enzyme-linked immunosorbent assay and other immunological or enzymatic assays without the need of dedicated laboratories and complex equipment demonstrated for the detection of the toxin staphylococcal enterotoxin B.

3. Current diagnostic technologies for major diseases have a number of shortcomings

In order to be accessible to low-income patients seeking care from peripheral healthcare facilities, diagnostic tests need to be inexpensive, portable, robust, capable of operating without heavy reliance on clean water or electricity, able to withstand ambient heat and humidity, and simple enough to be used by minimally trained healthcare workers.

A reliable supply of consumables and actionable test results are equally as important. Based on their ability to meet such requirements, diagnostic methods currently being used have a number of shortcomings, as summarized for four major disease conditions in **Table 1.**

The state of diagnostic technologies for four major diseases: Malaria, TB, HIV/AIDS and Lower Respiratory Infections

Malaria	
Diagnostic Needs	Identification of infection
Methods used in industrialized countries	N/A[2]
Methods used in developing countries	Usual diagnosis using RDT dual antigen; requires no lab intervention
Challenges with current mechanisms in developing countries	1. Rapid immunoassays can be of poor quality and cannot store data to link patients to care following a positive test result 2. They do not enable differential diagnosis between malaria and other causes of febrile illness 3. The RDTs have a poor shelf life and limited resistance to temperatures change
Promising Technologies	1. ELQ300, Anti-malarial compound and BK-SE36, Malaria vaccine 2. Non-invasive Malaria diagnostic devices
Hurdles to broad penetration	1. Healthcare delivery constraints (weak supply chain, limited quality assurance and control, inadequate guideline emphasis, staffing limitations) 2. Provider perceptions (entrenched case-management paradigms, limited preparedness for change) 3. Social dynamics of care delivery (expected norms of provider-patient interaction, test affordability) 4. Limited provider engagement in policy processes leading to fragmented implementation of health sector reform

[2]Very few patients are tested for malaria in industrialized countries, as the disease has been eliminated from these regions.

Tuberculosis	
Diagnostic Needs	1. Identification of active TB disease 2. Determination of drug susceptibility
Methods used in industrialized countries	1. PPD tuberculin test: injected just below the skin of your inside forearm 2. Bacteria bulture from sputum/sputum smear or chest radiograph 3. Blood tests: sophisticated technology to measure immune system's reaction to TB bacteria; QuantiFERON-TB Gold in-Tube test and T-Spot 4. Drug susceptibility testing (DST) via line probe assay (LPA)
Methods used in developing countries	1. DMN-Tre-upcoming technology used in Africa 2. Sputum microscopy followed by broad-spectrum antibiotics and chest radiography if smears are negative 3. Smear-negative and MDR-TB diagnosis: bacterial culture (or liquid culture) 4. Catridge-baded-NAAT test (Xpert MRB/RIF)
Challenges with current mechanisms in developing countries	1. HIV reduces the accuracy of both microscopy and radiography, so assessment of diagnostic approaches with existing methods and continuing research into new diagnostics are necessary 2. Detection of the drug resistance pattern and availability of highly active drug treatment is time consuming 3. Lack of simple, rapid triaging tests 4. High cost, implementation failures 5. Slow adoption of new tools, still highly dependent on smear tests
Promising Technologies	1. Low-cost fluorescent microscope 2. Rapid blood-based biomarker tests for quick diagnosis 3. AI powered x-ray image readers for rapid screening 4. POC molecular diagnostics 5. DNA and RNA sequencing for drug resistance testing
Hurdles to broad penetration	1. Inadequate clinical and laboratory infrastructure 2. Absent training programs for combined tuberculosis and HIV/AIDS care 3. Affordability of the tests 4. Regulatory and policy restrictions; Implementation failures

HIV/AIDS	
Diagnostic Needs	1. Identification of infection/disease screening 2. Disease staging to determine treatment initiation (CD4 count) 3. Monitor treatment efficacy/failure (viral load and drug resistance)
Methods used in industrialized countries	1. Viral load and drug resistance: Nucleic acid-based tests in central labs 2. HIV diagnostic test, FDA approved 3. Rapid Tests: a. OraQuick Advance Rapid HIV-1/2 Antibody Test (whole blood finger prick or venipuncture, plasma, oral fluid) b. Reveal Rapid HIV-1 Antibody Test (serum, plasma) c. Uni-Gold Recombigen HIV Test (whole blood finger prick or venipuncture, serum, plasma) d. Multispot HIV-1/HIV-2 Rapid Test (serum, plasma); INSTI HIV-1 Antibody Test (whole blood finger prick or venipuncture, plasma) e. Alere Determine HIV-1/2 Ag/Ab Combo Test (serum, plasma, whole blood finger prick or venipuncture) f. Clearview tests – Clearview HIV 1/2 Stat Pak g. Clearview Complete HIV 1/2 (whole blood, serum, plasma)
Methods used in developing countries	1. Screening: Rapid immunoassays that do not require lab facilities 2. Confirmatory tests: performed with a minimum of two to three different rapid assays in high prevalence areas 3. Centralized NAATs viral load, drug resistance and early infant diagnostic testing
Challenges with current mechanisms in developing countries	1. Sample collection prevents POC tests to be used widely at primary care settings 2. Significant management and operational infrastructure required for centralized testing, leading to underutilization of existing lab capacity, improper test reporting 3. Nucleic-acid tests require expensive lab equipment and trained personnel, making their widespread implementation in low-resource settings very difficult; There are currently no point-of-care viral load tests that can accept whole blood specimens
Promising Technologies	1. Mobile based diagnostic tests 2. RDTs for self-testing 3. POC technologies (Infant focused)– NAT based
Hurdles to broad penetration	1. Quality control/assurance, especially for self-testing products 2. Training and appropriate use of RDTs by healthcare providers 3. Responsible usage of HIV self-testing within the community

Lower Respiratory Infections	
Diagnostic Needs	1. Identification of pneumococcal infections and etiology • *Streptocaccus pneumoniae* • *H. influenzae* • RSV • Influenza • Other pathogens
Methods used in industrialized countries	Chest x-ray and/or bacterial culture from sputum or blood
Methods used in developing countries	Syndromic management or use of diagnostic surrogates (e.g. arm circumference, chest ausculation)
Challenges with current mechanisms in developing countries	Diagnostic approach to disease management is lacking due to: • Difficulty of sample acquisition (particularly sputum from children) • Lack of pathogen identification, which relies on bacterial culture with long lead-times • Poor link to appropriate therapy • Lack of radiography
Promising Technologies	1. Rapid tests for differential diagnosis of viral vs. bacterial infection 2. Multiplex tests
Hurdles to broad penetration	1. Selection of targets for multiplex tests 2. Proving cost-effectiveness and clinical value of multiplex tests 3. Training and appropriate use of by healthcare providers

Table 1: There are several gaps in the current state of diagnostics available to low-income populations and their healthcare providers for the four major infectious diseases—HIV/AIDS, TB, Malaria and lower respiratory infections. These gaps are different for each disease[3]. (Source: ITT analysis)

[3]Diarrheal disease, caused by bacterial, viral or parasitic agents, is primarily diagnosed by clinical symptoms and has been excluded from this table. Diagnostic techniques based on immunoassay, nucleic acid amplification and culture are available for multiple specific causes of diarrhea. However, all of these diagnostics require access to sophisticated laboratory facilities. As diarrheal disease is managed by supportive rehydration therapy and non-specific medications, specific diagnosis is generally not considered essential.

4. Diagnostics for patients in developing countries need to consider several other factors

In addition to meeting operational requirements of low-resource settings, several additional technical parameters must be considered in the design of appropriate diagnostics for developing regions. Ideal diagnostic solutions will account for broader health trends and the needs of national public health systems. Three significant dimensions are listed below.

Drug resistance

A number of infectious diseases are developing drug-resistant strains, in turn complicating the already difficult task of diagnosis and treatment. For such diseases, it is critical to go beyond simple detection and recognize whether or not the strain is drug-resistant, and identify what particular treatment the infecting pathogen will be sensitive to.

With TB, in particular, the emergence of multiple drug-resistant strains is making it important to identify the specific drugs to which the pathogen or bacterium is resistant to. This means that the diagnosis needs to go beyond a 'yes or no' detection of drug-resistant TB.

In cases of co-infections (like HIV-TB co-infection) such detection becomes even more critical as combining two separate treatments may reduce the efficacy of one or more drugs being administered to a patient.

Storing and transmitting data

One of the major challenges in timely diagnosis and treatment in rural, low-resource settings is the long turnaround time. Delays occur in pre-analytical (such as specimen transport), analytical (test processing) and post-analytical (results delivery) phases. In a centralized lab, up to 50 percent of tests are not delivered at all, with the average time of 61 to 90 days from test to start of treatment (Gous et al., 2018).

While mobile connectivity has improved speed of delivering test results, current systems are not holistic in nature and data remain unactionable to address adherence. For public health systems to plan broader disease control strategies, it is very helpful to track cases as well as epidemiological and health statistics obtained during diagnoses.

Additionally, there is strong need to store and transmit patient data from point-of-care to higher-level health facilities and national-level databases. This data may be used to prevent patient dropout due to lack of follow up, enable ongoing clinical management of patients that need protracted treatment, and to enable efficient inventory management, quality assurance and need-based training for healthcare providers.

The proliferation of mobile information and telecommunications platforms makes such a capability possible (Reid, 2012).

Multiplexing capabilities

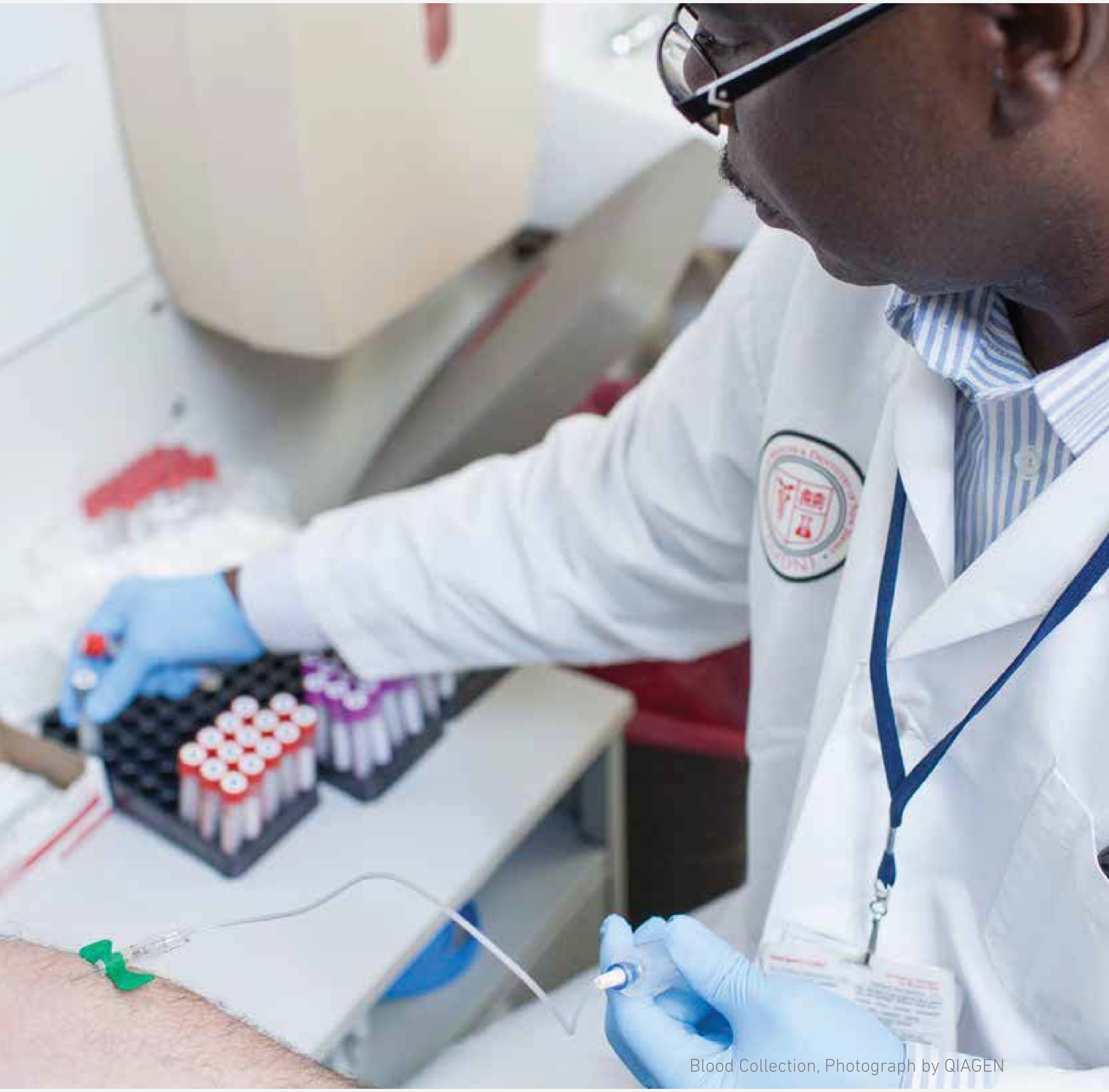
Often, poor patients are more likely to suffer from low immunity due to malnutrition, inadequate hygiene and other risk factors, and thus face a higher possibility of infection from multiple diseases or pathogens. Additionally, different diseases can present similar symptoms, such as fever. In such cases, a single device or platform capable of simultaneously diagnosing multiple diseases that present similar symptoms will be extremely valuable.

Specific examples of clinical scenarios in which multiplex testing would be desirable and examples of specific diagnostic panels are provided later in this section. The importance of multiplex testing must be carefully balanced against affordability; additional pathogen tests for a diagnostic device increases overall costs. The selection of multiplex tests should be determined based on the clinical actions that will be informed through this differential diagnosis, and the improved health outcomes that can be achieved by doing this.

KEY CHALLENGES

With the above criteria in mind, current diagnostic products and technology applications fall well short of what is required for affordable and effective diagnosis for a number of important diseases and medical conditions.

Several technical challenges play a role when it comes to developing point-of-care diagnostics for low-resource settings.



Blood Collection, Photograph by QIAGEN

1. Available immunoassay rapid diagnostic tests (RDTs) have significant limitations

Immunoassays have several limitations that restrict their suitability in low-resource settings.

First, high ambient temperatures and humidity, common to many developing countries, and the lack of refrigerated storage can cause degradation of patient samples and diagnostic reagents, which limits assay sensitivity and shelf life.

Second, antibodies can persist beyond the clearance of an infection. Immunoassays that rely on detecting antibodies in a patient can measure only the one-time existence of an infection and not whether the infection is active or has cleared (BVGH, 2012). Such tests can also result in a false negative result when there is either a low level of antigenemia or when the antigens have short life cycles (LaBarre, et al., 2011).

Third, due to inadequate regulations there is a proliferation of poor quality or counterfeit products (Mehta & Cook, 2010). Regulation of RDTs will become more and more important as the self-testing demand grows.

Finally, immunoassays cannot generally be used for identifying specific strains of pathogens or test for drug resistance. Thus, while lateral flow RDTs have represented an important advancement over diagnosis based entirely on clinical symptoms for a number of diseases, consistently high performance tests that allow for external quality control are essential.

2. NATs have proven difficult to develop for point-of-care use

NATs require the use of unstable or sensitive reagents, specific infrastructure or equipment, and highly trained staff. Integrating these essentials into portable, user friendly and affordable tools appropriate for use by minimally trained staff in low-resource settings is extremely difficult.

NAT is time-consuming and typically involves three steps: sample preparation (consisting of sample collection and processing), signal amplification and detection. Several challenges within each of these steps makes the current implementation of NAT at the point-of-care prohibitively complex (Chin, et al., 2013).

Sample preparation

An intrinsically complicated process, sample preparation involves cell or virus capture and isolation, lysis (breaking down of the cell wall or viral coat), and nucleic acid extraction and purification. This generally requires laboratory equipment such as a centrifuge or vacuum manifold.

Optimal sample preparation is critical to the outcome of the NAT assay. Post extraction, the nucleic acids are prone to degradation, which can lead to misinterpretation of results. Subsequent sequence amplification steps are highly sensitive to contaminants that result from incomplete purification. Further, the risk of cross-contamination between separate samples also poses a significant obstacle to the reproducibility and reliability of NAT assays.

Overall, the time-consuming nature of sample collection and processing and the training and infrastructure requirements associated with sample preparation limit the applicability of NAT at point-of-care in low-resource settings.

Signal amplification

Typically, NATs relies on a separate amplification step because there is insufficient nucleic acid in a raw sample for direct detection using current detection technologies. Most NATs relies on a polymerase chain reaction (PCR), a temperature-controlled and enzyme-catalyzed reaction based on thermal cycling of the sample-reagent mixture. Thermal cycling involves cycling the sample-reagent mixture through two temperature extremes, typically at relatively high rates of change. This generally requires complex equipment and stable electrical power. However, newer and simplified methods are increasingly available.

Isothermal amplification methods—which operate at a single temperature—typically require electrical power, although some technologies appear promising in addressing that hurdle (Piepenburg, et al., 2006). Reagents used for NATs typically require cold storage and technical training to be properly handled. The needs of current amplification methods—reliable power, expensive machines (like thermocyclers), high quality (reagent-grade) water, refrigeration and trained technicians—prevent deployment of NATs at the point-of-care.

Detection

Nucleic acids are typically detected through fluorescence (the most common method), phosphorescence, chemiluminescence, or through a color change resulting from a chemical or enzymatic reaction. Such optical methods usually require dyes and/or enzymes, which can degrade in high ambient temperatures typical in many developing countries, leading to higher assay background noise or reduced sensitivity.

Most biological samples contain autofluorescent compounds; when fluorescence is used as a detection technique it can also be highly sensitive to contaminants. Sample purity must be high to rely on fluorescent detection. In general, NAT detection techniques require complex optical instrumentation, stable power and trained technicians, posing challenges to implementing NAT at the point-of-care.

3. The ability to develop improved diagnostic tests is limited by the availability of disease biomarkers

In the context of diagnostics, biomarkers are measurable indicators of organisms or diseases in human tissue or bodily fluids. Known disease biomarkers are necessary to develop diagnostic tests. Ideally these samples should be easily obtainable.

Depending on the availability of biomarkers for specific diseases, multiple diagnostic technologies may be needed to analyze multiple types of samples. An expert panel organized by the American Society of Microbiology singled out the identification of novel biomarkers as "having the most potential" to contribute to the development of new point-of-care tests (Reid, 2012).

There are a range of challenges related to biomarkers for diseases prevalent in developing countries. For some diseases, relevant biomarkers have not been identified yet, while there are a number of diseases for which known biomarkers require sample types that are difficult to obtain.

For example, meningitis[4] can only be diagnosed by analyzing cerebral spinal fluid, which must be obtained through an invasive lumbar puncture. Tuberculosis, on the other hand, generally relies on sputum, which can be a difficult sample to obtain (from children) and process (for patients of all ages). Some biomarkers represent only a subset of the organisms responsible for a single disease, and other biomarkers depend on a host response that can be variable and can lack sensitivity.

Recent research has advanced our understanding of the role of biomarkers in cancer (Brenner, et al., 2014), tuberculosis (Wallis & Peppard, 2015), and Alzheimer's disease (Sheikh-Bahaei, et al., 2017).

There has been swift expansion in the potential range of biomarkers, including specific gene sequences and surface markers, ratios of expressed genes, quantitative measures of antibody or pathogen levels, and detection of specific metabolites, proteins and lipids.

New biomarkers, especially those available through easily accessible sample types, can support the development of new tests that can then run on the next generation of point-of-care diagnostic platforms.

However, discovery of novel biomarkers is scientifically unpredictable and requires significant additional investment. As biomarkers become available in accessible sample types, diagnostic test developers can easily incorporate them into new tests. Still, there will be challenges in getting clinicians to uniformly learn and adopt the new practices.

[4]Except for cryptococcal meningitis.

4. Multiplex diagnostic test panels to support clinical needs are yet to be defined

As mentioned earlier, there is increasing recognition of the value of multiplex diagnostic platforms that can diagnose multiple conditions within a single patient visit.

To perform a true differential diagnosis, a broad test menu must be available at the point-of-care. The Bill & Melinda Gates Foundation has been defining such panels of tests for a number of important conditions and clinical scenarios (**Exhibit 1**).

These represent complete panels required for treatment decisions and a departure from the historical focus on disease specific tests; except for the neglected infectious diseases category (BMGF, 2013).

Potential multiplex diagnostic platforms for point-of-care use

HIV	Maternal/ Neonatal health	Febrile	Respiratory	Enteric and diarrheal diseases	Neglected infectious diseases
HIV antibody	Preeclampsia	Malaria	Preeclampsia	Amoebiasis	Schistosomiasis
CD4	CBC	Pneumonia	Influenza	Campylobacter	Leishmaniasis
Viral load	Glucose	Dengue	RSV	E. coli	Japanese Encephalitis
CBC	Syphilis	G6 PD	TB+	Shigellosis	Trypanosomiasis
Liver function	HPV	Typhoid	MDR/XDR	Cholera	
Creatine	p24		CBC	Cryptosporidium	
TB+	HIV antibody				
MDR/XDR	Hepatitis				
	Serum iron				

Keys diagnostic platform required to perform test

Cell counting NAT (quantitative and non) Chemistry analysis Immunoassay/ Lateral flow

Exhibit 1: A number of diagnostic panels are required for thorough treatment decisions. This is a departure from the historical focus on disease specific tests. (Source: BMGF, 2013)

Other tests with a potential to greatly impact healthcare and health outcomes in developing regions include (Reid, 2012):

Bacterial versus viral infection

Syndromes such as fever or upper respiratory infections can be caused by many different pathogens like viruses, bacterium, fungus or parasites. No simple test that can determine the cause of such seemingly commonplace illnesses exists yet.

Such a test should ideally be able to determine the resistance profile of the causative agent; but even a simple differentiation among causative agents will go a long way towards enabling appropriate treatment (for example antibiotics versus antimalarials). These tests could be customized further to reflect and address specific needs of a region.

For example, a 'fever panel' in a malaria endemic area could capture various causes of fever including bacterial infection, viral infection and different malaria strains.

STD panel

Sexually transmitted diseases (STDs) affect patients and their partners, and can also be transmitted to fetuses by pregnant mothers. It would be useful to have a single test to differentiate between syphilis, herpes simplex, trichomonas, chlamydia and HPV. A rapid test for HPV can also be used as a screening test for determining the risk of contracting other STDs.

Central nervous system infections

Meningitis (with the exception of cryptococcal meningitis) can only be diagnosed by examining cerebral spinal fluid that is obtained through lumbar puncture. This is an invasive procedure and requires highly trained caregivers. A simpler test that can also differentiate bacterial and viral meningitis, and the pathogens responsible for encephalitis and meningitis, would be extremely useful for enabling appropriate treatment. This depends on the discovery of new biomarkers.

State of health panel

There are opportunities to develop panels of tests outside of infectious diseases, which might measure health indicators related to chronic or non-communicable diseases (NCD), such as diabetes or heart disease.

NCDs represent 43 percent of the global burden of disease and are expected to be responsible for 60 percent of the disease burden and 73 percent of all deaths by 2020 (WHO, 2013). A rapid test that provides information such as white cell count, lipid profile and other indicators could also be of great value in enabling effective clinical case management.

SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

Diagnostic tests that are robust, inexpensive and simple to use have the potential to greatly improve quality of healthcare in low-income countries. Today, approximately 60 percent of the target patient population in developing countries lacks access to advanced diagnostics tools (Nantulya, 2006). This is a result of poor infrastructure (unreliable access to power, lack of indoor climate control, poor cold chain storage conditions and lack of trained technologists), limited menu of available diagnostic tools, and cost barriers including both capital investments in equipment and per-test costs.

To improve diagnosis at the point-of-care in resource-poor settings, there is a clear need for simpler and smaller instruments. Test development should focus, in the short term, on single tests for critical disease-specific unmet diagnostic needs like point-of-care tests for HIV viral load monitoring or TB drug susceptibility.

In the medium term, platform technologies that offer broad menus of tests in a variety of sample types that previously required multiple detection technologies could be the answer. Finally, the ultimate breakthrough will be an integrated and comprehensive semi-open source diagnostic system that processes samples, performs assays and automatically reports results for a range of conditions, using components made by different manufacturers.

Breakthroughs:

1	2	3	4	5	6	7	8	9	10
11	12	13	14	15	16	17	18	19	20
21	22	23	24	25	26	27	28	29	30
31	32	33	34	35	36	37	38	39	40
41	42	43	44	45	46	47	48	49	50

32 Low cost, novel diagnostics for pneumonia

Pneumonia is currently diagnosed by a clinic consultation, not by a specific diagnostic test. This makes it difficult for care providers to identify different clinical scenarios, such as whether a patient has viral or bacterial pneumonia or quickly determine the infecting pathogen, which can help indicate the potential severity of the illness. Accurate diagnostics also has the potential to reduce medicine wastage, and reduce the risk of antimicrobial resistance.

While the gold standard for diagnosis is through a chest X-ray, the imaging test is not practical for clinics in low- and middle-income countries. Most diagnoses are made based on evaluation of respiratory rate and chest in-drawing. The technological challenges and time to market for a novel pneumonia diagnostic vary depending on what the clinical goal of the diagnostic would be.

A urine-based diagnostic for pneumococcus bacteria, for example, is now available. However, a diagnostic that can discriminate between bacterial and viral pneumonia, and severe and non-severe pneumonia, is much more technologically complex; in some cases, biomarkers have not been identified yet. The primary benefit of diagnostics that provide deeper information about the infecting pathogen would likely be a better understanding of the disease and its epidemiology, as opposed to reduced mortality.

Reducing mortality from severe pneumonia would likely rely on improvements in pulse oximetry and respiratory rate timers. Both are effective technologies, and while they could be refined further, and can be incorporated into multimodal devices that also measure other vitals, the key challenge is distribution to, and adoption at, the clinics, as opposed to major improvements in either the cost or technology.

However, even the impact from better oximetry and respiratory rate timers, or any accurate rapid diagnostic tests are likely muted, as a reduction in mortality will only happen if patients seek care, are diagnosed in time and in some cases have subsequent access to oxygen therapy, which is currently rare.

Current State

Development Stage: R&D

Time to market (years)

<3 4-6 7-10 10+

Deployment: Challenging

Associated 50BT Chapters

Global Health

SDG Alignment

1 NO POVERTY

3 GOOD HEALTH AND WELL-BEING

Impact

Lives Saved (# of People/Year)

<1M 10M+ 100M+ 1B+

Health Improved (# of People)

<1M 10M+ 100M+ 1B+

Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

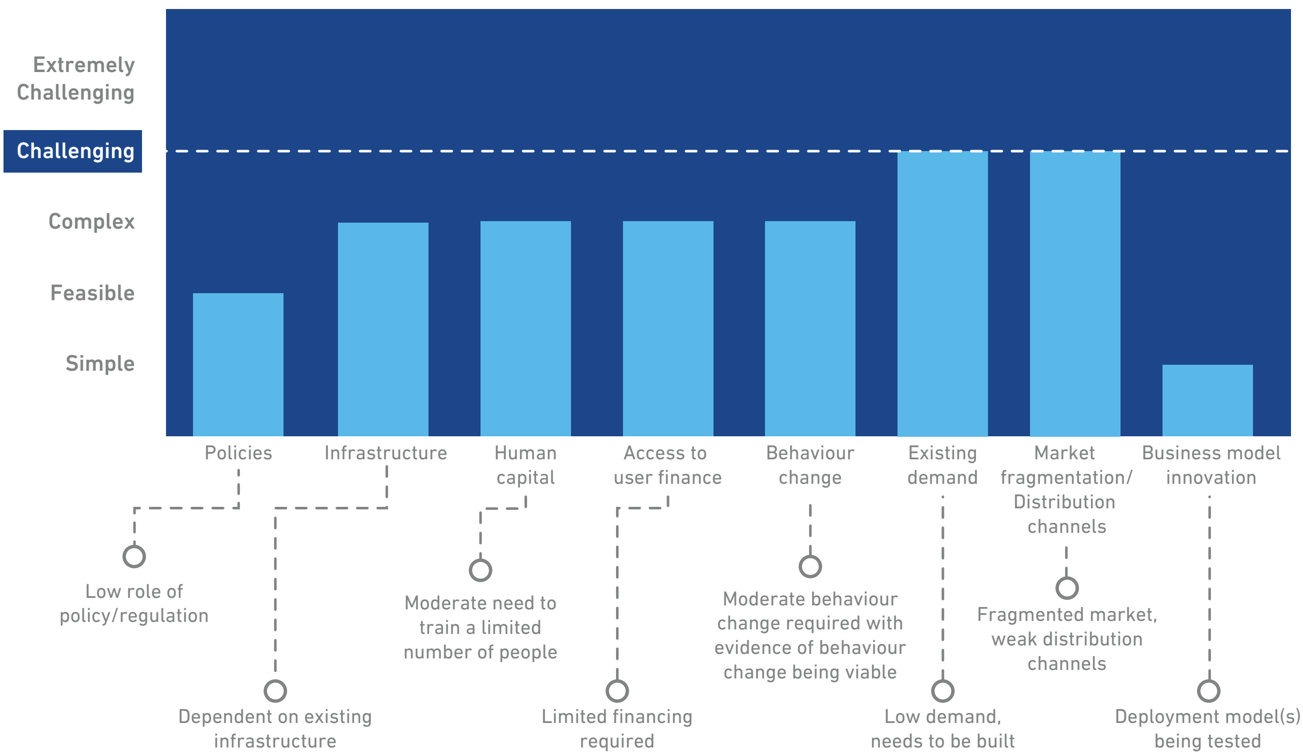
Ease of deployment varies by diagnostic type. In general, simpler devices like improved respiratory rate timers and pulse oximeters have fewer deployment barriers; they need less access to grid energy, less access to financing and less training. In each case however, lack of existing demand and market fragmentation are major hurdles in achieving scale.

There is currently no existing base for deployment of pneumonia diagnostics to rural clinics where they are most needed, so distribution of a new diagnostic would require creation of new channels as well as educating healthcare workers on the need and value of pneumonia diagnostics.

Since clinical diagnosis generally remains effective, and the downside to clinical diagnosis (like drug resistance) is neither immediate nor obvious, it will be challenging to convince healthcare funders and clinicians to devote scarce resources to purchasing and using pneumonia diagnostics.

Based on the above assessment, improved diagnostics for pneumonia are likely to be market ready in four to six years, and the difficulty of deployment is CHALLENGING.

Breakthrough 32: Difficulty of deployment



34 Automated multiplex immunoassays that can test for a broader range of diseases (compared to the current state) and are compatible with easily collected sample types

The development of point-of-care immunoassays that can use different types of samples (like blood, urine or sputum) and test for multiple biomarkers from a single patient sample represents a major breakthrough applicable to a wide range of disease conditions.

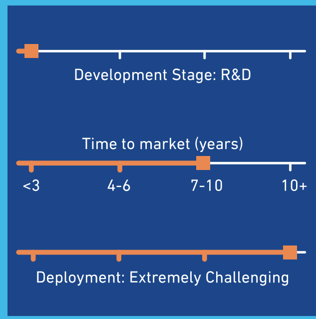
Next generation immunoassays will be multi-well, micro-scale, will integrate and automate steps from sample preparation through detection, and be appropriate for use in low-resource healthcare settings.

Several different types of point-of-care immunoassay platforms have been attempted, including antibody microarrays, immunosensors, microwell arrays and microfluidic chips, or combinations of these.

Microfluidics represents an important technology for point-of-care immunoassays, given that microfluidics offer increased surface-to-volume ratios, which can be exploited by immunoassays that capture analytes' surfaces.

However, challenges of developing such immunoassays have not yet been fully overcome, including the high sensitivity of detection required for measuring analytes in small sample volumes, the robustness and reproducibility in performing micro-scale assays, and the difficulty of manufacturing miniaturized component.

Current State

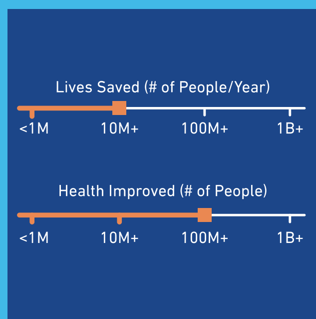


Associated 50BT Chapters

Global Health

SDG Alignment

Impact



Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

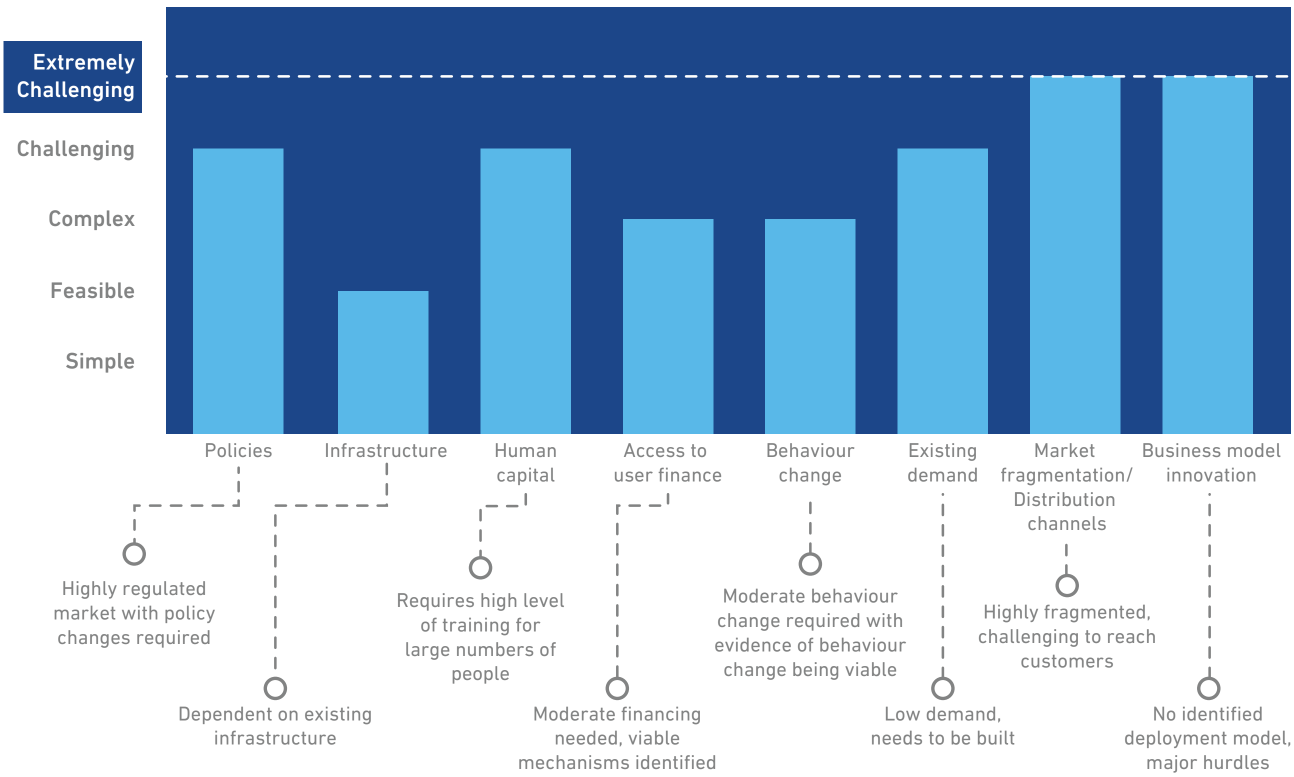
Overall, several hurdles limit the development, deployment and adoption of new diagnostic technologies. Development is hindered by the relatively small investments currently being made in developing diagnostics relative to developing new drugs and vaccines.

Deployment also rests on regulatory processes, WHO endorsement and the large capital expenditure required of countries that may look towards adopting new diagnostics on a large scale.

Regardless of how pressing a need for a new diagnostic may be, two other factors impact the end adoption: the costs and resources required to adequately train healthcare workers to use the new tests, and patients' willingness to pay for them.

Based on the above assessment, the projected time to market readiness is seven to ten years and the difficulty of deployment is EXTREMELY CHALLENGING.

Breakthrough 34: Difficulty of deployment



35 Point-of-care nucleic acid test (NAT) that is simple, robust, and compatible with easily collected sample types

A key breakthrough in disease detection is the development of point-of-care nucleic acid tests (NATs) applicable to a wide range of disease conditions. These tests should be compatible with simple sample types (such as whole blood), portable, rapid, robust despite high ambient heat and humidity, capable of being used by minimally trained technicians, and non-reliant on refrigeration, running water, and stable electricity. In addition, the technology should have a low price point to make it appropriate for use in peripheral healthcare facilities. Developing such a test poses significant technical challenges; it requires modular, instrument-free technologies for each of the NAT steps: sample processing, signal amplification and detection.

Sample preparation technologies

The manual, time-consuming and infrastructure-intensive sample collection, processing and purification associated with preparing an optimal sample for NAT must be integrated and automated so that minimally trained healthcare workers can perform testing. Non-invasive sampling technologies, simplified extraction techniques, sample concentration technologies and purification-free chemistries can help advance this goal.

Signal amplification technologies

The thermocycler, electricity and temperature control required for polymerase chain reaction (PCR) make NAT unsuitable for point-of-care adoption in low-resource settings. New technologies that are less sensitive to sample contaminants, have simpler thermal profile mechanisms that reduce sample processing requirements, and are not dependent on grid electricity, appear to be the way forward. Also critical is reduced reliance on cold chains and refrigeration. This will come from improvements in packaging, the ability to monitor temperature history, and the use of more stable substitutes in place of heat-sensitive reagents. Additionally, NATs that do not have to rely on stable grid power may depend on improved battery technology, solar chargers or generators, or any other new technology breakthroughs that provide instrument-free heat sources.

Detection technologies

Optical detection poses a challenge because of its potential dependence on extensive equipment. There are new detection technologies that do not rely on optical detection, including measurements of mass, magnetic properties, diffraction, or electrical potential that may enable development of more robust detection systems.

Current State

Development Stage: Engineering

Time to market (years)

<3 4-6 7-10 10+

Deployment: Extremely Challenging

Associated 50BT Chapters

Global Health

SDG Alignment

3 GOOD HEALTH AND WELL-BEING

Impact

Lives Saved (# of People/Year)

<1M 10M+ 100M+ 1B+

Health Improved (# of People)

<1M 10M+ 100M+ 1B+

Commercial Attractiveness

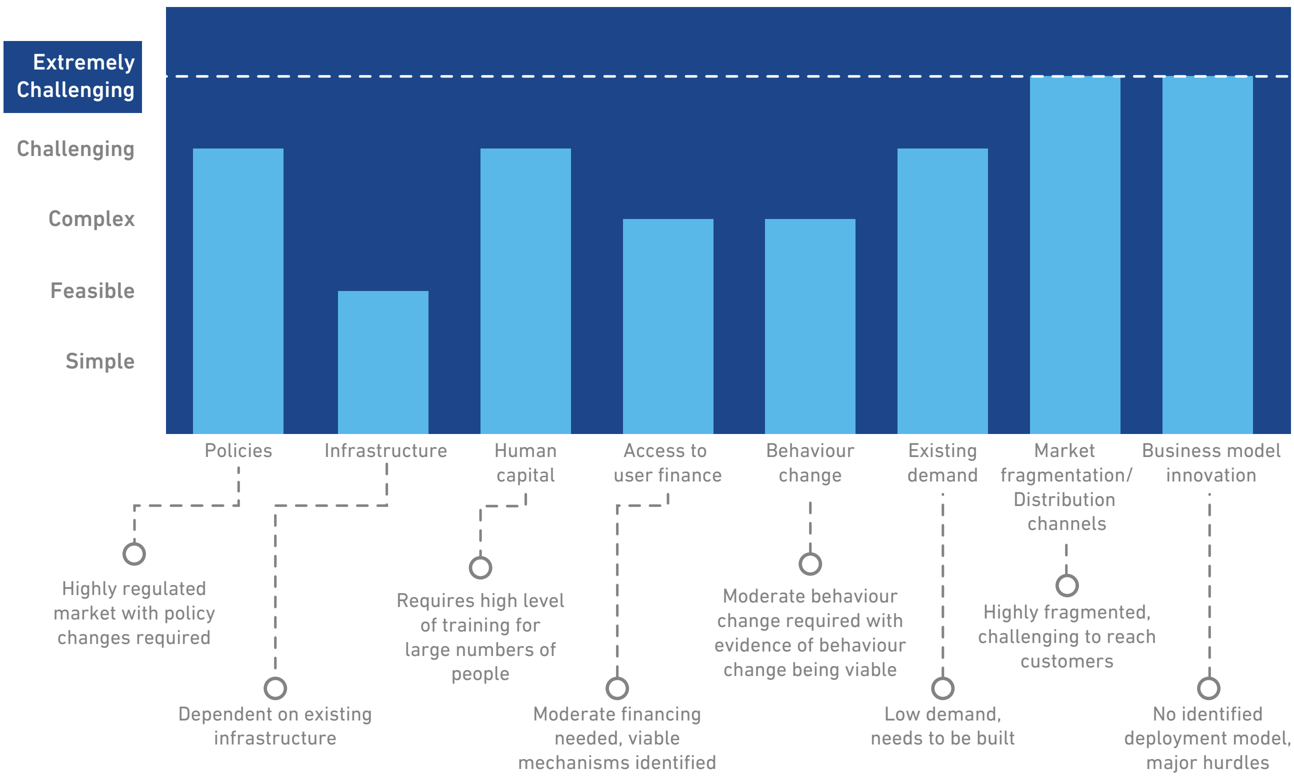
- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

Developing a point-of-care NAT will further depend on advancements in micro-fabrication and the ability to miniaturize test components that allow for multiplexing, reductions in sample size, and reduced reagent costs. Microfluidic platforms may yield a possible path forward for NATs as well, as demonstrated by the GeneXpert test for TB.

Deployment challenges include regulatory processes and WHO endorsement, as well as the large capital expenditure required of countries that may look towards adopting new diagnostics on a large scale. Regardless of how pressing a need for a new diagnostic may be, two important factors that will impact the end adoption are the costs and resources required to adequately train healthcare workers to use the new tests, and patients' willingness to pay for them.

Based on the above assessment, the projected time to market readiness is seven to ten years, and the level of difficulty is EXTREMELY CHALLENGING.

Breakthrough 35: Difficulty of deployment



36 Affordable, home-use point-of-care diagnostics suite (blood, urine, vitals) for the common NCDs

Point-of-care testing is essential for the rapid detection of diseases at the point of care, which facilitates faster disease diagnosis, reduces costs and improves outcomes. Moreover, home-use tests are increasingly designed to be simple to administer and interpret, thus overcoming the challenge of paucity of trained personnel. In the last few years, there has been a move towards integrating tests with mobile applications due to ease of data capture, better user experience and widespread adoption of smartphones. These include both standalone mobile health applications and more integrated testing applications.

The latest improvements in point-of-care diagnostics are a result of continuous developments in biosensors, lateral flow tests, as well as integrated or lab-on-a-chip technologies. These include tests for diabetes, cardiac conditions and cancer. Many of these technologies have already been developed and commercialized in developed economies but are yet to find adoption and successful commercial models for widespread adoption in developing economics.

For example, testing of EG Antigen for cervical cancer, developed by Arbor Vita is currently available only in the United States. In 2018, the US Food and Drug Administration approved the use of in-home genetic tests for breast cancer developed by genetic testing company 23andMe. Molecular diagnostics offer great promise but are less available in low-resource settings.

Data analytics and artificial intelligence, such as image detection methods, are also showing promise in enhancing and reducing the complexity of robust diagnostic methods such as the pap smear, and can help scale up proven diagnosis methods into low-resource setting. Such technologies can increasingly be deployed in home-based and point-of-care settings, due to growing capacity for data networking.

Current State

Development Stage: Engineering

Time to market (years)

<3 4-6 7-10 10+

Deployment: Complex

Associated 50BT Chapters

Global Health

SDG Alignment

3 GOOD HEALTH AND WELL-BEING

Impact

Lives Saved (# of People/Year)

<1M 10M+ 100M+ 1B+

Health Improved (# of People)

<1M 10M+ 100M+ 1B+

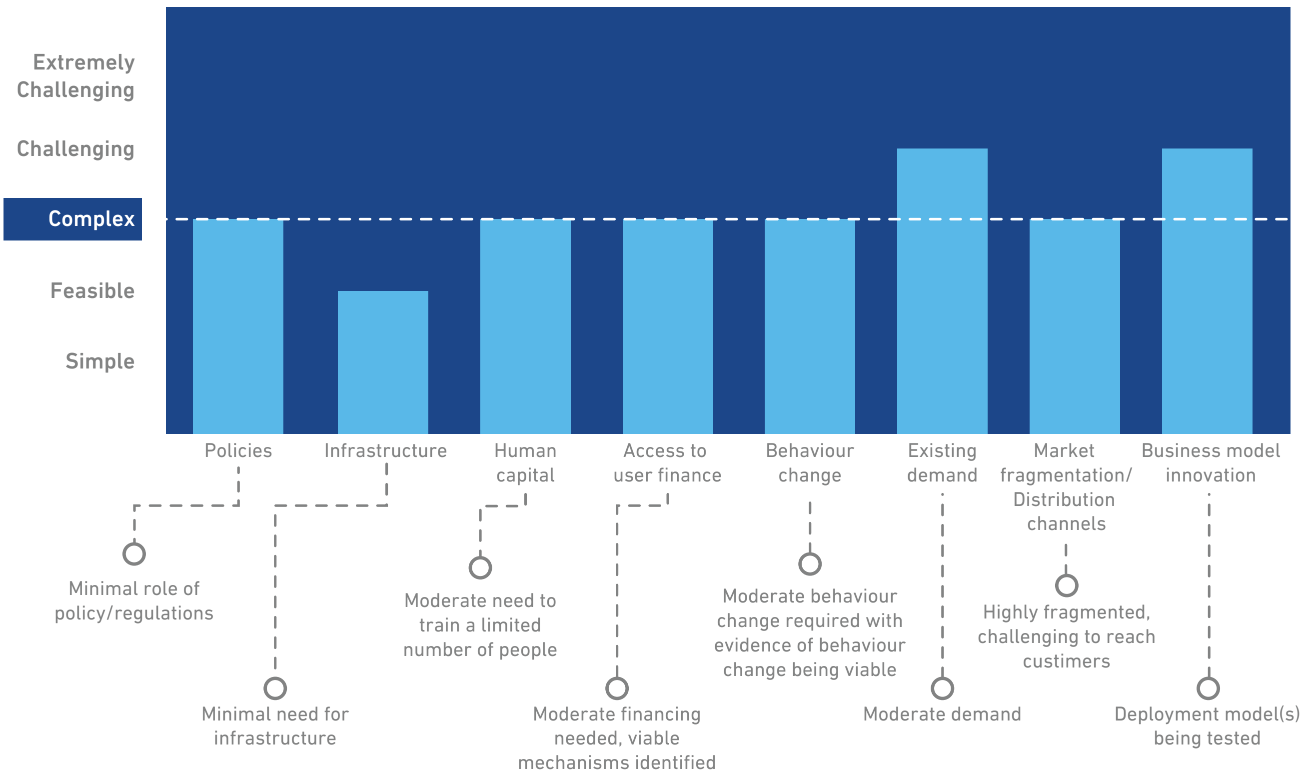
Commercial Attractiveness

- **Attractive for industrialized markets (high profits)**
- Attractive for emerging markets (lower profits)
- Emerging markets potential; requires derisking (sustainable)
- Non-commercial (unprofitable)

Widespread deployment of home-use point-of-care diagnostics devices for common NCDs will depend particularly on consumer demand for such service. Business models will need to focus on enhancing demand for the product through motivating customer self-interest.

Initial products with limited capabilities are currently on the market, and more sophisticated devices with improved performance will likely appear in the next 5 years. The difficulty of deployment is estimated to be COMPLEX.

Breakthrough 36: Difficulty of deployment



DIAGNOSTICS GLOSSARY

Assay: A term used to describe the procedure used for conducting a diagnostic test.

Analyte: Entity or target that is being analyzed (can be an ion, a protein, a cell, a molecule, among others).

Enzyme-linked immunosorbent assay (ELISA): A biochemical technique used mainly in immunology to detect the presence of an antibody or an antigen in a sample. In ELISA, an unknown amount of antigen is affixed to a surface so that it can bind to the antigen. This antibody is linked to an enzyme, and in the final step a substance is added that the enzyme can convert to some detectable signal.

Flow cytometry: The analysis of characteristics of a particle or cell as it flows in a fluid through a beam of light.

Fluorescence: The emission of radiation (usually visible light) by a substance that has been exposed to light or other electromagnetic radiation.

Immunoassay: A biochemical test that measures the concentration of a substance in a biological liquid, typically serum or urine, using the reaction of an antibody or antibodies to its antigen.

In vitro diagnostics (IVD): Medical device products including instrument and reagents that utilize a variety of methods and formats to perform tests on human samples in order to assess disease risk, diagnose a condition or monitor a patient's health.

Lateral flow test: A simple device intended to detect the presence (or absence) of a target analyte in sample. Lateral flow tests are a form of immunoassay in which the test sample flows along a solid substrate via capillary action, and are often produced in a dipstick format.

Microfluidics: Deals with the behavior, precise control, and manipulation of fluids that are geometrically constrained to a small, typically sub-millimeter, scale.

Multiplexing: Simultaneous measurement of multiple analytes in single reaction vessel.

Nucleic acid: Macromolecule composed of chains of monomeric nucleotides. These molecules carry genetic information or form structures within cells. The most common nucleic acids are deoxyribonucleic acid (DNA) and ribonucleic acid (RNA). Nucleic acids are universal in living things, as they are found in all cells and viruses.

Polymerase chain reaction (PCR): A technique to amplify a single or few copies of a piece of DNA across several orders of magnitude, generating thousands to millions of copies of a particular DNA sequence.

Thermal cycling: A temperature modulation process used to promote biochemical reactions.

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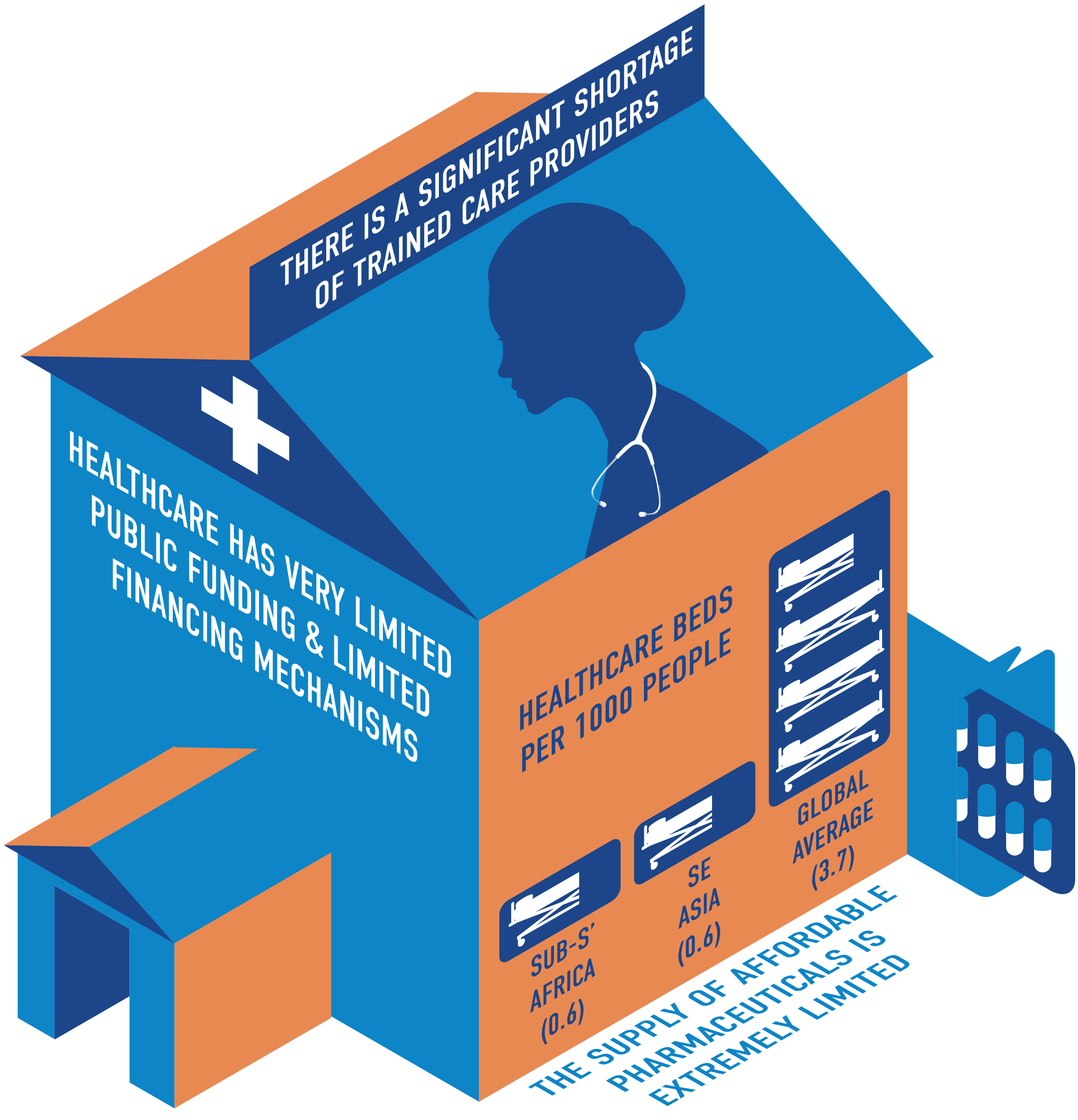


HEALTHCARE DELIVERY

INTRODUCTION

Delivery of quality, affordable healthcare for low income communities in developing countries remains a challenging and elusive goal.

More than half of the world's people have limited access to essential health services, and 400 million have no access to any health service (WHO/World Bank, 2017).

More than 800 million people (almost 12 percent of the world's population) spent at least 10 percent of their household budgets to pay for health care (WHO, 2018). Even with greater access to care, the vast gap between what providers know and what they do in practice means receiving proper treatment is an even greater challenge (Das, et al., 2018).

The problem is systemic. There are very few functioning peripheral clinics; management systems and supply chains are weak; existing medical devices are too expensive; there is a shortage of qualified providers whose incentives are not well-aligned with performance; and there is far too little funding in most developing countries to build the health system from the bottom-up.

External aid, which has historically focused on major infectious diseases, has proven neither sufficient nor sustainable for structural change. Though studies have shown that 90 percent of health conditions can be handled at the primary care level (Doherty & Govender, 2004), and 63 percent of child deaths in the 42 countries that account for 90 percent of global child mortality could be prevented each year through more effective primary care (Lancet study, 2003), primary healthcare systems in LMICs simply do not currently have the required support to deliver high quality patient-centric care, not to mention managing the changing disease burdens.

Evidently, sustainable solutions will have to be systemic. Clinicians have to be better trained and certified, policies have to be reformed in order to ensure governance and accountability, people have to be convinced to invest in preventative care, and financing mechanisms like affordable health insurance have to become widely available. In addition, the absence of affordable medical devices and the lack of access to electricity and clean water pose significant barriers to building functional low-cost peripheral clinics. Importantly, health outcomes are not just a function of the strength of the health system, but also of broader living conditions that this report covers in chapters on water security and sanitation, among others.

The good news is these issues are getting the attention they need. Universal Health Coverage (UHC), adopted as a SDG in 2015, aims to ensure individuals and communities receive the health services they need without suffering financial hardship. The scope goes beyond financing and includes all components essential to a well-functioning health system. Investing in improving in the delivery of primary care is essential in achieving UHC (SDG, 2015).

There are three breakthroughs that can improve the delivery of healthcare:

- Breakthrough 31. Integrated suite of digitally enabled primary care devices including point-of-care diagnostics, therapeutic devices and clinical operations
- Breakthrough 38. Low cost off-grid refrigerators for preserving vaccines (and other temperature sensitive pharmaceuticals) in remote settings
- Breakthrough 39. A thermo-stabilizing mechanism for vaccines and other temperature sensitive pharmaceuticals

Major investments in global health since the announcement of the Millennium Development Goals (MDGs)—from initiatives and organizations like PEPFAR, GAVI, and the Global Fund to Fight AIDS, TB and Malaria—have led to significant progress and improvements in a number of health conditions. However, these initiatives have largely been vertical programs aimed at combating specific communicable diseases, with limited investment in system-strengthening (Travis, et al., 2004). Consequently, there is now recognition of the value of diagonal approaches in which effective disease-specific programs also build elements of sustainable delivery systems (Kim, et al., 2013). Efficient and effective health service delivery, in particular for primary care, has a central role in achieving SDG 3 to "ensure healthy lives and promote wellbeing for all at all ages."

CORE FACTS AND ANALYSIS

1. There are numerous challenges that impede the delivery of effective healthcare in low-resource settings

The historical lack of investment in development of healthcare infrastructure and delivery systems remains a fundamental hurdle to improving overall national health outcomes. One important contextual factor to consider, however, is that some of the basic constraints of the past few decades may no longer be as difficult to overcome today.

Proliferation of technologies like solar-power, mobile networks and low-cost ICT devices like smartphones and tablets have made efficient and effective healthcare delivery a much more viable prospect now. Delivery can evolve from a hub-and-outreach model to a hub-and-spoke model in which brick-and-mortar clinics can be constructed in tandem with larger, better-equipped facilities. System innovations using digital technologies are increasing at a rapid rate.

Solutions that aim to influence behavior change and increase demand for services and products; strengthen the capacity of health care workforce for more effective task-shifting; and improve the quality of data collected, the way data is managed and used can all help the growth of such hub-and-spoke facilities and improve quality and efficiency of care, especially at the primary level.

While the previous chapters discussed the context and challenges associated with various health conditions that disproportionately affect low-income populations, this chapter focuses on the actual delivery of care. Delivering healthcare requires six structural elements:

1. Funds and financing mechanisms at multiple levels: Funding for public health systems; business financing for entrepreneurs interested in building clinics and providing care; and financial services like health insurance, for low income populations so that patients can afford services

2. Infrastructure: Networks of easily accessible clinics for routine care, with adequate facilities for escalation in the event of emergencies and special needs with reliable supply chain and transport

3. Human capital: Adequate numbers of trained and licensed physicians, nurses, midwives and health workers, with minimal reliance on untrained or unlicensed health practitioners

4. Pharmaceuticals: A reliable supply of effective and affordable medications for prevention and treatment of conditions common to the population

5. Equipment and medical devices: To ensure the clinics are well provisioned and functioning regularly, preserve vaccines and other sensitive materials like blood, conduct lab tests and help clinicians perform routine as well as emergency operations

6. Information and governance: Data on patient history, population-level trends and performance of clinics, clinicians and the health system as a whole in terms of access to care and quality of care, which can be utilized to develop standards, monitor compliance to those standards and hold providers and administrators accountable

All available data about health systems in low-income countries show that there are significant gaps along each of the above structural elements. The most important of these gaps are discussed further in this chapter.

KEY CHALLENGES

The hurdles to healthcare delivery, especially in rural areas, are structural and multi-faceted. The absence of a robust tax base leads to a lack of public funding, which then leads to a lack of investment in infrastructure, human capital and oversight.

1. There is very limited public funding of healthcare, with even more limited financing mechanisms

Per capita annual health expenditure in Africa and Southeast Asia, respectively, are $116 and $169; this is 4 to 5 percent of the expenditure in European countries ($2,507), and about 10 to15 percent of the global average of $840 (WHO, 2016).

In Africa and South-East Asia, the bulk of health expenditure is on private systems; a reflection of both the poor quality of public health systems as well as the higher cost of private systems.

In addition, the lack of affordable and appropriate insurance schemes or other financing mechanisms results in much higher out-of-pocket health expenditures in Africa and South Asia; 35 percent of health spending in Africa and 43 percent in South East Asia is out-of-pocket (WHO, 2015) (**Exhibit 1**).

Distribution of healthcare expenditure

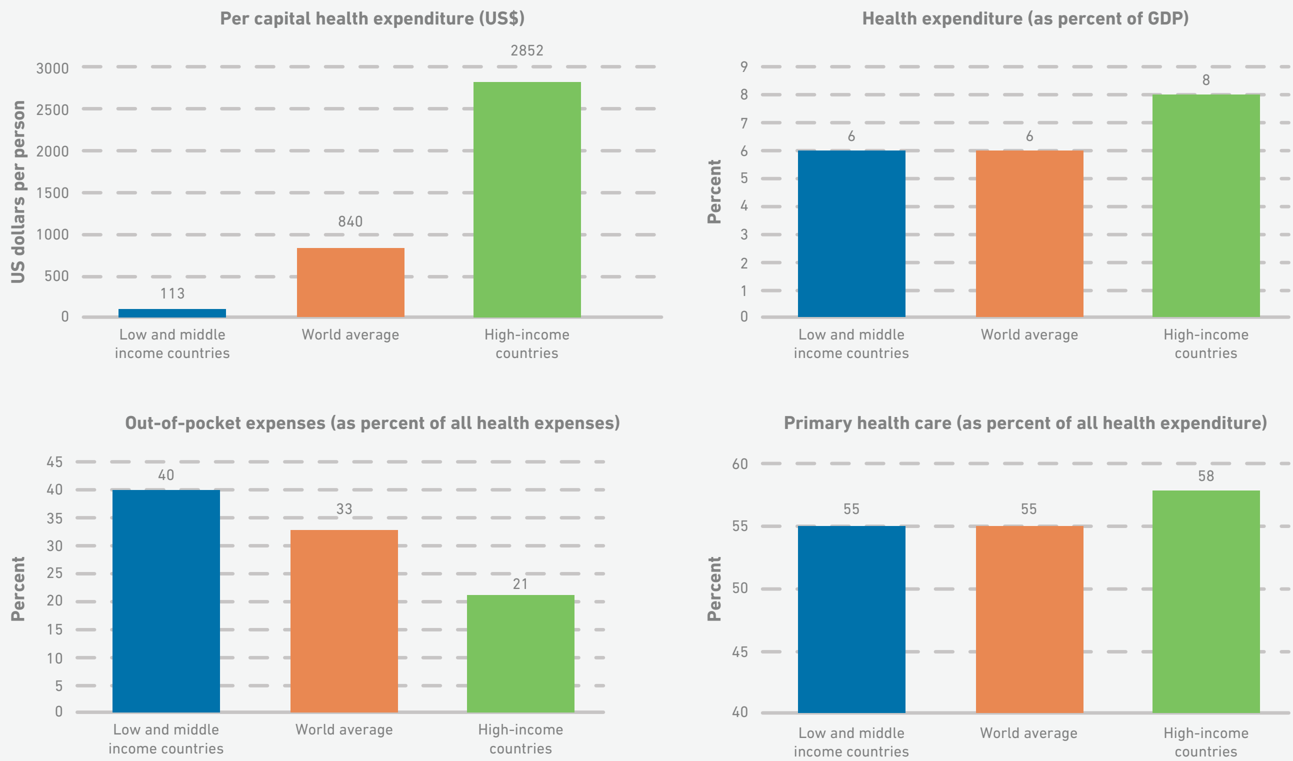


Exhibit 1: Healthcare spending per capita in low- and middle-income countries lags significantly behind world averages and high-income countries. As a result of lower public investment in health, citizens of countries in these regions incur much higher out-of-pocket expenditure. (Source: WHO, 2016)

2. Healthcare infrastructure—hospitals and clinics—is very sparse

One measure of healthcare infrastructure availability is the number of healthcare beds—across urban hospitals, rural clinics and remote outposts—available to the population. In low-income countries, there are approximately 9 healthcare beds for every 10,000 people[1], compared with 57 in high income countries (Peters, et al., 2008) (**Exhibit 2**).

Beyond these quantitative measures, several studies (Gawande, 2003; WHO, 2006; Dastur, 2008) have shown that even available clinical facilities tend of be of very low quality; few clinics have reliable electricity, lighting, running water, clean sanitation facilities and general hygiene.

As a result, patients are often treated at facilities that are not equipped to address many conditions, and clinicians have limited scope of escalating care to better-equipped facilities. Supply chain and transportation is also a big challenge and affects everything from procurement and supply of essential medicines, consumables for diagnostics, delivery of test results, emergency transport, among others.

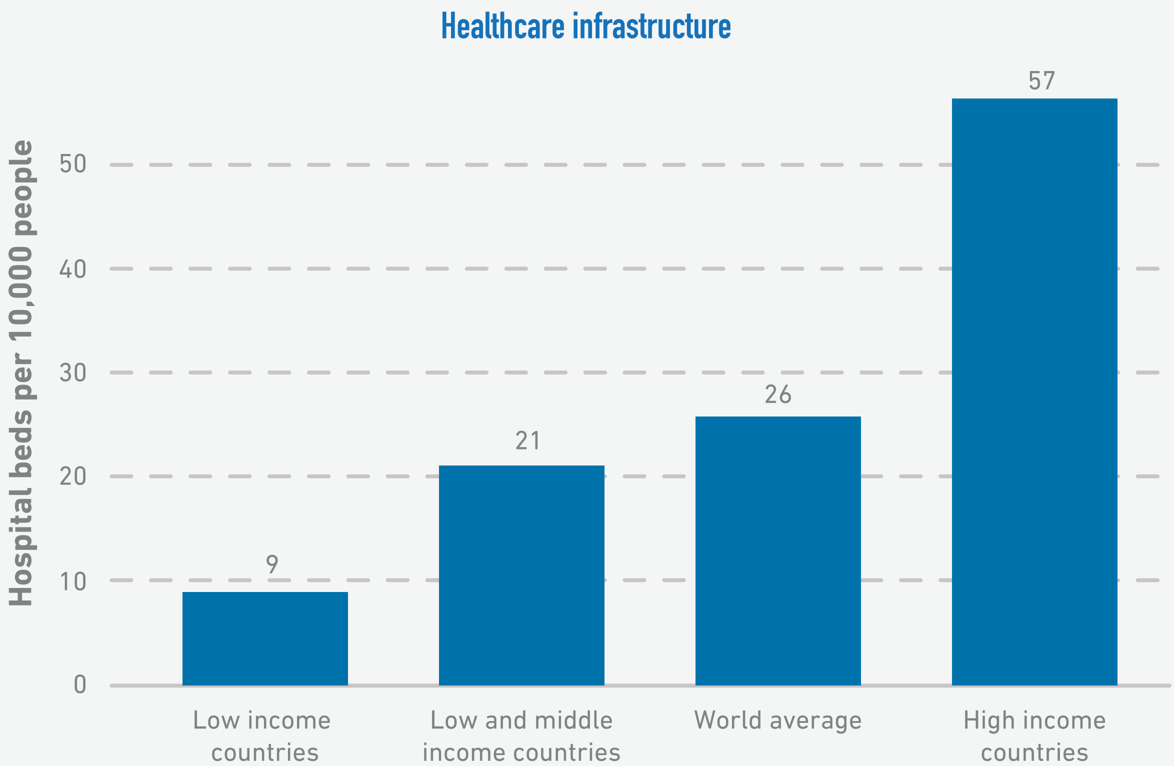


Exhibit 2: One of the most significant challenges to delivering adequate healthcare in low- and middle-income countries is the lack of hospitals and clinics, often measured as the number of beds per 10,000 people. (Source: Peters, et al., 2008)

[1]Data on the number of healthcare beds is very sparse, and these estimates represent averages from a small number of countries.

3. There is a significant shortage of human capital in the form of physicians, nurses and other trained care providers

In addition to the severe dearth of optimally functioning clinics, there is also a significant shortage of trained clinicians in developing countries (**Exhibit 3**). In sub-Saharan Africa, for example, there are fewer than 0.2 physicians and 1.1 nurses or midwives per 1,000 people.

In South Asia, there are only 0.75 physicians and 1.7 nurses or midwives per 1,000 people. In comparison, high income OECD countries have 2.8 physicians and 7.4 nurses or midwives for every 1,000 people, while the global average is 1.5 physicians and 3.1 nurses or midwives for every 1,000 people (World Bank, 2013).

This shortage of trained personnel has serious consequences for those in need of care. The majority of births in sub-Saharan Africa and South Asia take place at home and are administered by untrained health workers.

Hence, most patients at all stages of life often end up relying on unlicensed, untrained 'quacks' (Economist, 2008; Monitor, 2013) who frequently misdiagnose conditions and prescribe wrong medications.

However, the quality of care by trained providers is not necessarily superior. Researchers have found that the quality of care provided in the public sector is similar to that by informal providers in rural India (Das, et al., 2016). They also found that training improved the ability of informal providers in India to correctly manage the kind of conditions they may see in their clinics, though it did not decrease their overuse of unnecessary medicines or antibiotics (Das, et al., 2016).

These studies help pave the way to better understand the levers for improving quality of care.

Density of clinics and health workers

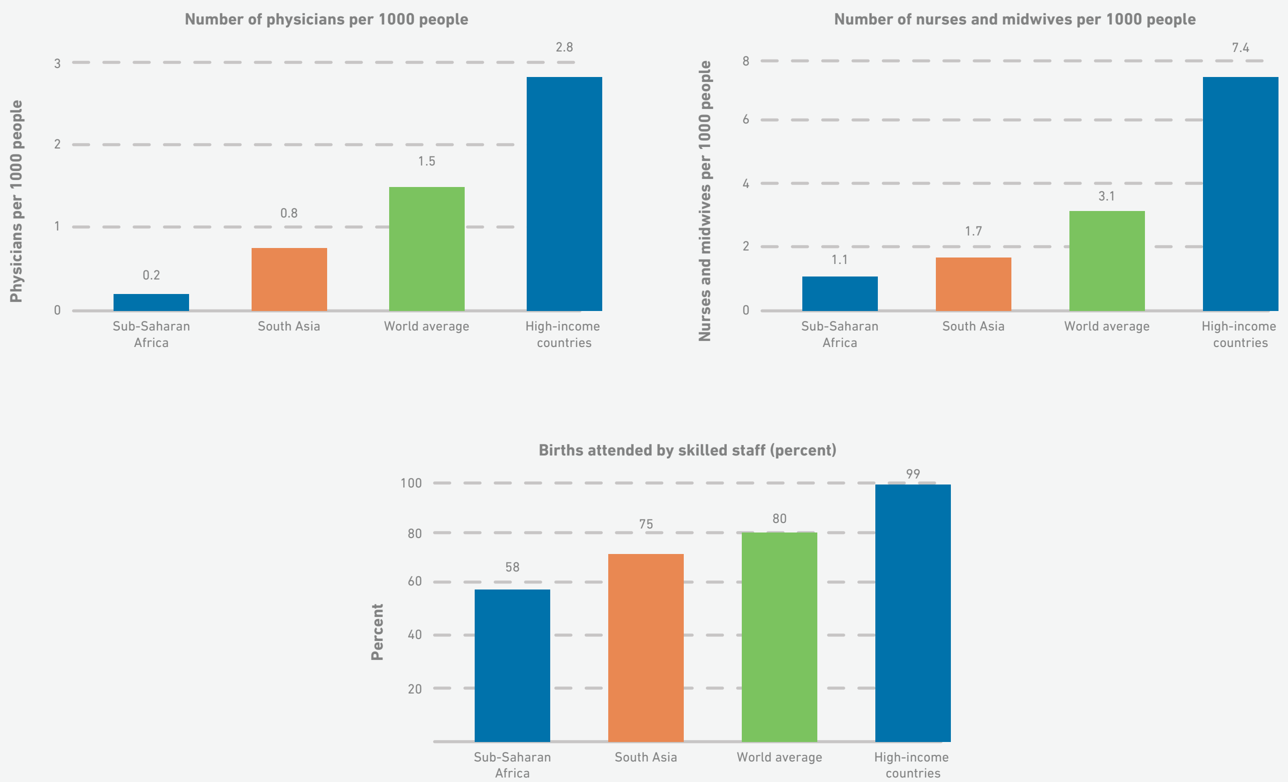


Exhibit 3: There is a major shortage of trained clinicians (physicians, nurses and midwives) to administer healthcare in developing countries. One consequence is that the majority of births are administered by untrained health workers. (Source: World Bank, 2013 & 2014)

4. The supply of affordable pharmaceuticals is extremely limited

The problem of inappropriate prescription only exacerbates the more widespread problem of inadequate access to affordable medicines. There is very little systematically collected data on the availability and affordability of medications.

In a survey of 27 developing countries, an average of only 35 percent of selected medicines were available in public sector health facilities (UN, 2008) (**Exhibit 4**). Availability was higher (63 percent) in private health facilities.

When medicines are not available in the public sector, patients will either have to purchase them from the higher-priced private sector or forgo treatment altogether (WHO, 2007). When drugs are available, even the lowest cost generics tend to be highly unaffordable.

Drugs sold in East Africa tend to cost 290 to 360 percent of benchmark international prices; hence, a month's worth of generic reference medications for a household costs between five and seven days' wages for the lowest wage rung of government employees in those countries.

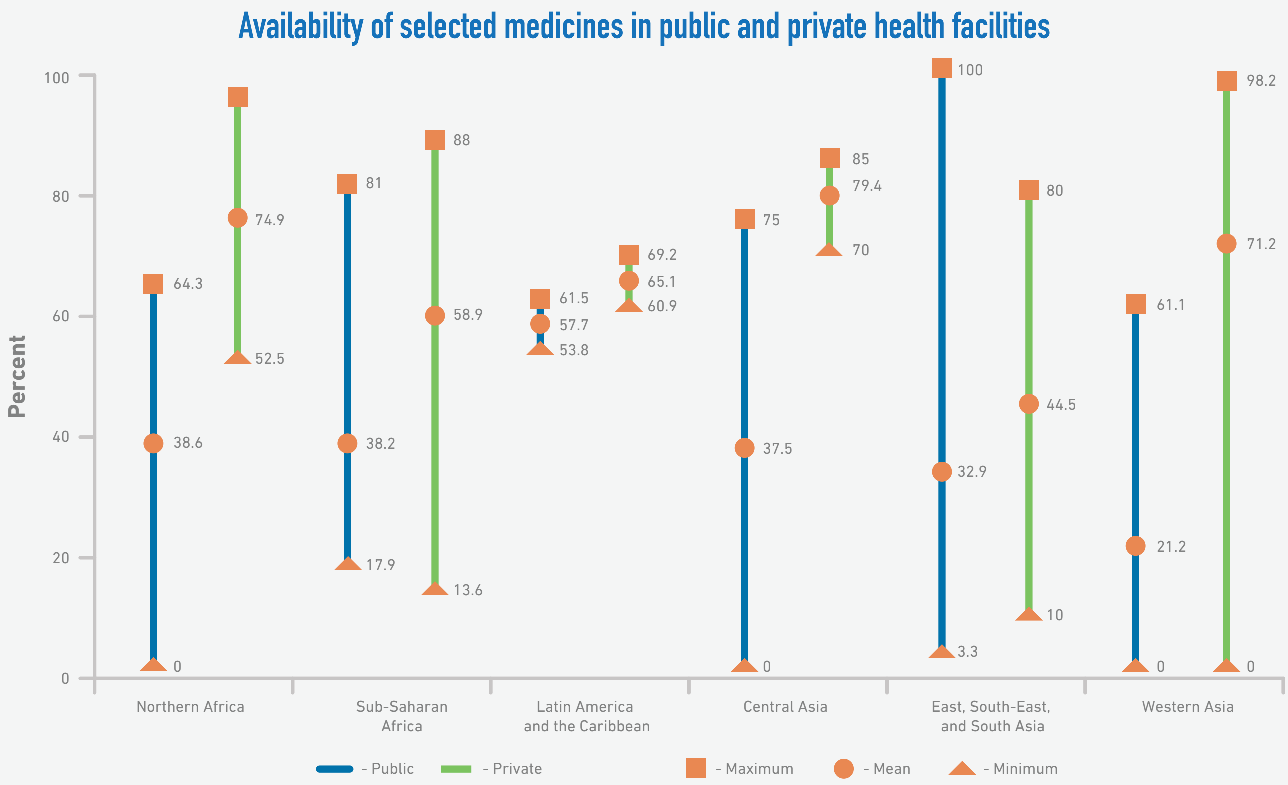


Exhibit 4: Essential drugs are typically more available in private health facilities than in public ones. (Source: UN, 2008; survey of 27 developing countries)

[27]Data on the number of healthcare beds is very sparse, and these estimates represent averages from a small number of countries.

5. Most essential medical devices on the market are far too expensive for low-income populations, and those made for developing country settings are not robust or functional enough

Many clinics, especially those in rural areas, lack basic amenities such as electricity, lighting, running water and sanitation. Urban clinics, on the other hand, tend to have access to some of these core amenities.

However, sophisticated equipment like radiology machines, centrifuges, autoclaves, medical refrigerators for vaccines and other sensitive pharmaceuticals, and diagnostic devices (beyond RDTs and basic microscopes) tend to be available only in a fraction of the medical facilities (**Exhibit 5**).

For example, for every 1 million people in sub-Saharan Africa, there are only 0.1 MRI scanners, 0.4 CT scanners and 3.6 mammography scanners, whereas OECD countries have 20.2 MRI scanners, 36.1 CT scanners and 123.3 mammography scanners per 1 million people (WHO, 2010).

According to a 2013 study in several countries in sub-Saharan Africa and South Asia by the Bill and Melinda Gates Foundation, as many as 85 percent of primary health centers, responsible for national vaccine delivery do not have any vaccine refrigerators.

In those that do have a refrigerator, between 15 percent and 50 percent of equipment are older than the recommended 10 years, after which time they are more susceptible to breakdown and poor temperature control (Ashok, et al., 2016).

As a result of the lack of functioning vaccine refrigerators, a large number of children remain adequately immunized, and approximately 1.5 million children under 5 years old die each year from vaccine-preventable diseases (WHO, 2016). Also, irrespective of the country's wealth, about one third of vaccine-storage units, which range from small refrigerators to huge cold rooms, are colder than is safe (The Economist, 2017).

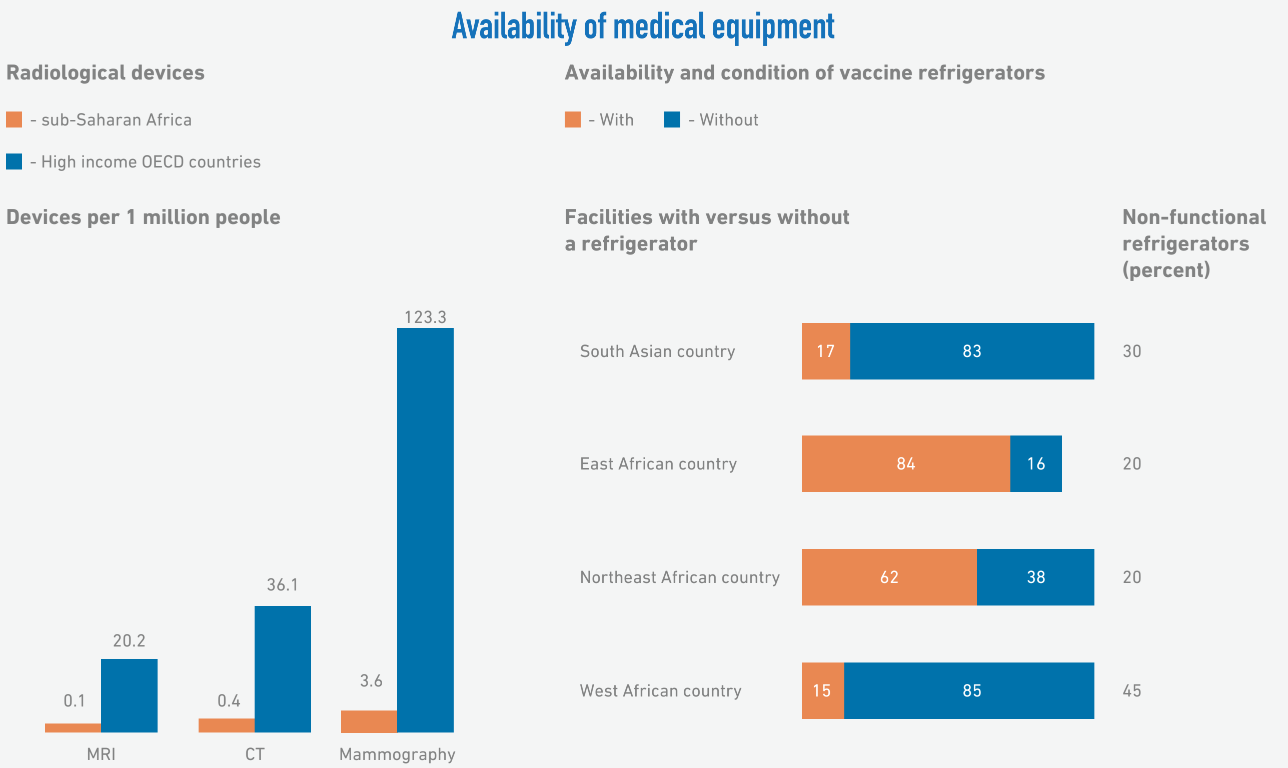


Exhibit 5: Clinics in sub-Saharan Africa and South Asia generally lack basic equipment such as refrigerators and radiology machines. The lack of vaccine refrigeration leads to large gaps in immunization. (Source: WHO, 2010; Gates Foundation, 2013)

6. There is inadequate information collected on patients or populations, leading to a lack of transparency

Most healthcare record keeping in developing countries is done on paper, if at all. This lends itself to significant problems with governance, which in turn, impacts quality of care.

There are leakages in budget and resource management; jobs are 'purchased'; there is limited meritocratic performance management of individuals, facilities, or systems; and there is significant bribery and corruption (Lewis & Pettersson, 2009).

Fortunately, the recent emergence of mHealth technologies has shown tremendous promise in remote data collection, monitoring, communication and procedural support, training of health workers, diagnosis and telemedicine (UN Foundation and Vodafone Foundation, 2009).

While the collection of data has now become more widespread, challenges remain—on effective management, long term behavior change of providers and integration of data for efficient decision-making.

As per the most recent report on Universal Health Coverage by the WHO (2015) there are major data gaps in almost every area affecting planning, targeted implementation, performance improvement, and accountability to civil society, parliament and development partners, among others.

For instance, most low- and lower- middle-income countries lack civil registration and vital statistics (CRVS) systems, well-functioning health facilities and community information systems, disease surveillance systems, health workforce and health financing accounts.

SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

Clearly, the development of sustainable, large-scale health systems and delivery structures requires substantial funding, ideally through a local tax base powered by a robust economy.

Still, targeted gains can be achieved in the absence of substantial funding or economic development—an interim state until low-income countries reach a point where they have high-caliber institutions to train large numbers of clinicians, dense networks of facilities, adequate equipment, a functioning supply chain of medicines and consumables, and robust information management systems.

Efforts such as vaccine and blood delivery by unmanned air vehicles (UAVs), AI-powered diagnostic algorithms, and decentralized health information systems have been trialed in recent years to address the challenges in healthcare delivery.

The potential of these technologies is discussed further in the Emerging Technologies chapter of this report. Beyond these potential innovations, we believe there are three scientific and technological breakthroughs that can significantly improve delivery of healthcare.

Breakthroughs:

1	2	3	4	5	6	7	8	9	10
11	12	13	14	15	16	17	18	19	20
21	22	23	24	25	26	27	28	29	30
31	32	33	34	35	36	37	38	39	40
41	42	43	44	45	46	47	48	49	50

31 Integrated suite of digitally enabled primary care devices including point-of-care diagnostics (for basic blood, urine, and vitals tests), therapeutic devices for common conditions, and clinical operations (such as sterilization, refrigeration)

Among the many structural challenges in healthcare delivery in developing countries is the virtual absence of adequately equipped clinics needed to support the provision of primary care. The majority of clinics, especially in rural areas serving low-income populations, lack even the basic amenities, let alone the equipment necessary to provide essential services. With the shortage of human resources, it is particularly important to expand and maximize the capabilities of locally available providers (often mid-level providers like nurses or clinical officers with varying levels of training) for patient-centered care at primary care facilities.

To build a clinic with the equipment necessary to provide basic primary healthcare would likely cost in excess of $100,000. This is based on preliminary research on costs of essential infrastructure (like solar panels and lighting), medical devices (like sterilizer and ultrasound) and diagnostics (such as rapid diagnostic tests and urine test analyzer) that are already available on the market, and the cost of constructing a basic building. In the absence of adequate public funding, this is too expensive for low-income populations by a factor of 10, based on our high-level assessment. In addition, the logistics of procuring the various components and assembling them into a functioning clinic require considerable effort.

A digitally-integrated suite of devices for primary care is needed, that includes point of care diagnostic devices for basic blood, urine and vitals tests. It would also include therapeutic devices for common conditions, for example, warming, phototherapy and oxygen concentration devices. It would also support clinical operations, such as sterilization devices and refrigeration for thermo-sensitive pharmaceuticals. A power management system would be integrated, including renewable energy supply where appropriate. A platform for patient and clinic management is at the core, and needs to be built using a provider- and patient-centered design approach. The focus should be on making the work of health professionals easier and better, and improving on the patient experience to ensure utilization. While maternal and neonatal intensive care devices are likely beyond the scope of this suite, health outcomes for mothers and newborns are nonetheless expected to be significantly improved, due to higher overall standards of primary care during prenatal and postnatal periods.

Such an integrated suite of devices could be a significant breakthrough if it:

- combines an integrated suite of low-cost and energy-efficient devices required to provide basic primary care:
  - Diagnostic devices and tests for relevant medical conditions including nutrition deficiencies, anemia, malaria, HIV, syphilis and hypertensive disorders

Current State

Development Stage: Engineering

Time to market (years)
<3 4-6 7-10 10+

Deployment: Challenging

Associated 50BT Chapters

Global Health

SDG Alignment

3 GOOD HEALTH AND WELL-BEING

Impact

Lives Saved (# of People/Year)
<1M 10M+ 100M+ 1B+

Health Improved (# of People)
<1M 10M+ 100M+ 1B+

Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

  - Sterilization devices for equipment
  - Ultrasound devices
  - Medical lighting
  - Locally manufactured oxygen or oxygen concentrators
  - Refrigeration to store vaccines and other thermo-sensitive pharmaceuticals;

- integrates power management, computation/imaging, data and communication so that the various devices can function in an easy-to-install plug-and-play mode;

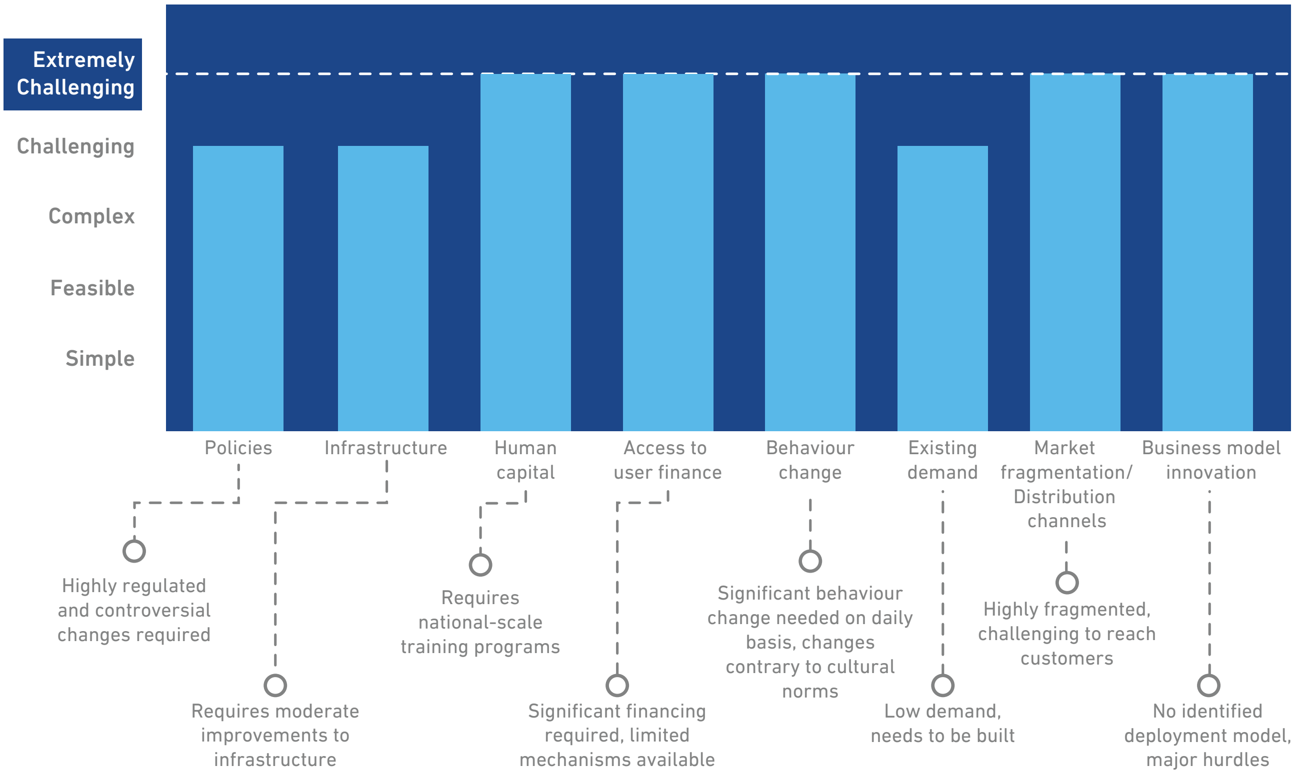
- builds on a digital platform that augments provider knowledge, experience and clinical workflows with decision support tools and diagnostic algorithms for more precise, patient-centered care; allows for remote consultation with clinicians and specialists; and enables data systems that collects and generate high-quality, timely information for decision-making and enables patient-centered care;

- costs approximately $10,000 to $15,000, based on our high-level assessment of financial feasibility, given published data on how much low-income rural families in sub-Saharan Africa and South Asia spend on healthcare.

While some of the listed devices are available at the appropriate price point, many are still priced for industrialized markets. Given the broad interest in developing individual devices, we believe enough of them are available at the right price point to begin assembling a suite of devices. There are also efforts underway to develop a digital platform to integrate the various devices. Many information and communication technology platforms exist or are in development, but most only focus on a particular area of the health delivery system or are focused around certain health conditions. It is important to note that there is no one-size-fits-all solution, particularly the design of the digital platform, across low-resource settings.

Even once such technology-enabled delivery system is developed, it will face a large number of deployment challenges. There is not enough public funding to procure a sufficient number of such clinics, the private market is underdeveloped and fragmented, and the regulatory requirements are unclear. Moreover, significant behavior change, encouraged by some form of insurance or financing to allow affordable access, is required for most low-income rural communities to seek regular and formal care. A dependable supply chain for consumables and maintenance of technologies will also be required. Hence, the difficulty of deployment will be EXTREMELY CHALLENGING.

Breakthrough 31: Difficulty of deployment



38 Low cost off-grid refrigerators for preserving vaccines (and other temperature sensitive pharmaceuticals) in remote settings

Vaccines and a number of other pharmaceuticals are highly temperature sensitive. Thermostable mechanisms likely represent the long-term solution for deploying these life-saving pharmaceuticals to remote parts of the world. In the meantime, refrigeration will continue to play a critical role in preserving and delivering them to those in need.

Larger storage and health facilities tend to have access to reliable refrigerators powered by grid electricity or diesel-powered generators. Smaller, rural facilities, however, have neither the necessary funding, nor access to reliable power sources.

Existing refrigeration technologies have proven unreliable or unaffordable for small, remote health centers, and for last-mile outreach. Currently, most remote health centers use mechanical compression (requiring high levels of energy, environmentally questionably coolants, and/or batteries) or absorption (requiring kerosene or gas as the fuel); these technologies are energy-intensive, heavy, and difficult to maintain.

As a result, a large number of such refrigerators are non-functioning. While there are reliable technologies for larger-scale clinics, these refrigerators are too large and too expensive for small health centers; and they still do not address the problem of last-mile outreach. Outreach campaigns have no access to active refrigerators, and have to use ice-lined cooler boxes which often lead to freezing and keep the vaccines cold only as long as the ice does not melt. As such, an affordable, portable, solar-powered refrigerator will be crucial, especially for outreach campaigns to remote areas.

In recent years new refrigeration technologies like smaller-scale vapor compressors and solid-state thermoelectric cooling mechanisms have been introduced, and are beginning to be used for small refrigerators. One such technology is a vaccine storage device called Arktek™ that can keep vaccines at appropriate temperatures for a month or more. The super-insulated device uses only ice—no propane, batteries, electricity, solar panels or other power sources are necessary at the point of use.

Current State

Development Stage: Engineering

Time to market (years): <3 | 4-6 | 7-10 | 10+

Deployment: Challenging

Associated 50BT Chapters

Global Health

SDG Alignment

3 GOOD HEALTH AND WELL-BEING

9 INDUSTRY, INNOVATION AND INFRASTRUCTURE

Impact

Lives Saved (# of People/Year): <1M | 10M+ | 100M+ | 1B+

Health Improved (# of People): <1M | 10M+ | 100M+ | 1B+

Commercial Attractiveness

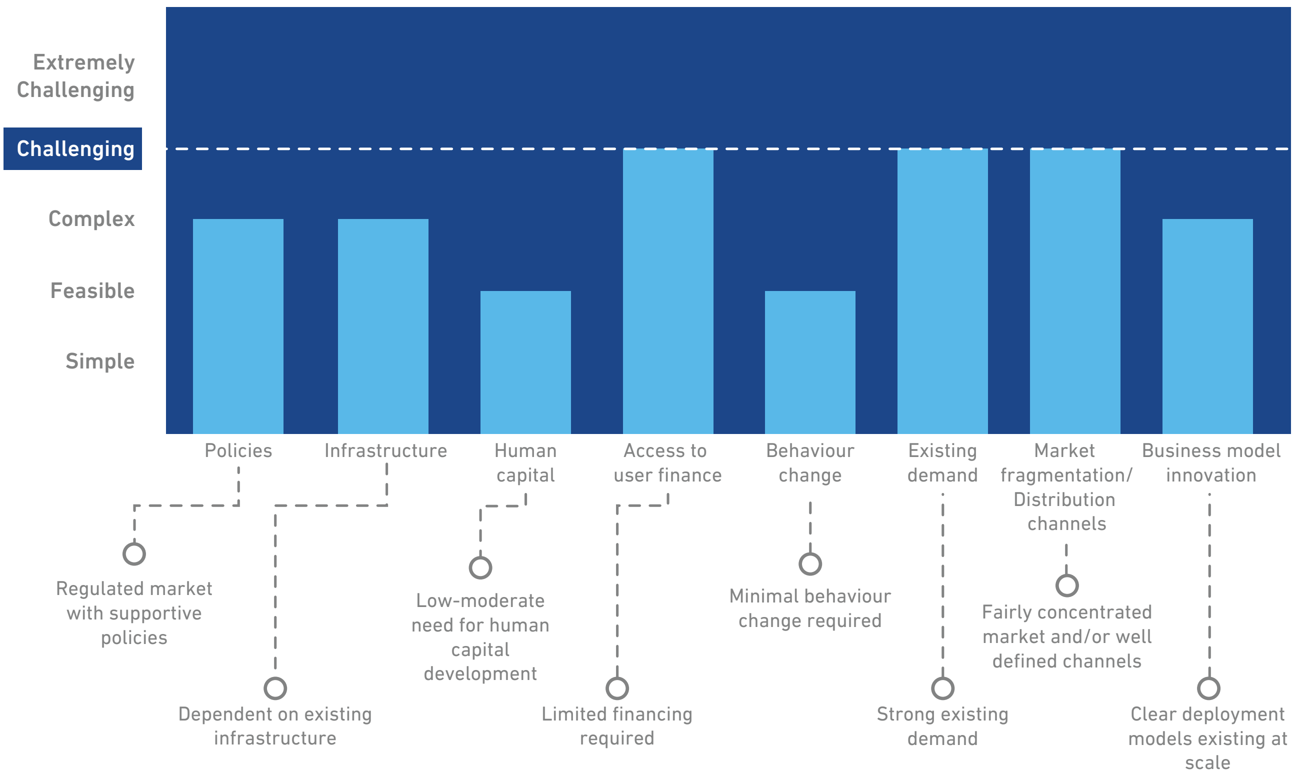
- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

Arktek™ can handle travel over rough roads and use in harsh environments, making it ideal for rural areas and for outreach work, or as a stationary device at rural health posts. Clinical trials of Arktek™ have been conducted in Senegal and Ethiopia, and the device has received positive feedback from users. In another initiative, the UNICEF is conducting drone delivery trials of vaccines in Vanuatu. Although this is innovative, viability of a scale up plan is yet to be proven.

While this is positive news, there is still no affordable market-ready technology available, nor proven refrigeration method at the scale needed for sustained outreach campaigns. A number of emerging approaches have been validated and the technology is being actively developed in research institutions and industrial facilities.

Once developed, the deployment challenges for these technologies will include a highly fragmented market with limited access to finance, sparse distribution channels, limited technical capacity along the value chain and a difficult path to creating demand. Hence, deployment will be CHALLENGING.

Breakthrough 38: Difficulty of deployment



39 A thermo-stabilizing mechanism for vaccines and other temperature sensitive pharmaceuticals

Many vaccines are thermosensitive, and need to stay between 2 and 8 degrees Celsius continuously, from the point of manufacture to the point of administration. Other life-saving pharmaceuticals like Oxytocin—used to treat postpartum hemorrhage after women give birth—are also equally reliant on refrigeration (although the requisite temperature range can vary for different types of pharmaceuticals).

While a new generation of low-cost refrigeration technologies can make progress on vaccine preservation, the long-term solution is to obviate the need for refrigeration altogether.

The main reason these pharmaceuticals are temperature sensitive is the vulnerability of the pathogens in typical live-attenuated vaccines and the intrinsic instability of protein structures in pharmaceuticals. Therefore, the lack of electricity and refrigeration in remote areas means that many millions of individuals do not have access to critical vaccines and medications. A mechanism (such as stabilizing additives) to thermally stabilize these pharmaceuticals can substantially increase their viability and availability.

While a number of efforts are underway to develop stabilizing formulations for vaccines (like nanostructured polymers, viscous liquids like propylene glycol and novel drying sprays), virtually all of them are in early stages and none have proven applicable to the range of vaccines, especially in field tests.

Given the complexity of the R&D required, the need for rigorous clinical trials and the required approvals by various regulatory agencies, it is unlikely that a proven solution becomes market ready within the next 10 years.

Current State

Development Stage: R&D

Time to market (years): <3 | 4-6 | 7-10 | 10+

Deployment: Feasible

Associated 50BT Chapters

Global Health

SDG Alignment

3 GOOD HEALTH AND WELL-BEING

10 REDUCED INEQUALITIES

Impact

Lives Saved (# of People/Year): <1M | 10M+ | 100M+ | 1B+

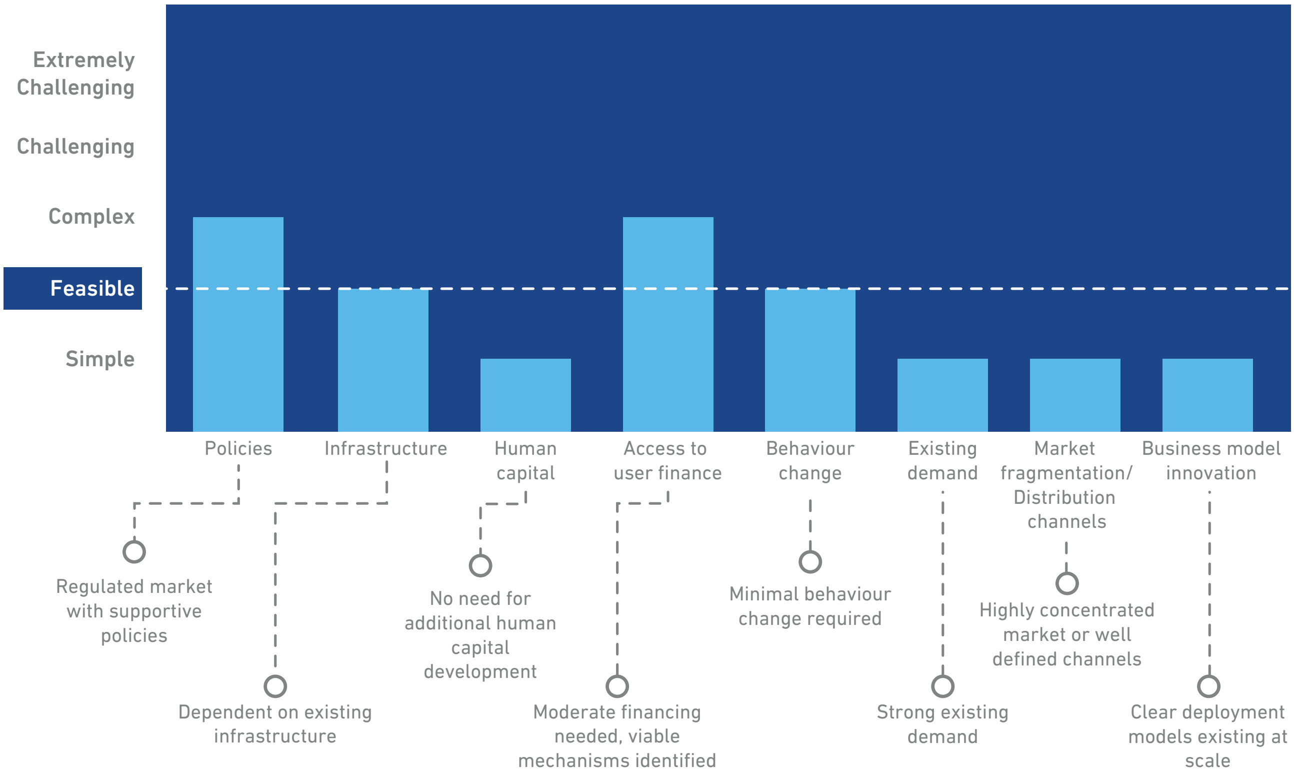
Health Improved (# of People): <1M | 10M+ | 100M+ | 1B+

Commercial Attractiveness

- **Attractive for industrialized markets (high profits)**
- Attractive for emerging markets (lower profits)
- Emerging markets potential; requires derisking (sustainable)
- Non-commercial (unprofitable)

Once such a technology becomes viable, the established channels for vaccine procurement and distribution, relatively strong coordination of the market for vaccines (for example through the major institutions responsible for global immunization like the WHO, GAVI and UNICEF) and the demand for such a breakthrough from these institutions will make deployment relatively FEASIBLE.

Breakthrough 39: Difficulty of deployment



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DIGITAL INCLUSION

DIGITAL INCLUSION

INTRODUCTION

The digital divide (opposite of digital inclusion) has traditionally been defined as the gap in access to the internet, mobile phones and other types of information and communication technologies (ICT) and their services, between wealthier and poorer societies.

Digital divides exist between economic strata within individual countries, as well as between countries. The nature of these types of digital divide vary, as will their solutions. Here we focus on characterizing the digital divide between industrialized countries and developing countries.

In the developing country context, ICT-enabled services would need to compensate for major gaps in physical infrastructure, public and private institutions and technical human capital. For example, telemedicine is proving to be a valuable ICT-enabled service for connecting rural clinics (which typically do not have qualified clinicians) to physicians in urban areas for remote consultation. Hence, the definition of digital inclusion, especially in context of developing countries, needs to go beyond merely access to the internet and mobile phones, and include access to a broad range of ICT-enabled services and tools required for human development.

The proliferation of mobile technology has laid a strong platform for the adoption of an increasing array of ICT-enabled services. However, to achieve true digital inclusion a number of gaps need to be filled. These include the cost of smartphones that are currently on the market, very sparse last-mile broadband connectivity in rural and remote areas, and a lack of data about, and ID systems for, citizens and businesses. We believe that three specific breakthroughs will be critical for achieving digital inclusion, especially for low income populations.

- Breakthrough 40. A new generation of wireless broadband network technologies that radically cut the cost of expanding coverage to rural areas
- Breakthrough 41. Affordable (less than $50) smartphones that support full-fledged internet services and need limited electricity to charge
- Breakthrough 42. Productized biometric ID systems, linking birth registry, land title registry, financial services, education history, medical history, and other information critical for ICT enabled services

Recent years have witnessed a truly remarkable digital revolution in developing countries and globally. However, low-income populations in developing regions need a much broader range of ICT-enabled services than their counterparts in industrialized countries, to compensate for the lack of strong institutions and physical infrastructure. Until devices and platforms to enable such services are developed, and the corresponding services actually provided, these populations cannot be considered digitally included. By this expanded definition, there is a long way to go to achieve broad, global digital inclusion.

CORE FACTS AND ANALYSIS

Digital inclusion, or conversely, the digital divide, has a number of definitions in common and institutional parlance. For example, according to the Oxford English Dictionary (2018) it is "the gulf between those who have ready access to current digital technology (especially computers and the Internet) and those who do not; also, the social or educational inequality resulting from this." Stanford University (2018) uses a U.S. country-specific definition: "the growing gap between the underprivileged members of society, especially the poor, rural, elderly, and handicapped portion of the population who do not have access to computers or the internet; and the wealthy, middle-class, and young Americans living in urban and suburban areas who have access."

And the OECD (2018) defines it as "the gap between individuals, households, businesses and geographic areas at different socio-economic levels with regard to both their opportunities to access information and communication technologies (ICTs) and to their use of the Internet for a wide variety of activities." Others have simply used measures like mobile phone penetration or internet access.

Within this context, a population can be considered digitally included if they have affordable access to the same ICT products and ICT-enabled services as their wealthier counterparts in their own or other countries. In industrialized countries, dramatic changes and innovations in information and communication technologies in the last 30 years have revolutionized the very way people live, work and access services. In developing countries too, there has been a remarkable increase in ICT penetration, and in particular, mobile phones in recent years.

Today, even very poor individuals can speak with relatives who may have migrated long distances and receive targeted bits of information hitherto completely unavailable to them. Such widespread access to mobile phones has paved the way for a host of services, specifically for low income populations, that were previously almost entirely unavailable to them. Examples like M-Pesa, Kenya's by-now famous mobile money service, have leapfrogged western modes of financial transaction for a vast majority of unbanked people.

However, access such as being able to own a mobile phone or another ICT device and use a few successful ICT-enabled platforms like M-Pesa is an insufficient measure of digital inclusion.

1. Digital inclusion in the developing country context must account for the critical role of ICT in compensating for gaps in institutions, infrastructure and human capital

Most definitions of digital inclusion focus on the relative gap between the digital haves and the have nots, rather than on the specific ICT needs of low-income populations, and whether or not those needs are being met. While it is clear that long-term sustainable development is unlikely without fundamental structural improvements, new ICT-enabled tools are a critical interim bridge.

Low income countries are that way because they lack essential pillars of development: strong institutions, robust infrastructure and a depth and breadth of human capital. In healthcare, for example, these gaps manifest themselves as the absence of physicians and nurses and a dearth of equipped and functioning clinics. In high income countries such as France and Italy there is a physician for every 300 people, whereas in sub-Saharan African countries like Zambia and Guinea there is one for every 10,000 people (WHO, 2018).

Similarly, when it comes to education in lower income countries, there are significant gaps in the number of trained teachers, adequately equipped school buildings, suitable tools for instruction and accountability of educators to students and parents. In the face of such structural gaps, telemedicine tools can help patients in rural areas remotely consult with trained physicians, and online education videos (e.g., the Khan Academy) can provide quality instruction to those who can access them. Such examples are beginning to demonstrate the ability of ICT to compensate for structural gaps, at least partially.

Any meaningful definition of digital inclusion, therefore, needs to be in terms of whether the full range of such devices, and tools and services that help alleviate key human development challenges, are available to those who need them. **Table 1** describes some of the major structural gaps developing countries face, and promising ICT-enabled levers that constitute digital inclusion.

Examples of ICT enabled services to improve human development in low income countries

Area of human development	Key gaps for low income populations and countries (current or historical)	Examples of ICT devices and ICT enabled tools and services required for digital inclusion
Health	Acute lack of adequately trained physicians, nurses and other clinicians, especially in rural areas Sparse lab infrastructure for conducting reliable diagnostics Weak patient-clinician linkages and entrenched behaviour patterns, which limits treatment compliance Limited accurate data on patient health and epidemiological trends	Telemedicine tools for remote consultation with better trained physicians in urban areas Point-of-care diagnostic devices enabled by smartphones and other ICT devices, to reduce reliance on high level of clinical expertise SMS-based reminder apps Biometric patient IDs for tracking health metrics at the individual, community and population levels
Agricultural development	Smallholder farmers do not have access to true market prices, weather forecasts, and other critical information Agriculture ministries have limited capacity for quality extension services	Mobile phone-based services for weather forecasts market prices, contact information for dealers and other value chain partners, etc. Video-based extension services, delivered to farmer groups, with call-in for Q&A
Financial services	Acute lack of brick and mortar banks in rural areas Limited mechanisms for remittances, or other forms of money transfer to distant locations	Mobile money services like remittance
Education	Teachers have very limited training Most schools are not adequately equipped with instruction tools Limited access to up-to-date books	Remote video content and instruction Digital textbooks, with interactive content, customized for local context
Electricity, water and other utilities	High cost and complexity of managing small-scale utilities for rural populations Limited mechanisms for billing and collection of payments	Distributed utility management tools Mobile phone-based billing/payments systems
Miscellaneous public services	Limited accountability to citizens, and limited citizen voice in providing feedback Limited access to critical public services (e.g., rapid response police, or protection/rescue)	Digital reporting platforms to name-and-shame unresponsive public servants Citizen reporting for disaster response

Table 1: Current definitions of digital inclusion do not focus on the specific needs of low-income populations. While long-term sustainable development cannot happen without structural changes, ICT devices and ICT-enabled services are a critical interim bridge. (Source: ITT analysis)

2. The structural foundation for ICT connectivity was originally built for fixed line phones and gradually expanded to become a network of networks

- **The Public Switched Telephone Network (PSTN)**

The infrastructure for ICT connectivity is based on a global network of networks called the Public Switched Telephone Network (PSTN). The network began many decades ago in industrialized countries with a plumbing of copper wires used for the early generation of fixed line telephones, carrying only analog signals. The PSTN has since evolved into a network of networks, with new types and layers of cables added with each passing generation of technologies.

Today, it combines the old copper wires with coaxial cables (the original delivery mechanism for cable TV), extremely fast underground and undersea fiber-optic cables, wireless cellular towers and even satellites.

The combined network delivers information and media streams-- now digitized-- over long distances, seamlessly bridging across networking mechanisms like copper, coaxial, fiber-optic, wireless and satellite (Kushnick, 2013).

Exhibit 1 shows a schematic of the PSTN. Core or backbone networks typically have high bandwidth and interconnect distant regions (such as between cities or countries), edge networks provide last-mile access (for example, to individual homes within a residential area) and the backhaul connects edge and backbone networks.

In the evolution of the PSTN, two major inflection points have dramatically increased information flow and access, the range and quality of ICT enabled services, the ease of accessing them and the scale at which they are used. These points are the internet and mobile telephony, which are discussed below.

A sketch of the Public Switched Telephone Network

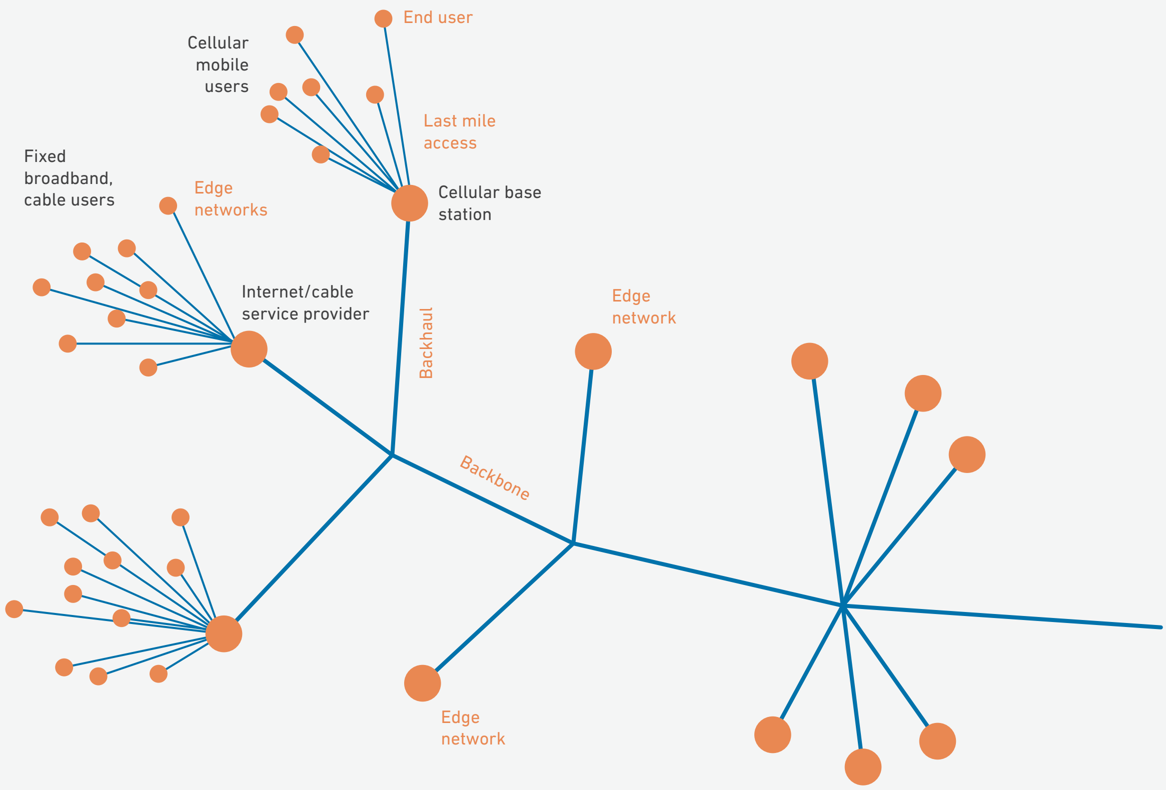


Exhibit 1: A simplified schematic that shows the organization of the Public Switched Telephone Network (PSTN) today as a conglomeration of diverse networks. Edge networks are closer to clusters of habitation, while backbone networks connect edge networks across cities, countries and continents.

- **The Internet and World Wide Web, as the primary vehicles for data exchange around the world**

Until the 1980s, various precursors of the internet (for example, the ARPANET) were used exclusively by a small number of government and research institutions, over the PSTN. The advent of the Internet protocol suite (TCP/IP)[1] allowed consumers and businesses to engage in email and other limited transactions. In the 1990s, the introduction of the World Wide Web (WWW)[2] allowed users to freely publish—and make accessible to everyone else on the Internet—information about themselves and their services, using rich media. Conversely, it also allowed any internet user to access content published by other internet users.

This changed, qualitatively and quantitatively, how information is shared and consumed by those having access to the network. Cloud computing made it possible to provide services remotely, in a distributed, relatively seamless fashion to deliver feature-rich applications and Software As A Service (SAAS).

Along the way, the advent of search engines led to the phenomenon that became Google. The internet, as we know it today, is not run by any one company. It is managed by all its participants to collectively self-regulate via non-profit organizations like ICANN (the Internet Corporation for Assigned Names and Numbers), which oversees assignment of unique identifiers on the internet.

A key feature of the internet is its resilience. Information can be re-routed across multiple paths (over the various member networks, which collectively enable strong redundancies) until it reaches its destination. In effect, the internet is never down. The internet is now the primary vehicle for data exchange around the world and a platform for an infinite range and number of services, with very low barriers to entry. Anybody can provide or use services with relative ease. This makes the internet a tremendous equalizer and an unmatched platform for development.

- **Mobile telephony, to obviate the need for dense networks of underground cables at the last mile**

Until recently, telephone networks, especially in developing countries, were controlled by public sector monopolies. Installation of landline phones often took several months (sometimes years), and their reliability after installation was questionable at best. Only a small portion of the population in the developing regions had these telephones. Market liberalization eroded stifling monopolies, brought competition and large injections of capital and resulted in massive tariff reductions.

Quick, cost-effective deployment of cellular networks, combined with newer, cheaper backhaul and backbone technologies, drove the leapfrog effect in developing countries from fixed line to cellular services. The pre-paid business model innovation combined with cheap handsets made mobile telephony ubiquitous and accessible to a wide swath of users who could not have dreamt of owning a fixed landline before. Over the last decade dramatic advances in mobile phone technology, with respect to bandwidth, reliability and cost, have made communication a reality for populations hitherto cut off from the rest of the world.

The first generation, or 1G, networks developed in the 1980s used analog signals for voice calls with bulky and expensive phones. Wireless radio channels were restricted to one call at a time, limiting the calls each cell could support. Signals could be intercepted by anyone with a radio scanner tuned in to the right frequency. By the 1990s, digital signals and improved networking protocols to enable multiple channels of communication led to 2G systems, with radically better network utilization, more security and data services (like SMS, multimedia messaging, mobile internet, international and satellite roaming).

Later, 2G improvements such as EDGE and GPRS increased data speeds even more. In the early part of the new millennium 3G networks were introduced, with even higher data speeds, better spectral efficiency, energy efficient transmissions and data encryption.

[1]TTCP/IP together allow information to be routed repeatedly across multiple paths until it reaches the destination anywhere on the PSTN. The Internet Protocol (IP) is a standard, simple and open protocol, which allows any computing device to send messages over the network. Service providers can use the Transmission Control Protocol (TCP) for end-to-end transmission reliability. This, combined with the redundancy afforded by the large number of member networks, makes the internet highly resilient.
[2]The World Wide Web is based on a system of globally unique identifiers for digital resources on the Internet (UDI, URL, and URI), an easy-to-use publishing language (HTML) and a protocol to allow for links to dynamic content (HTTP). Together, these make it easy for people to publish content on the internet using a standard web browser.

This allowed sophisticated, secure and data-intensive services such as Voice over IP (VoIP), video conferencing and financial transactions. By 2014, advanced 3G and 4G networks were achieving faster transmission speeds than most high-speed cable internet services (Telcoantennas, 2014).

All the network innovations thus far have focused on smartphones, but the current generation of 5G technology will also enable IoT connectivity between millions of devices. It is expected that 5G technology will have lower latency (time taken to move data from one source to another) and higher throughput than previous versions.

The 5G network will connect a grid of people, sensors and machines enabling IoT intercommunication. In August 2018, The US Federal Communications Commission set rules for bidding on the 5G spectrum band (Economic Times, 2018). Several telecom providers are investing resources to build cloud infrastructure, distributed network architecture, and operating models to successfully operate a 5G network to dominate this market.

Through the combination of internet and mobile enabled services, the move to information based economies and widespread liberalization of telecom has allowed information to flow freely and cheaply between different types of networks, as well as between distant networks. The same service can thus be provided in a network-agnostic manner in the PSTN (for example, the internet can be accessed via mobile phones, and phone calls can be made using the internet and computers). This is a result of the digitalization of all kinds of information, where both voice and video are sent as data using the Internet Protocol as the universal lingua franca for connecting disparate networks.

- **Satellites and aerial vehicles have the potential to provide global, universal broadband connection**

Ground-based networks are challenged to provide ICT-enabled service in rural areas of developing countries, because the network economics of conventional cellular technologies that work for urban areas, which are typically densely populated, do not translate well to sparsely populated rural areas.

Ground-based technologies require disproportionately more infrastructure to providing connectivity to rural inhabitants than for the same number of people in urban areas, including towers, base stations, backhaul and electricity provision (through the grid or off-grid options like diesel generators).

Aerial platforms, whether based on satellites or atmospheric vehicles, could radically improve the economics of rural broadband coverage. A high platform allows greater spans of the network, and operates wirelessly over large distances with equipment that costs less and uses less energy.

A growing alternative for digital communication is to use satellites in orbit around the Earth. A large number of such satellites are required to provide continuous coverage. Although low- and medium-Earth orbit (LEO and MEO) services are becoming increasingly commercially available, they are still too expensive for widespread use.

In 2018, SpaceX received approval from the United States Federal Communications Commission to deploy 4,425 low-Earth orbit broadband satellites, as well as 7,518 very-low Earth orbit (VLEO) non-geostationary broadband satellites (FCC, 2018). Once deployed, these satellites are expected to boost capacity and reduce latency. However, the business model regarding these SpaceX satellites, and their relevance to digital inclusion for low-income populations, remain unclear.

Yet another approach is to use aerial equipment in the stratosphere, for example with balloons or drones. Using balloons at altitudes of 18 to 25 kilometers to provide internet connectivity to rural areas via wireless links is the goal of Loon LLC, a subsidiary of Alphabet Inc. Apart from short pilots in Brazil, Peru and elsewhere, the technology has not reached the desired scale of impact.

Facebook has also experimented with solar-powered drones at altitudes of about 20 kilometers to provide data connectivity using infrared lasers. Their aircraft Aquila had a successful first test flight in 2016, powered by onboard solar cells. The drone has a wingspan of 42 meters but weighs only 450 kilograms. However, despite successful technology demonstrations, the project has not been implemented in practice at any locations so far.

3. There is a wide range of digital and ICT development status between different countries of the world

A country's ability to use data analytics depends on how much (and what kinds of) data it collects. As such, we introduce the Data Density Index (DDI) as a measure of the strength of a country's data infrastructure and readiness for utilizing data to advance its development objectives. The DDI is a composite of indicators that cover four key areas of digital development:

- Business: How engaged are the country's businesses in using ICT?
- People: How widespread is ICT use (including social media) among the country's citizens?
- Government: How committed is the country's government to using ICT in its operations?
- Infrastructure: How well developed is the country's ICT infrastructure?

In DDI calculations, the Business indicator is derived from three metrics in the Networked Readiness Index calculated by the World Economic Forum (WEF, 2016): ICT use for business-to-business transactions, internet use for Business-to-consumer transactions and Impact of ICTs on business models.

The People indicator is derived from the ICT Development Index calculated by the International Telecommunications Union (ITU, 2017c) and the Use of Virtual Social Networks metric reported by the World Bank (2018). The Government indicator is derived from the E-Government Index calculated by the United Nations Department of Economic and Social Affairs (2018).

The Infrastructure indicator is derived from the Telecommunication Infrastructure Index calculated by the United Nations Department of Economic and Social Affairs (2018) and the international internet bandwidth per user reported by the World Bank (2018).

To derive the indicators, each metric was first normalized[3] to a value between zero and one, where one corresponded to the highest score among all the world's countries. A simple average of all of the metrics comprising each indicator was then calculated for each country. Finally, each indicator was multiplied by 25 and summed for each country (thus giving equal weight to the four indicators), resulting in a maximum DDI score of 100. The DDI was calculated in this way for 144 different countries for which data were available.

Together, these indicators are intended to capture the five V's often used in the data analytics industry: Volume (are there enough data points captured in the ecosystem?), Variety (is the sample data adequately representative of the range of uses across the broader population?), Value (is the data being captured meaningful or useless?), Veracity (is the data accurate, or are there errors?) and Velocity (is the data current, and being updated with adequate regularity?).

Exhibit 2 shows the calculated DDI scores for a selection of countries. The exhibit also demarcates three categories of countries: data deficient, data sufficient and data rich. We define data deficiency as having a DDI score of 60 or less. The answer to the "how much data is enough" question is complex and depends on the variance between different population segments across the different data types.

The threshold of 60 is a simplification based on a high-level analysis of income and economic population pyramids in developing countries. Above this minimum threshold and up to a DDI score of 80, we consider a country to be data sufficient. With the use of appropriate statistical methods, it is possible to extrapolate to the broader population from a sample; therefore, it is not necessary to have complete penetration of data platforms to capture data representing all of the population. As such, we make the (admittedly simplified) assumption that beyond a DDI score of 80, it is likely that more than enough data is captured about a country's population; therefore, we consider such countries to be data rich. Not surprisingly, most developing countries are still data deficient despite the recent explosion in smartphones and related apps; this is largely due to the lack of robust data platforms for public services.

[3]Because of the extremely large range of the international internet bandwidth metric (measured in kilobits per second per user), the logarithm of these scores were calculated prior to normalization.

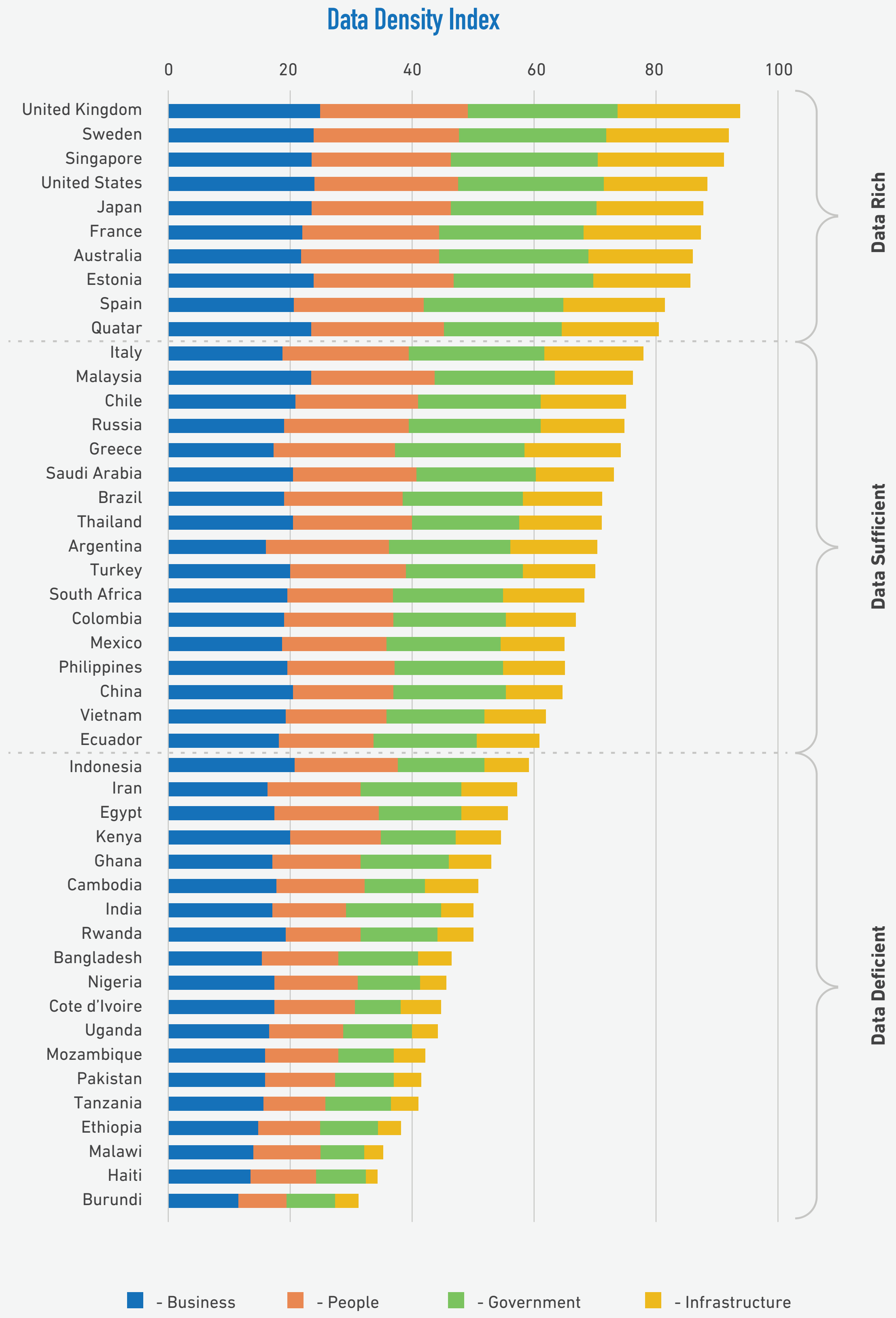


Exhibit 2: The Data Density Index of selected countries around the world, based on indicators of four key areas of digital development: Business, People, Government and Infrastructure. Based on these indicators, we categorize countries into three groups: data deficient, data sufficient and data rich. Despite the recent explosion in smartphones and related apps, most developing countries are still data deficient due to the lack of robust data platforms for public services. Note that since some of the metrics comprising the composite DDI are proxies, the DDI is directional rather than precise. (Source: ITT, 2018)

Exhibit 3 shows the relationship between the DDI and the Human Development Index (HDI) calculated by the United Nations Development Programme (UNDP, 2018). As expected, there is a strong correlation (r2 = 0.91) between the two indices. Nevertheless, some countries have DDI scores that are significantly higher or lower than would be expected based on their HDI scores.

For example, Bahrain, UAE, South Africa, Kenya and Rwanda have higher-than-expected DDI scores. Other countries have lower-than-expected DDI scores, including Iran, Venezuela, Algeria, Sri Lanka and Gabon.

Human Development Index versus Data Density Index

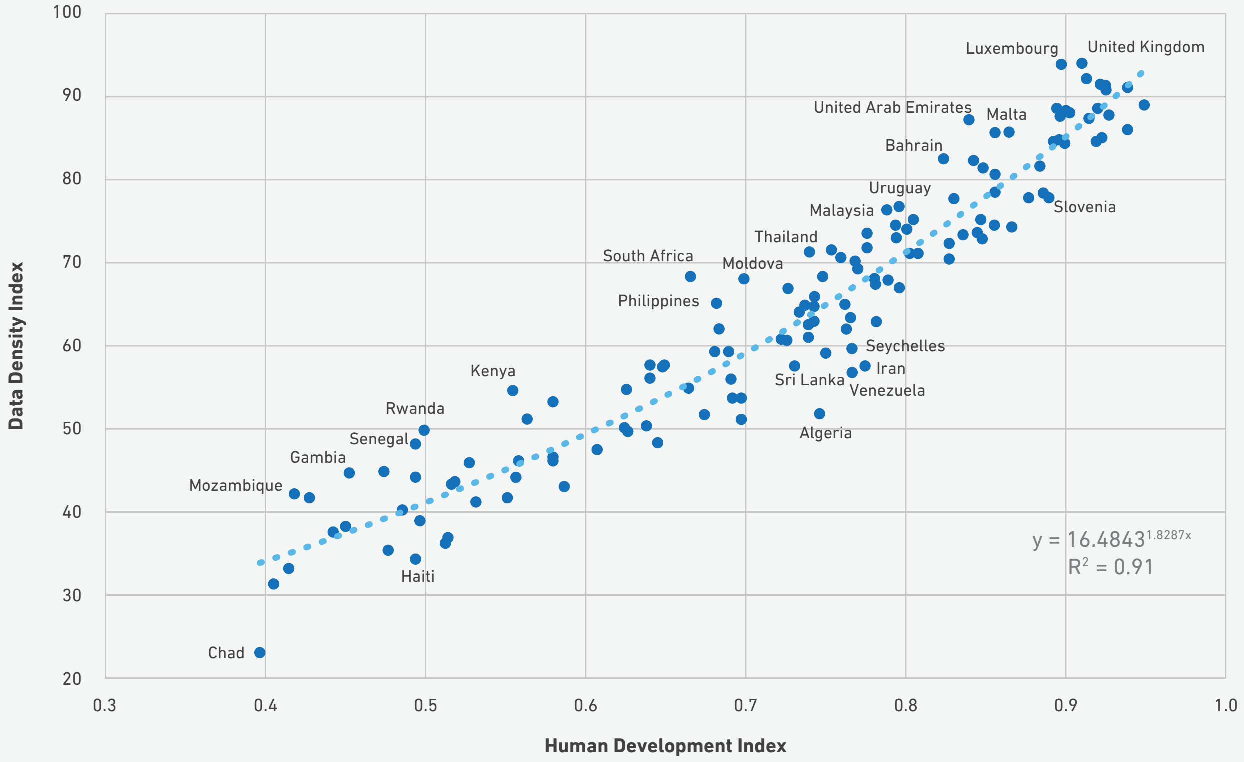


Exhibit 3: There is a strong correlation between the Data Density Index and the Human Development Index. On this figure, countries are labeled if their DDI scores are at least 8 points higher or lower than their predicted DDI score based on exponential fit. (Source: ITT, 2018)

4. The large discrepancy in access and use of digital technology between countries is diminishing

In every region of the world, mobile phones are outstripping fixed line phones as the default. As **Exhibit 4** shows, there are 104 mobile phone subscriptions per 100 people around the world, compared to 13 fixed phone lines. In developing regions, this difference is more pronounced (ITU, 2017a). Mobile broadband penetration is now 52 percent in Asia but only 26 percent in Africa (ITU, 2017a). The mobile connectivity gap has decreased significantly during the last decade, as more people in developing regions gain access to the technology (**Exhibit 5**).

Globally, roughly 300 million new mobile subscriptions are added each year, with South Asia and sub-Saharan Africa experiencing the highest growth rates. Nevertheless, there remains a pronounced discrepancy in access to, and use of, communications technology between industrialized and developing countries (ITU, 2017b). **Exhibit 6** shows the difference in ICT Development Index (IDI) between countries. The IDI is an index developed by ITU (2017b) that uses 11 parameters measuring the ICT access, use and skills of a country. Most sub-Saharan African and South Asian countries have relatively low IDI scores, while industrialized countries have higher scores.

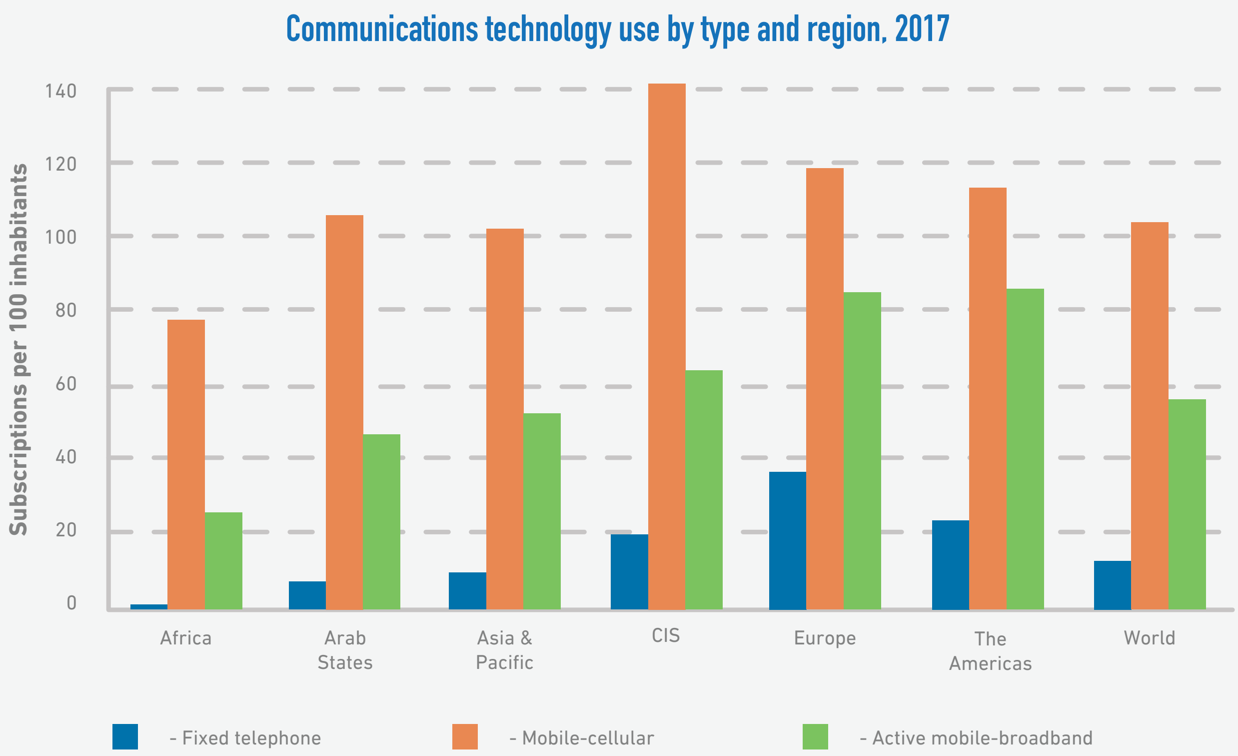


Exhibit 4: Mobile networks are much more ubiquitous than fixed phone networks, reaching close to universal coverage in some developing countries. (source: ITU, 2017a)

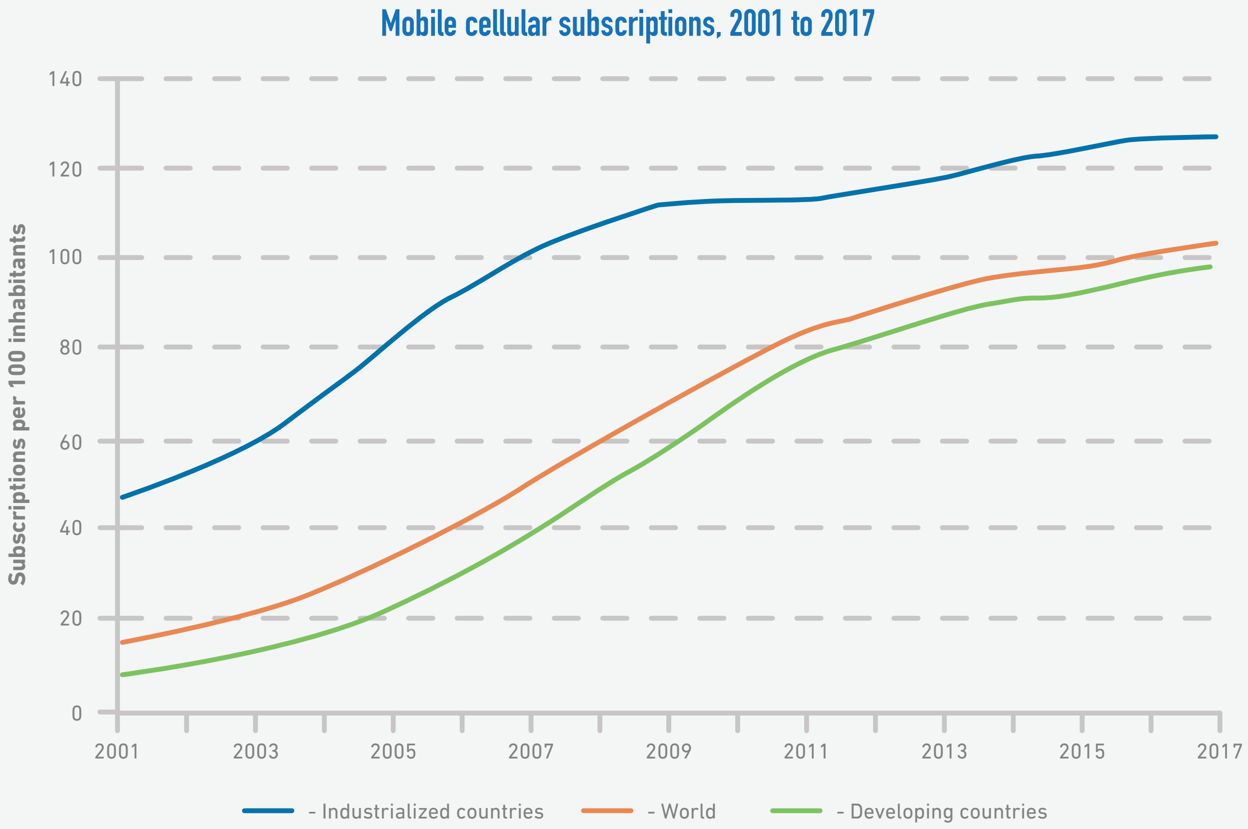


Exhibit 5: The global gap in mobile cellular connectivity has decreased during the last decade, as more people in developing regions gain access to the technology. (ITU, 2017a)

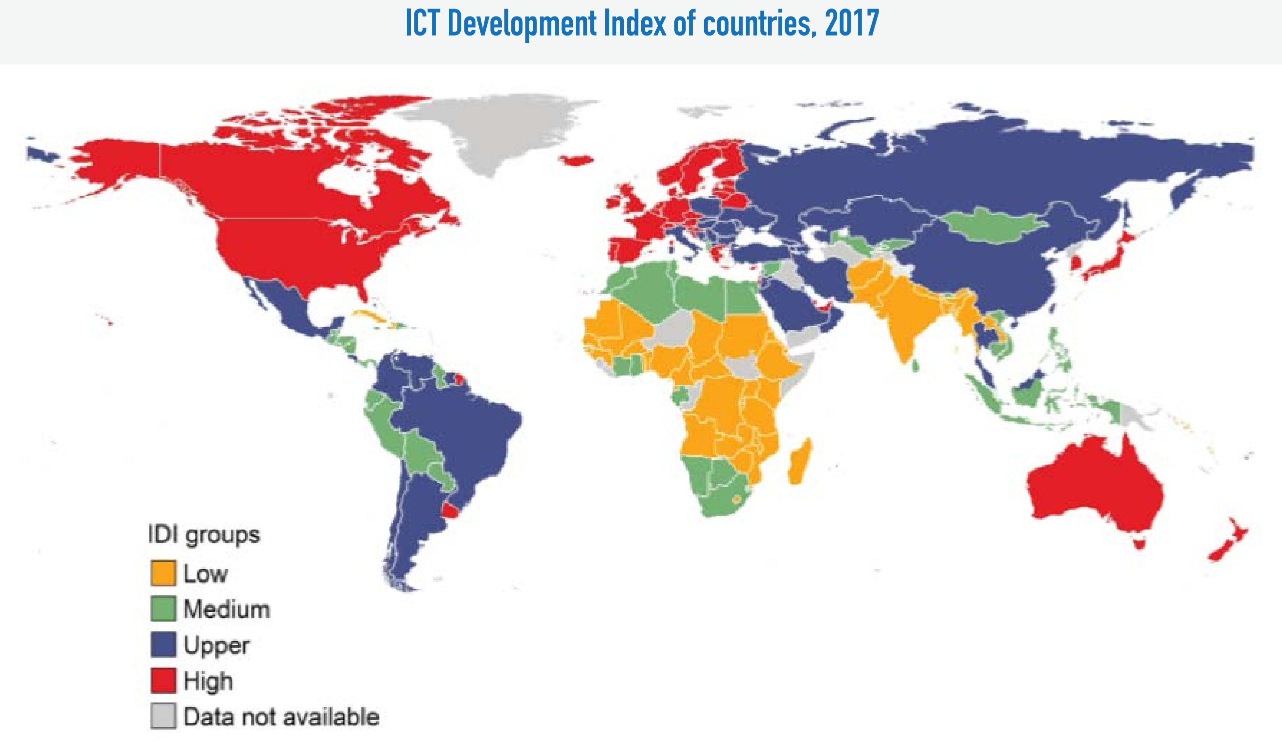


Exhibit 6: There is a large discrepancy in access and use of communications technology between industrialized and developing countries. (Source: ITU, 2017b)

5. Despite the overall increase in mobile subscriptions, low income rural populations still lack access to both mobile and broadband services

The promising statistics on the growth of mobile phone subscriptions can inspire misplaced confidence. To begin with, it is important to acknowledge that subscriptions in South Asia and sub-Saharan Africa are still significantly lower than other parts of the world (**Exhibit 2**). Second, relative to incomes phone subscriptions are much more expensive to users in developing countries than in wealthier countries (**Exhibit 7**).

Third, rural populations don't have the same access as their urban counterparts, partly due to lower network coverage and partly because they are poorer.

Exhibit 8 shows coverage rates for India, Ghana and South Africa; it also shows that rural users are much more likely to share a phone than urban users. Similarly, Malawi has a coverage rate of 94 percent, but only 21 percent of the population has a mobile phone (GSMA, 2013a, 2014). Finally, most of the networks in developing countries are 2G, especially in rural areas; broadband (3G or better) networks are usually restricted to urban areas.

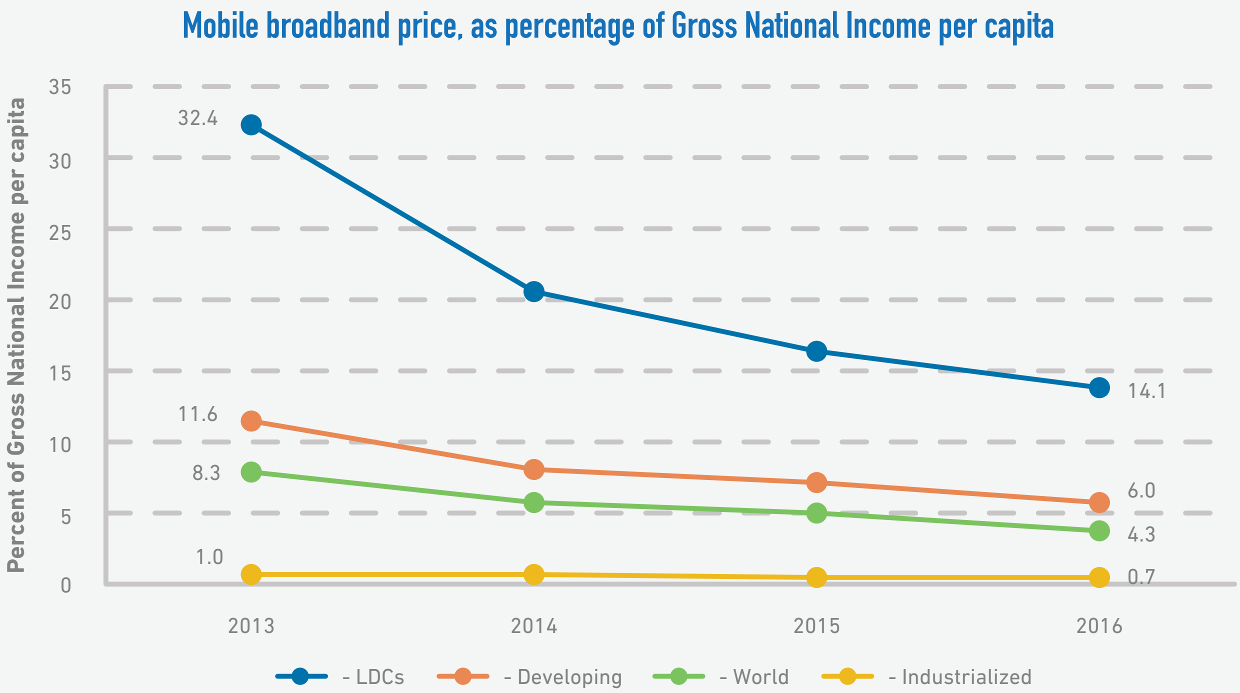
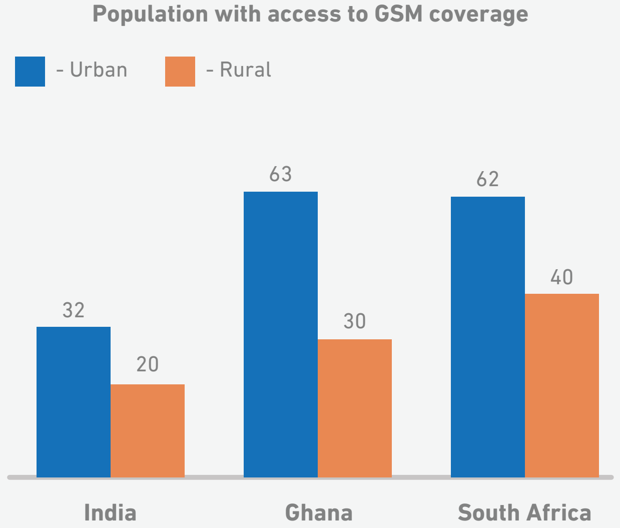


Exhibit 7: The price of mobile broadband as a proportion of income is higher in developing countries than in industrialized, which makes it less affordable to low income populations. (Source: ITU, 2017a)

Mobile coverage and use in rural versus urban areas



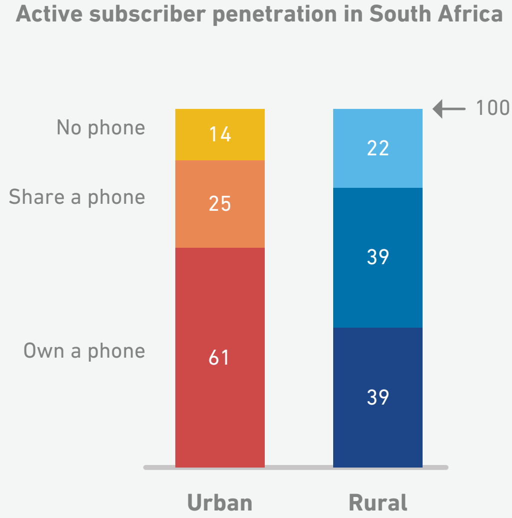


Exhibit 8: Rural mobile coverage and use of cell phones is disproportionately low, especially in developing countries. Also, a significant number of people in rural areas share phones. (Source: GSMA, 2013a, 2014)

Access to high-speed internet opens doors to a plethora of services, such as:

- Mobile payment services: There has been a surge in usage of mobile payments in recent year in developing countries. Platforms such as iPay in Bangladesh and digital wallet Paytm in India have been adopted by many. For example, Paytm has about 300 million registered users in India in 2018.
- E-commerce: A wide range of E-commerce companies benefit from improved access to the internet and increase in smartphone users. Many companies also develop mobile applications, rather than the now conventional shopping websites, for enhanced shopping experience and sales. Within India, 40 percent of demand for online shopping now comes from small towns. Jumia, Africa's largest e-commerce portal, now has around 160 million registered users.
- Agricultural extension: Providing farmers with timely access to relevant information on for instance, soil and weather, enables increased agricultural productivity. For example, CABI-Plantwise provides online diagnosis and advice to reduce losses from farm pests, SkySquirrel Technologies Inc uses drones and computer vision for crop analysis, and PEAT uses machine vision for diagnosing pest and soil problems.
- Education: The internet has improved the access to education for the underserved communities through online educational tools. Many free educational videos are now available. The most widely used tools are from the Khan Academy, with around 100 million users across the globe, and Edx.org.
- Entertainment: Radio has displaced interpersonal engagement to become the main source of entertainment for most of the world's rural populations. Technologies such as the DigiPlex mobile theater vans now offer viewers in rural India a good quality movie experience at an affordable charge.

6. Only smartphones and tablets have the necessary capabilities to support the services and applications needed for true digital inclusion

Just as computers evolved from room-sized mainframes to bulky desktops to laptops, and eventually tablets, mobile phones have simultaneously evolved to become smaller, lighter and more like computers in their capabilities. There are several categories of mobile phones: at one end of the spectrum are inexpensive and simple basic phones; at the other end are smartphones, essentially pocket-sized computers with touchscreens, designed to support full-fledged internet services by exploiting the broadband capacity of 3G+ networks. In between the two ends of the spectrum are feature phones. Smartphones offer a fundamentally different set of capabilities than basic phones and feature phones. There are three essential dimensions along which the capabilities of these devices are different.

- **User and data collection interface**

  These interfaces determine how the user interacts with the device. Basic phones typically have a number pad, on which the number buttons can be used, with some inconvenience, to enter letters of the alphabet when texting. Most of today's basic phones also have a still camera. Feature phones have keypads (which incorporate the full range of alphanumeric characters) or touchscreens to allow users to select which application they wish to launch. Many feature phones also have video cameras. Smartphones have a range of interfaces: touchscreens, voice-activated control and ports for freely exchanging data with other computing devices. Some even have inbuilt thumbprint and face scanners for security.

- **Processing power, storage capacity and a platform for installing new applications (or "apps")**

  These capabilities collectively determine a device's breadth of functionality. Basic phones do not really have a processor and cannot support data-rich applications, being limited to only voice or SMS. Feature phones typically come with a number of essential functions (such as address book, calendar, calculator and alarm clock) and users can download only limited additional applications, if any.

  Smartphones, on the other hand, have processors, operating systems and storage capacities comparable to computers of the recent past. These phones work quite like small, general purpose computers with a broad range of powerful functions including email, music and videos playback, GPS-enabled maps and document and image processing.

  They can support any of the thousands of applications developed by a whole ecosystems of app developers, which the user can download at will. Indeed, beyond the basic functions like voice calls, texting and email, it is possible that the same brand of smartphone is used so differently by two users that they might as well be two different devices altogether. This capability of smartphones to be programmed and hyper-customized to the needs or whims of each user, sets them apart from any handheld consumer device ever developed in the past.

- **Modes of wireless communication**

  These modes determine the ways in which the device can transmit and receive wireless data. All mobile phones use ultra high frequency (UHF) radio signals (also used for over-the-air TV broadcasting) for communication with phone towers. Whereas basic phones are limited to a single mode of communication in that range, smartphones use a number of other modes, such as Bluetooth (for bilateral communication with another Bluetooth-enabled device at distances of up to 150 to 200 feet) and Wi-Fi (for connecting to internet hubs within a distance of 50 to 100 feet).

  Many smartphones are also equipped with RFID (radio frequency identification for communication with uniquely tagged objects or devices) and near-field communication (NFC, a variant of RFID) also used in smart cards at shopping checkout stations within a few inches from the user. Feature phones tend be closer to basic phones in their modes of communication.

Recently, affordable high-end feature phones have been introduced to the market, with many features hitherto supported only by smartphones. This has led some to conclude that feature phones can spearhead digital inclusion (GSMA, 2013a).

However, feature phones by definition still have one fundamental design constraint relative to smartphones. Their operating logic firmware is burnt into the hardware and can therefore vary from one model to another even with the same brand. This makes it harder for developers to make the same app work with different types of phones.

On the other hand, the operating logic of smartphones is software (meaning, an operating system like in computers), and virtually all the smartphones in the world operate on a very small number of operating systems—Google's open-platform Android and Apple's proprietary iOS.

This means that as long as software developers can write apps compatible with those operating systems, they will be usable on virtually all smartphones.

Referring back to **Table 1**, the types of ICT-enabled services low income populations need in order to be truly digitally included simply cannot be provided through basic or feature phones. Basic phones can increasingly be used for important services, such as financial transactions like M-Pesa and agricultural extension like weather reports and planting advisories.

Nevertheless, only smartphones and tablets have the required capabilities, especially the ability to support a broad range of apps that are custom-developed for the needs and demands of specific communities and market segments.

Therefore, even as the explosive growth of mobile, SMS- and voice-based services are being celebrated as milestones, we believe real digital inclusion cannot be achieved without smartphones.

Currently, because of the prices of even the least expensive smartphones, basic phones and feature phones comprise the majority of devices that low-income populations use to access information in developing countries (**Exhibit 9** and **Exhibit 10**).

Adult ownership of cellphones and smartphones, 2015

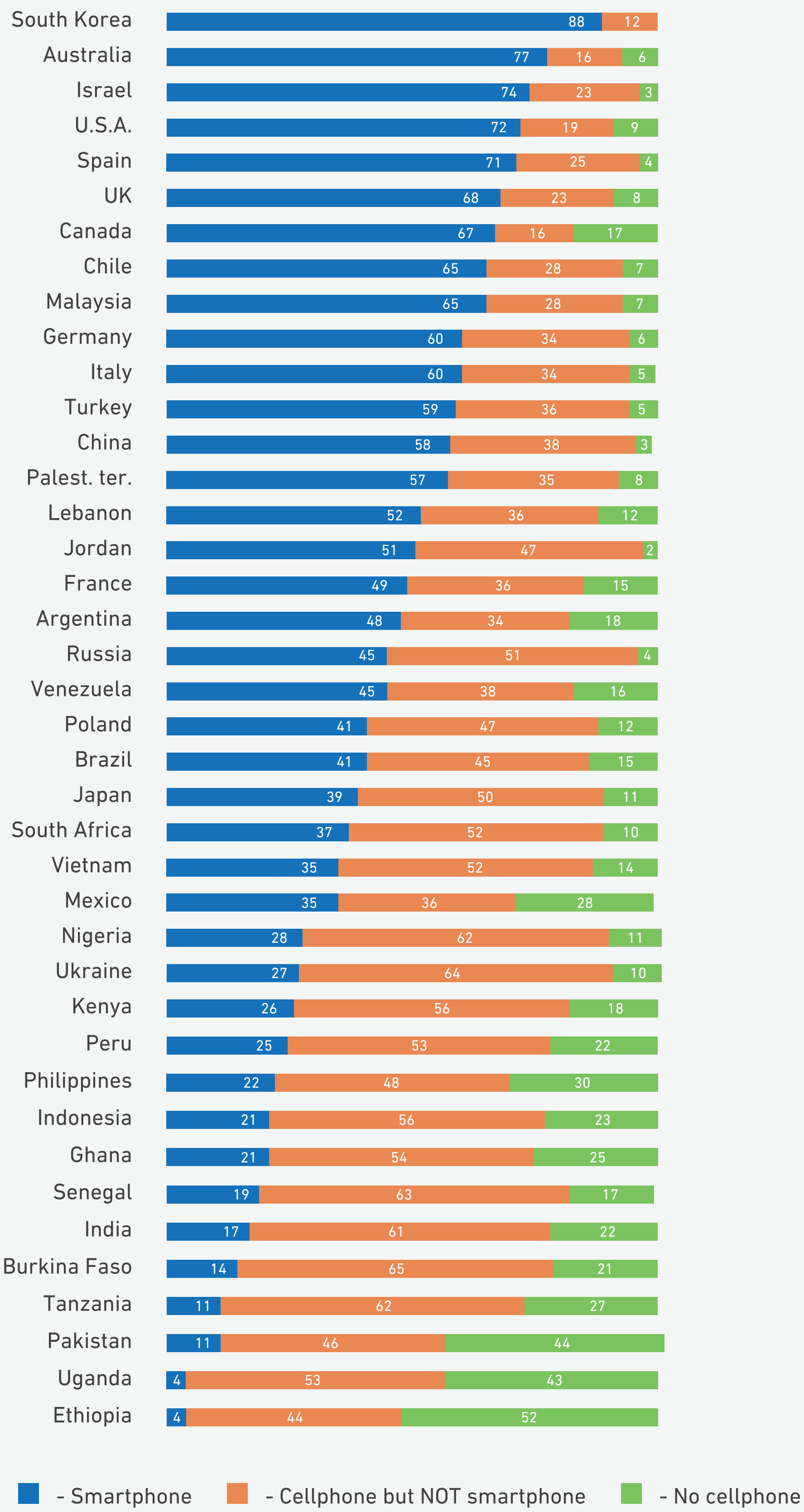


Exhibit 9: A smaller percentage of people in developing countries own cellphones, and particularly smartphones, compared to people in industrialized countries. (Source: Pew Research Center, 2016)

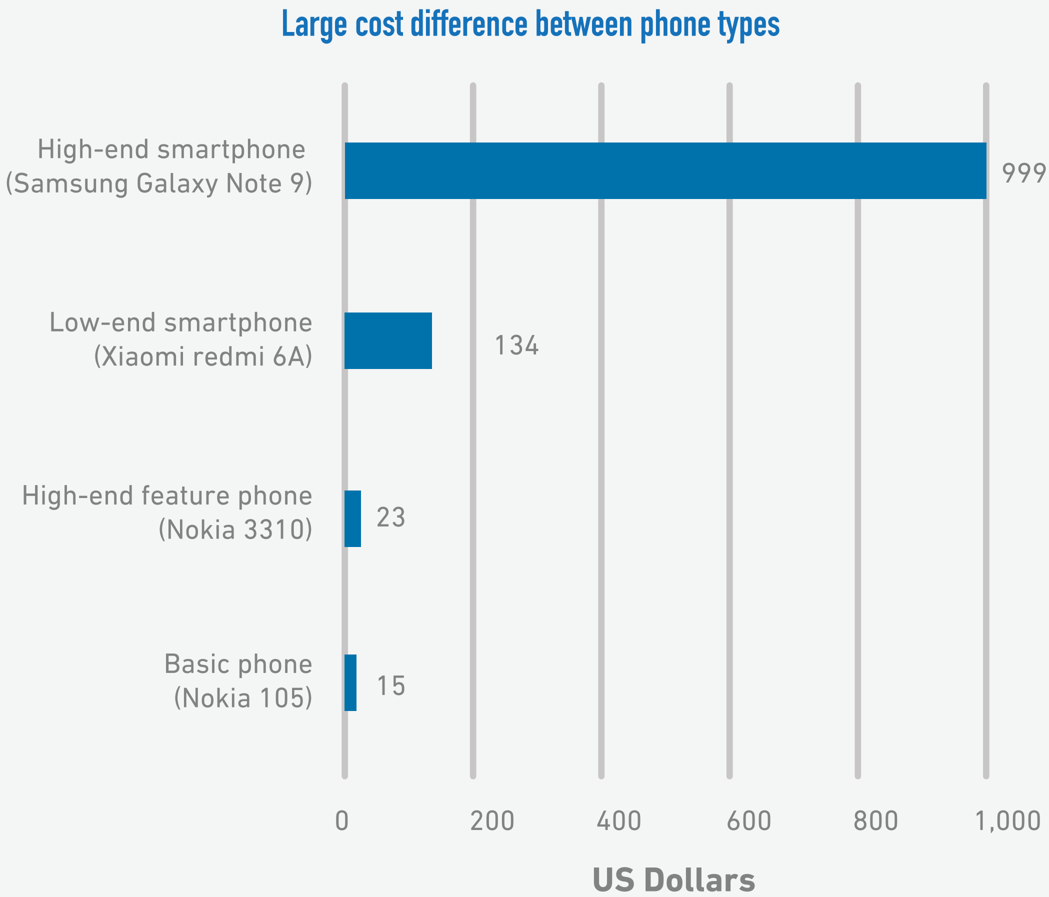


Exhibit 10: Smartphones are two to 10 times more expensive than high-end feature phones, and significantly more expensive than basic phones. (Source: Internet survey by ITT, 2018)

7. Smartphones prices are dropping rapidly, becoming increasingly affordable for low income consumers

Many factors contribute to the retail price of smartphones. The cost of manufacturing is only one. Still, examining the bill-of-materials (BOM) is instructive on the challenges involved in making them affordable.

Exhibit 11 shows the BOM for a hypothetical $50 smartphone (Cooper, 2015). The biggest single costs are the RAM storage and the system-on-a-chip, each of which cost about $10. The display costs about $8, while the battery and camera together cost about $5.

Most of the manufactures have worked on innovative solutions to bring down the costs of the smartphone. Approaches have included using low-cost alternatives to the traditional branded system chips, and reducing the design costs by following a standard reference design and not spend a lot of money on the appearance of the phone.

In addition, numerous advancements in battery technologies have enabled significant reduction in the cost of the power source used in mobile phones.

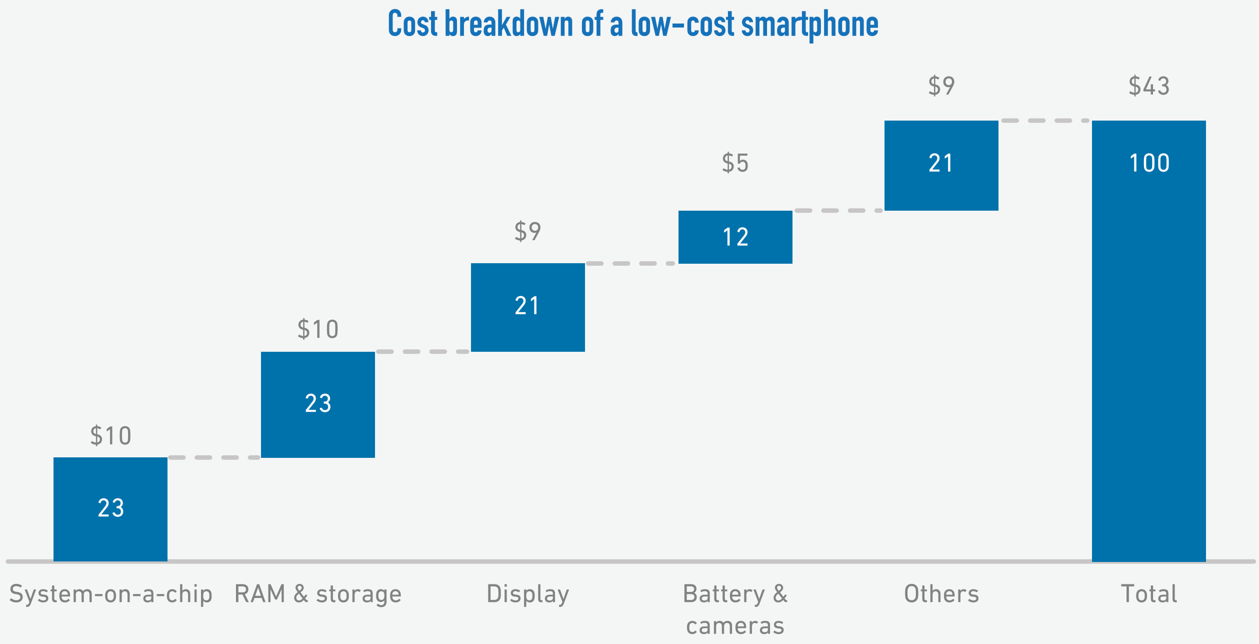


Exhibit 11: Components for processing applications (processors and memory chips) and display (glass and touchscreen parts) are the most expensive parts of a low-cost smartphone. (Source: Cooper, 2015)

Although smartphone prices are dropping, there are several reasons why the digital divide gap still exists. Here are the four most important:

1. Infrastructure: There is lack of access to a good network or lack of electricity that can facilitate the network access.

2. Affordability: Broadband is still expensive, so are smartphones for most of the underserved communities.

3. Skill and awareness: Education plays an important role here, and there is also a cultural divide between men and women over smartphone ownership.

4. Local adoption: There are language barriers, as almost 80 percent of the content on the internet is only available in 10 languages.

To increase the impact of low-cost smartphones, there must be significant improvement to infrastructure coverage and quality, provision of financial assistance to those who cannot afford to get online and establishment of public Wi-Fi.

8. A citizen ID system is a critical enabler of accountable services and of broader digital inclusion

In industrialized countries, governments and businesses alike collect an extraordinary amount of information about individuals like birth, educational history, income, financial transactions, residential history, ownership of property, taxes and even death. The citizen ID plays a critical role in this process, by validating that an individual, in fact, exists and that people are who they claim to be.

The information linked to IDs is used to provide a range of public and private services and for participation in the broader social and economic system. Indeed, in the typical industrialized country, it is hard to imagine any citizen or business functioning without a primary or derivative ID for even a day and the importance of individual IDs cannot be overstated. With the ever-increasing volume of data collected, services are promising to become hyper-customized to an individual's very particular needs and wants.

While some developing countries have systems for issuing IDs for their citizens, these are not mandatory. As a result, these IDs are not issued until applied for, nor are they used widely, especially in rural areas. In the absence of IDs for individuals and businesses, and in the absence of a system of services linked to IDs, citizens of those countries continue to live in informal economies. They cannot easily establish citizenship or legal title of land or property and cannot access loans and other formal mechanisms of finance.

Furthermore, if repressive governments so wish, the fact that these citizens ever even existed can be denied. In addition, few small businesses have any legal standing, independent of their owner. Investing in business growth then becomes either a personal risk for the owner or depends solely on trust between the owner and an investor. In other words, the absence of IDs is a fundamental barrier to economic and human development.

In the broader context of global development, the absence of insightful information about particular population segments can lead to uninformed decisions based on broad generalizations about the global poor. It would then become a case of assuming that the 2 billion low-income people in developing countries constitute one monolithic population, rather than an amalgam of many complex and different population segments.

The need for some type of ID has also been recognized by the governments of many developing countries, where formal ID systems are weak, if present at al. This has led to a range of Know Your Customer (KYC) requirements, which are mandated by the Central Bank of a country and include information that must be collected and authenticated to validate an individual's ID before providing them a bank account for using financial services. In India, for example, KYC-verified customers who had been with a bank for more than six months could recommend another person to become a customer by certifying their photograph and address.

More recently, and recognizing the challenges faced by the very poor in verifying their identity, several developing countries have bootstrapped effective ID systems. India's Aadhar identification system, for example, is a 12-digit unique identity number that can be obtained by residents of India based on their biometric and demographic data.

Aadhar has now registered around 1 billion Indian citizens making it the largest such database in the world (UIDAI, 2018). Rwanda has also embarked on an ambitious national ID program. Similarly, Kenya's national ID system, in line with KYC requirements, has been critical to the rapid growth of M-Pesa (Oyebode, 2013). **Exhibit 12** illustrates the strong correlation between the existence of a national ID system and the percent of population with bank accounts (Jentzsch, 2009).

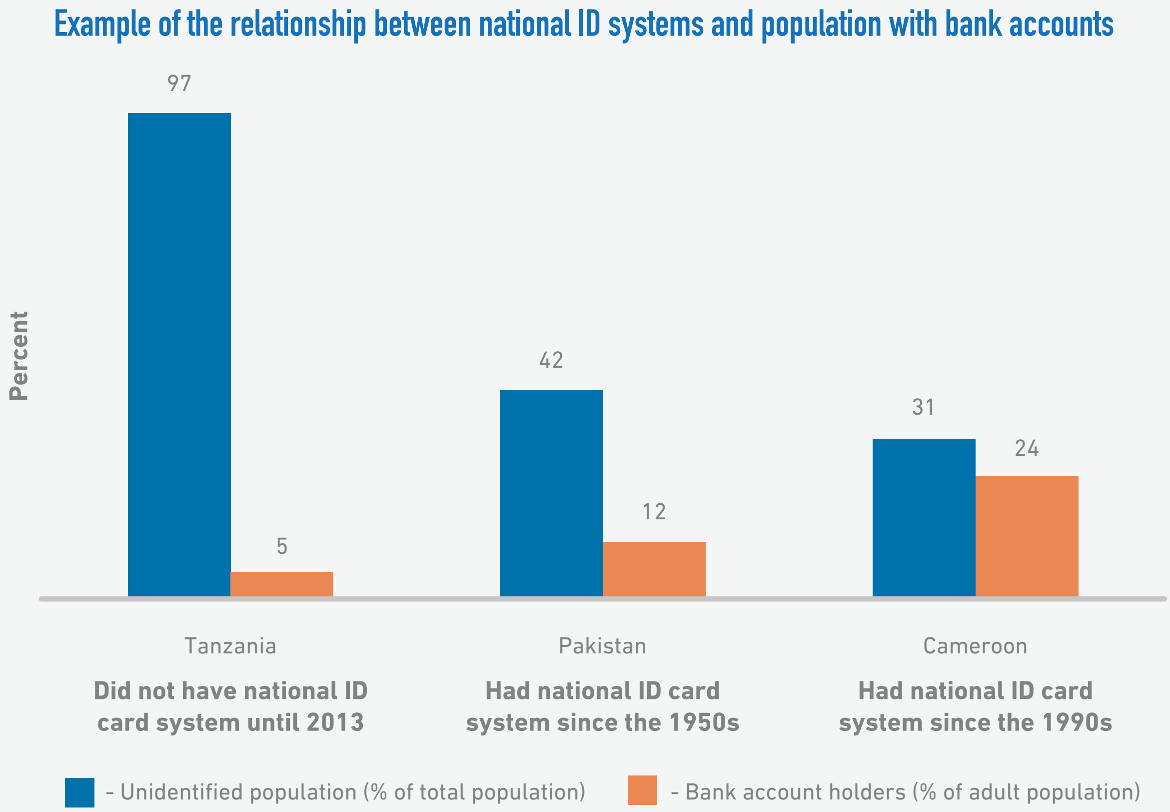


Exhibit 12: Having a national ID appears to significantly improve access to financial services. (Source: Jentzsch, 2009)

ID is established using a combination of at least three modes: something one can carry (like a plastic card), something one knows (like a password) or something physically intrinsic and unique to each individual (biometric data such as fingerprints, iris or face). The more the modes of identification, the more robust, yet complicated and costly, the authentication will be. A key factor in scaling the Aadhar system is its fingerprint biometric. Biometric-based ID systems are generally accurate, scalable and relatively fraud-proof.

They can be digitized and individuals no longer have to carry any documents which can be lost, stolen, damaged or forged. There are, however, differences in the various types of biometrics with respect to cost and accuracy. Fingerprints, for example, have higher false positive rates than iris scans but are less expensive and intrusive. Facial recognition, on the other hand, has not proved reliable yet under imperfect lighting and other complex conditions.

An emerging example of a digital ID system is the ID2020, a public-private partnership aimed at improving lives through digital identity (ID2020, 2019). Led by Accenture and Microsoft, ID2020 seeks to harness the power of blockchain to provide digital identity for the displaced.

ID2020 works on a model in which it brings together development organizations, private sector companies, governments and NGOs around a pooled fund, used to implement digital identity programs with clear governance models and high potential impact.

Partners work together to define technical requirements, ensuring that the technologies developed meet the needs of both individuals and institutions and to prioritize and structure pilot projects for scale, impact and replicability.

It is important to note that there are serious and legitimate concerns about mandatory ID systems, and about biometric IDs in particular. Digitized systems make it possible for governments and other powerful parties to easily access large volumes of information about citizens and communities. This opens the door for easy abuse of information.

By enabling surveillance of targeted individuals and communities, biometric ID systems can aid the creation and maintenance of authoritarian states. The more integrated the ID systems are with other aspects of life, the easier surveillance becomes. One can imagine the dangers of a system which has facial recognition, GPS-based tracking of mobile phones and any data on ethnic or religious identity. Integration of personal information also exposes people to hacking and theft of personal information.

It will be very important that stringent international standards, with respect to protection of privacy and civil rights, as well as for data security, are in place before such systems are deployed. Most industrialized countries lack comprehensive laws about biometric data, and many African and Asian countries do not meet international criteria that are considered to be adequate for hosting and protecting data (ITU, 2012; Scientific American, 2013a).

9. The Internet of Things (IoT) is enlarging the scope of ICT-enabled services

The Internet of Things (IoT) is an emerging and evolving phenomenon, generally consisting of an integration of components that merge the physical world and the virtual (computer-based) world. While there is no universally acceptable definition of IoT, it has been described as "the growing range of Internet-connected devices that capture or generate an enormous amount of data every day along with the applications and services used to interpret, analyze, predict and take actions based on the information received" (US Department of Commerce, 2017).

IoT is not a single device or a product, but a conceptual structure that includes tangible items like sensors and actuators as well as intangibles like software and data. The technological components of the IoT include building blocks like machine-to-machine interfaces and protocols, microcontrollers, RFID technology and other wireless communication, sensors, actuators and software (CERP-IoT, 2010). A host of synergistic technologies can also add value to the IoT, such as machine vision, robotics, user interfaces, biometrics, geo-tagging and others (**Exhibit 13**).

Examples of data generated by the Internet of Things

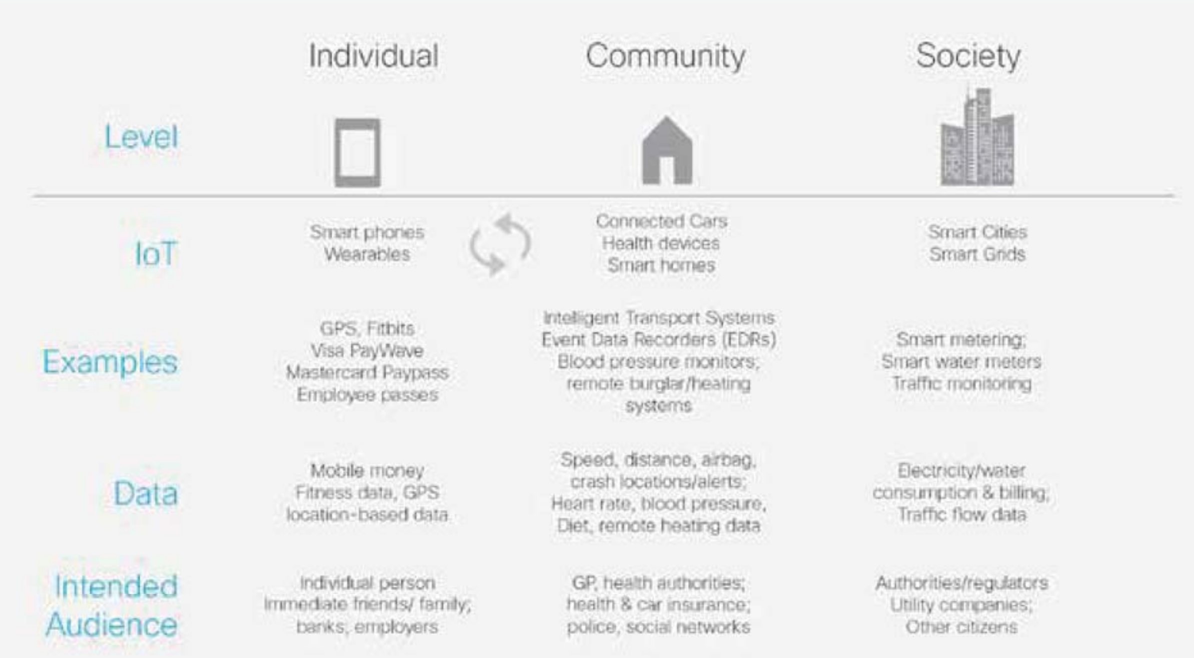


Exhibit 13: The Internet of Things could generate a wide range of data at the individual, community and societal levels. (Source: ITU, 2016)

The objective of IoT is to expand knowledge and control of the world. by integrating data processing with physical devices to sense and influence their surroundings. Communication channels include person-to-person, person-to-machine, machine-to-person and machine-to-machine. The IoT is expanding rapidly:

In 2008 the number of connected devices surpassed the number of people. The number of connected devices is projected to reach 20 billion by 2020 (Exhibit 14). Researchers estimate that IoT will contribute more than 14 trillion dollars to world economy by 2025 (McKinsey, 2015).

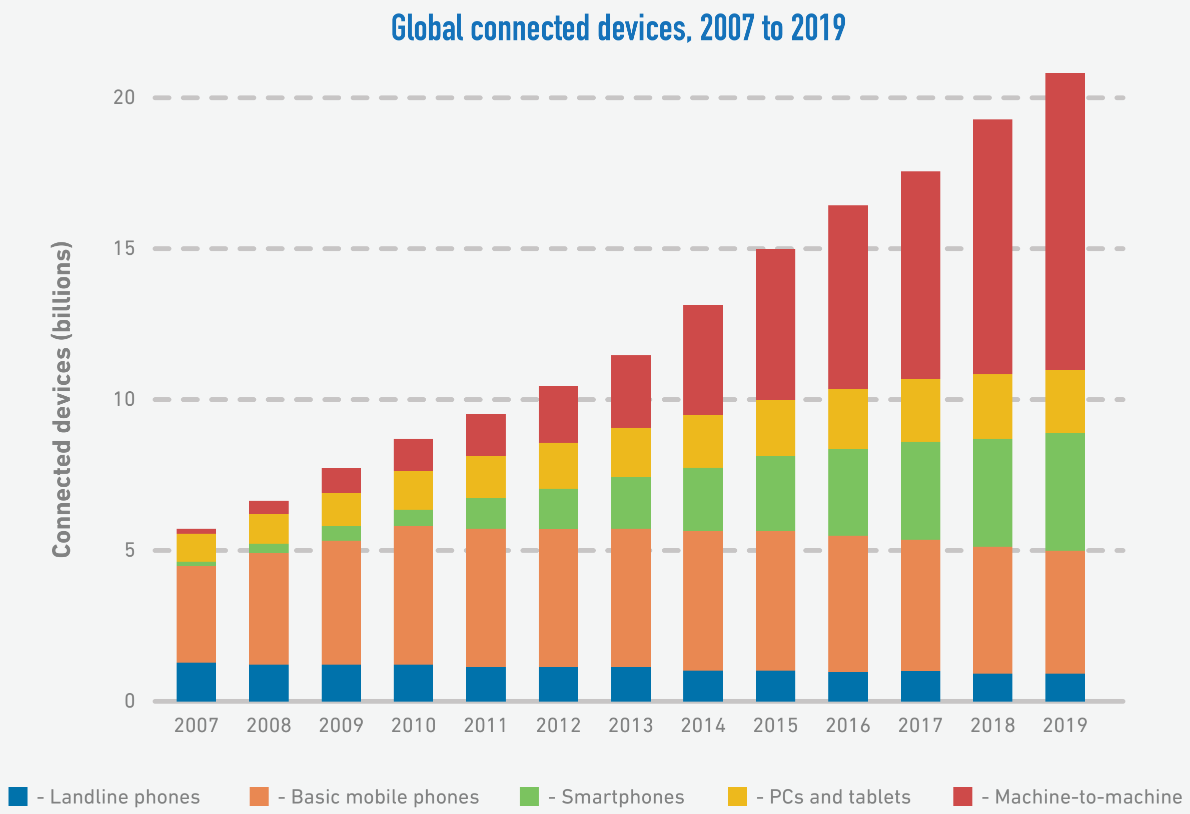


Exhibit 14: The number of connected devices continues to increase rapidly, and the fastest growing segment is machine-to-machine communication that forms the core of the Internet of Things. (Source: ITT analysis based on Gartner, 2017; GSMA, 2017; ITU, 2017b; Newzoo, 2018; IoT Analytics, 2018; Ericsson, 2018; Cisco, 2019)

The World Economic Forum projects that 84 percent of IoT deployment has the potential to address challenges surrounding the SDGs (WEF, 2018). They estimate that 75 percent of these IoT projects concentrate across five SDGs: industry, innovation and infrastructure (25 percent), smart cities and communities (19 percent), clean energy (19 percent), good health and well- being (7 percent) and sustainable consumption (5 percent). The link between IoT and sustainability is not currently well understood.

For example, in sectors like energy, a commercial application of IoT sensors used to track energy consumption can have downstream benefits like energy use reduction, development of conscientious users and cost savings for utility companies. There is a need to disseminate the awareness around benefits of employing IoT solutions to multiple stakeholders for IoT solutions to have a tangible impact on achieving SDGs.

Two trends have influenced the increasing utilization and integration of IoT to provide services in developing countries. First, more people in developing countries have access to telecommunication services than basic services like sanitation, water and electricity. In 2015, for example, more than 95 percent of the world's population lived in areas with network coverage of 2G or better (ITU, 2016).

Second, the cost of ICT infrastructure development has significantly decreased over the last decade and supply chains continue to be simplified. There has been a proliferation of service delivery applications that leverage these reduced costs to make basic services accessible to the poor.

Some sectors where application of IoT technologies is showing promising impact are:

- **Healthcare:** In developing countries, sensors are being used to monitor cold chain supply networks to monitor and track the temperature at which vaccines are stored. Mobile based thermal sensors record the temperatures in real time and a warning is issued to the responsible person if the temperatures exceed a threshold level. IoT technologies are also being used to address immediate challenges in humanitarian response, such as the Ebola outbreak in West Africa. The United States Agency for International Development (USAID) has supported and employed IoT solutions via connected wearable technologies. Sensor Technology and Analytics to Monitor, Predict, and Protect Ebola Patients (or STAMP2 for short) has been tested on Ebola patients in the United States and is being scaled up to meet the needs of government agencies such as USAID for its Ebola treatment strategy in Liberia (ITU, 2016).

- **Agriculture:** IoT technologies can be used to produce crops efficiently and monitor harvest during storage and handling. Chemical sensors have the potential to detect soil health and measure soil moisture, pH value and nutrient levels. Micro-weather stations are using IoT technologies to monitor and predict weather more accurately, and to transmit the information to smallholder farmers for them to plan farming activities.

- **Human Rights:** Wearable devices, or smart electronic devices that can be incorporated into clothing or worn on the body as implants or accessories, have the potential to capture significant information and evidence to shed light on transactions involving corruption and human rights violations. However, they also have the potential to be used in violations of privacy.

Even though the expansion of internet and mobile broadband coverage has been speedy in developing countries, some key challenges will have to be addressed for IoT to achieve its potential impact. First, economic sectors in developing countries are more labor intensive and may not use IoT-enabled devices to conduct their day-to-day operations. Investments would need to be made in behavior change and awareness activities that can lead to adoption at scale. Second, connectivity may be available only at a basic level to operate applications on a small scale, and the full range of IoT services might not be accessible in some areas. Furthermore, concerns have been raised that increasing interconnection of devices leads to heightened risk of lethal disruption by hackers (Schneier, 2018). For example, malicious hackers could cause automated cars to crash, implanted medical devices like pacemakers to fail and electrical power grids to go offline.

Despite these challenges, IoT technologies, especially those attached to sensors for environmental toxicity, health and other under-documented aspects of society in lower-income settings, have the potential for significant democratization of information, transparency and accountability. As such, they have the potential to make a sizeable contribution to the SDGs and beyond. While expansion of IoT is expected to increase transparency, it is also expected to decrease privacy.

KEY CHALLENGES

Digital inclusion in the context of global development is still far from being a reality. Given the full potential of existing ICT tools and what needs to happen to further human development, the Mobile for Development (M4D) movement has had negligible impact. Most existing solutions are bespoke, designed for specific user segments, rather than scaled across markets. This has led to a proliferation of incremental, duplicated services (GSMA, 2013b).

Additionally, even these few existing solutions are typically developed by individuals and companies from industrialized markets, who have limited insights into user needs and constraints in low income settings. There is clearly a stark lack of local ICT capacity in most developing countries. Unfortunately, there are a number of other major hurdles as well.

1. The cost of expanding coverage of wireless networks to rural areas is very high

Despite the explosion of mobile networks, a sharp urban-rural divide remains. Even when they are within the network, coverage in rural areas remains spotty and is typically not broadband. To provide sufficient bandwidth to a last mile channel for end users, transmission needs to support high throughput of traffic.

This requires high-efficiency modulation, meaning high signal-to-noise ratios in conveying a message signal such as a bit stream, inside another signal that can be physically transmitted. Distance is a significant limiting factor for this. The farther the transmitting node from the end user, the lower its effective bandwidth will be.

Since rural areas are less densely populated than urban areas, they need a larger number of base stations to serve the same number of people. This requires more equipment (towers, servers, telephony switches) and longer backhaul connections, which leads to higher capital and operating costs. Another challenge is the need for electricity.

Rural areas in developing countries are typically off-grid and diesel and batteries are more expensive than grid power. These factors increase the cost of expanding network coverage to rural areas (where economic conditions are generally weaker) and exacerbate the rural-urban digital divide (GSMA, 2013a; Scientific American, 2013b). Not surprisingly then, network sites are concentrated in areas that are on-grid, and mobile penetration in developing countries is almost double in urban areas compared to rural areas (**Exhibit 15**).

Network coverage in on-grid versus off-grid areas

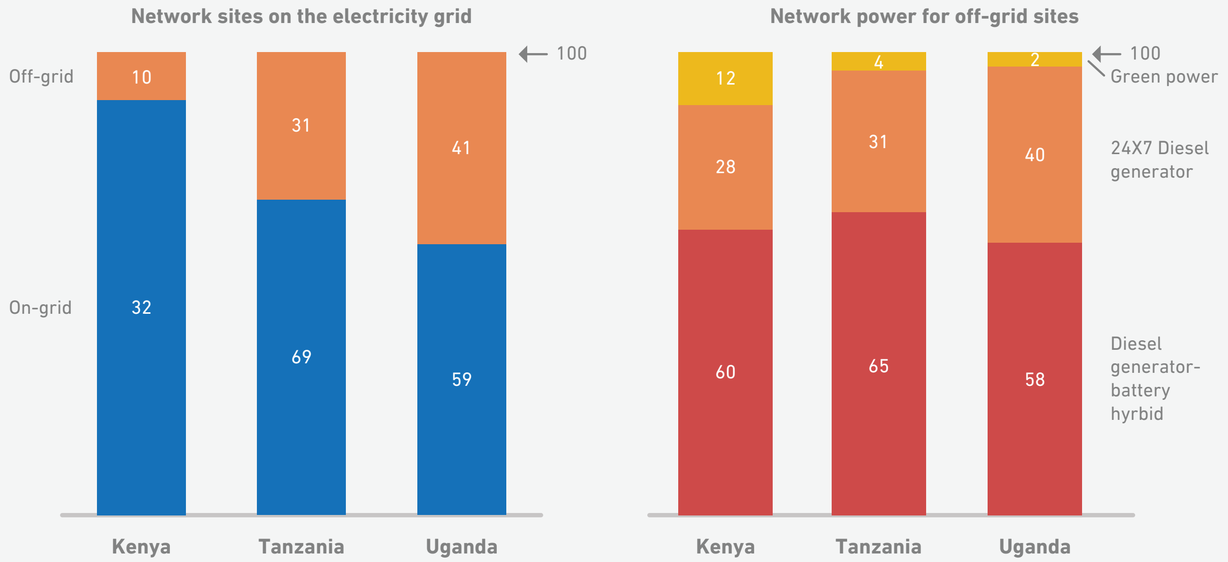


Exhibit 15: Mobile networks sites are very sparse in areas that are off-grid and where mobile towers are powered mostly by diesel generators and batteries. Renewable energy solutions are yet to be widely used. (Source: GSMA, 2013a)

2. Institutions to develop and oversee reliable ID systems are weak or non-existent in developing countries

In a country like the United States, a consortium of agencies—the Department of Motor Vehicles, the municipal birth registry, the passport agency, the Social Security Administration and others—collectively ensure that citizens are part of the formal governmental system. The first official ID (birth certificate) is issued shortly after a child is born, on the strength of the parents' ID. Such institutions are weak in developing countries and usually do not reach low income or rural populations. As a result, only 44 percent of children in sub-Saharan Africa are registered today, with rates going as low as 3 percent in countries like Somalia. Globally, almost 50 million births are not registered (UNICEF, 2010).

While technologies for expanding robust national ID systems exist, and are not a barrier per se, there are practical barriers such as the lack of funding or political will on part of the government, a lack of awareness or interest on the part of citizens and the logistical complexity of bootstrapping such a system in which the majority of people do not have any proof of their identity.

3. As the volume and usage of data increase, so do the risks of unauthorized access to data

Internet and ICTs are increasingly widespread not only in industrialized, but also in developing countries. ICTs already play an integral part of many sectors including government, commerce, communication, military and others. Financial transactions are increasingly made digitally, for example with Kenya's M-Pesa mobile phone-based money transaction app that is used by millions. However, as our modern world becomes more dependent on ICTs, cyber security threats have become more significant.

There is a large variety of external data threats based on software or social methods. Common types of malicious software (or malware) include viruses, trojan horses, ransomware and worms. Viruses are software designed to infect and modify other programs or content. Trojan horses (or Trojans) comes disguised as non-harmful software, then steals, blocks or deletes victims' data from their computer. Ransomware is a malicious software that encrypts users' data and threatens to block it or release it to the public, forcing users to pay ransom. Worms are similar to viruses, but with a goal of infecting one computer from another.

Another external threat is social engineering, which includes cybercrimes with a heavy emphasis on psychological techniques. These include phishing, in which offenders steal victims' personal information by contacting them via email, phone call or text messages and by pretending to be legitimate institution (see **Exhibit 16**). Watering hole attacks are similar to phishing, but the victim is a group or organization.

In addition to these external threats, data is often vulnerable to internal threats from within an organization. Motivations may include personal financial gain, social justice concerns and general rage against the machine. One of the most dangerous aspects of internal threats is that they cannot be prevented by more traditional security measures, which are more focused on protection from external agents.

Data security is a substantial risk factor for global digital inclusion. The problem is experienced in all countries. Some of the factors contributing to inadequate cybersecurity are poorly-secured networks, lack of cyber laws and shortage of well-trained IT security experts both in private and government agencies. A particular problem with developing countries is that they tend to use existing popular templates rather than creating their own, which makes it easier for hackers to enter and manipulate systems. Generally, cyber-criminals will continue to exploit trending topics, such as cryptocurrencies and new ICOs. As these topics attract greater interest from the general public, successful attacks can reap large rewards.

Prevalence of phishing attacks

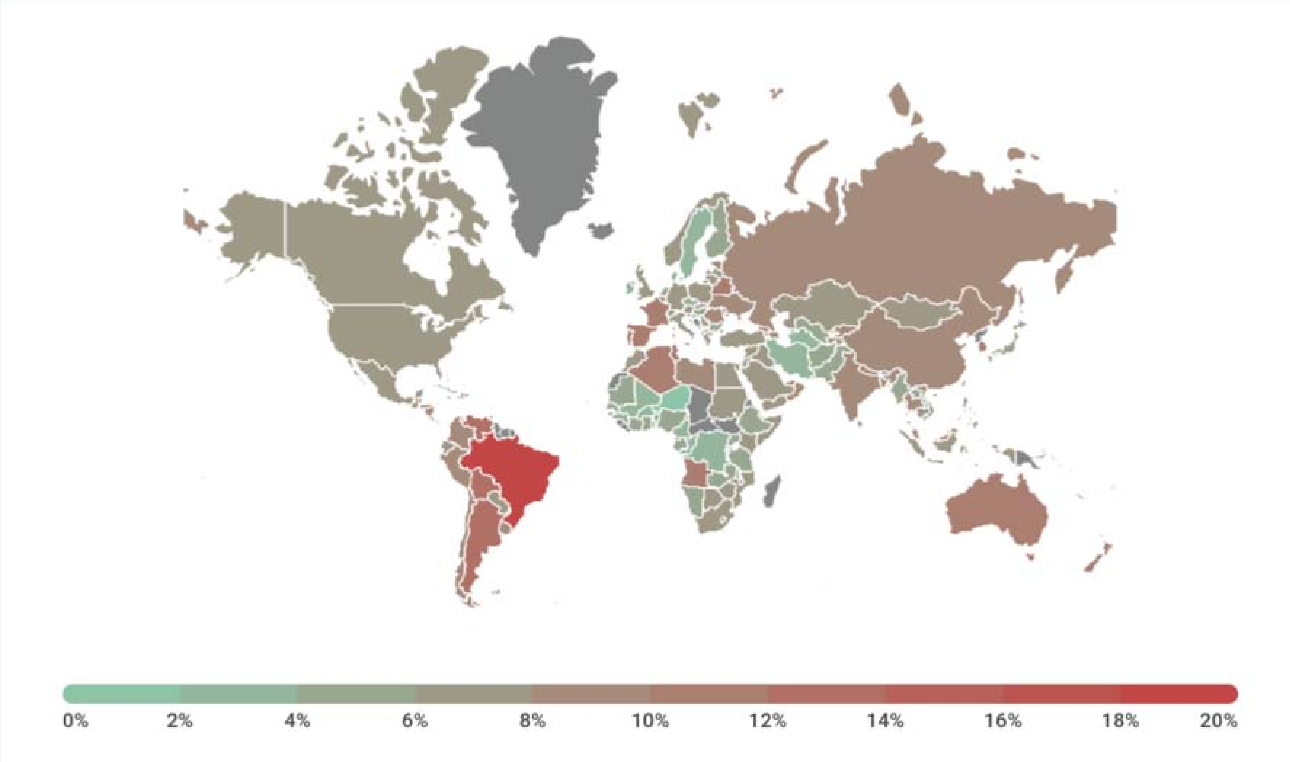


Exhibit 16: The country with the largest percentage of users affected by phishing attacks in 2018's first quarter was Brazil. (Source: Kaspersky, 2018)

The Aadhar personal identification database in India, the largest of its sort in the world, faces several data security challenges. For example, leakage of data appears commonplace. There have been thefts and misuse of official accounts with authorized access, leading to data use by uncredentialed people. Personal Aadhar data has been sold to companies and individuals for as low as $10.

A further challenge is external hacking of the government databases of the Aadhar system. Linking Aadhar numbers with various databases, such as bank accounts, PAN cards and credit cards, whether by convenience or by legislation, has potential for significant disruption if the data were misused.

SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

Digital inclusion, by definition, is about access to technologies, and the services those technologies enable. In developing countries, ICT and ICT-enabled services can go a long way in compensating for gaps in physical infrastructure, institutions and human capital. The proliferation of mobile phones and the internet and the services they have enabled bodes well for the potential impact of true digital inclusion on broader human development.

We believe that three breakthroughs—two of which are broad and systemic—can pave the way for true digital inclusion for low income populations.

Breakthroughs:

1 2 3 4 5 6 7 8 9 10
11 12 13 14 15 16 17 18 19 20
21 22 23 24 25 26 27 28 29 30
31 32 33 34 35 36 37 38 39 40
41 42 43 44 45 46 47 48 49 50

40 A new generation of wireless broadband network technologies that radically cut the cost of expanding coverage to rural areas

Ground-based networks are challenged to provide ICT-enabled service in rural areas of developing countries, because the network economics of conventional wired or cellular technologies that work for urban areas, which are typically densely populated, do not translate well to sparsely populated rural areas.

Ground-based technologies require disproportionately more infrastructure to providing connectivity to rural inhabitants than for the same number of people in urban areas, including towers, base stations, backhaul and electricity provision (through the grid or off-grid options like diesel generators).

Aerial platforms, whether based on satellites or atmospheric vehicles, could radically improve the economics of rural broadband coverage. A high platform allows greater spans of the network, and operates wirelessly over large distances with equipment that costs less and uses less energy.

A growing alternative for digital communication is to use satellites in orbit around the Earth. A large number of such satellites are required to provide continuous coverage. Although low- and medium-Earth orbit (LEO and MEO) services are becoming increasingly commercially available, they are still too expensive for widespread use.

In 2018, SpaceX received approval from the United States Federal Communications Commission to deploy 4,425 low-Earth orbit broadband satellites, as well as 7,518 very-low Earth orbit (VLEO) non-geostationary broadband satellites. Once deployed, these satellites are expected to boost capacity and reduce latency.

However, the business model regarding these SpaceX satellites, and their relevance to digital inclusion for low-income populations, remain unclear.

Yet another approach is to use aerial equipment in the stratosphere, for example with balloons or drones. Using balloons at altitudes of 18 to 25 kilometers to provide internet connectivity to rural areas via wireless links is the goal of Loon LLC, a subsidiary of Alphabet Inc. Apart from short pilots in Brazil, Peru and elsewhere, the technology has not reached the desired scale of impact.

Current State

Development Stage: Engineering

Time to market (years)

<3 4-6 7-10 10+

Deployment: Challenging

Associated 50BT Chapters

Digital Inclusion Food Security

SDG Alignment

Impact

New Income Generated (# of People)

<1M 10M+ 100M+ 1B+

Improved Quality of Life (# of People)

<1M 10M+ 100M+ 1B+

Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- **Attractive for emerging markets (lower profits)**
- Emerging markets potential; requires derisking (sustainable)
- Non-commercial (unprofitable)

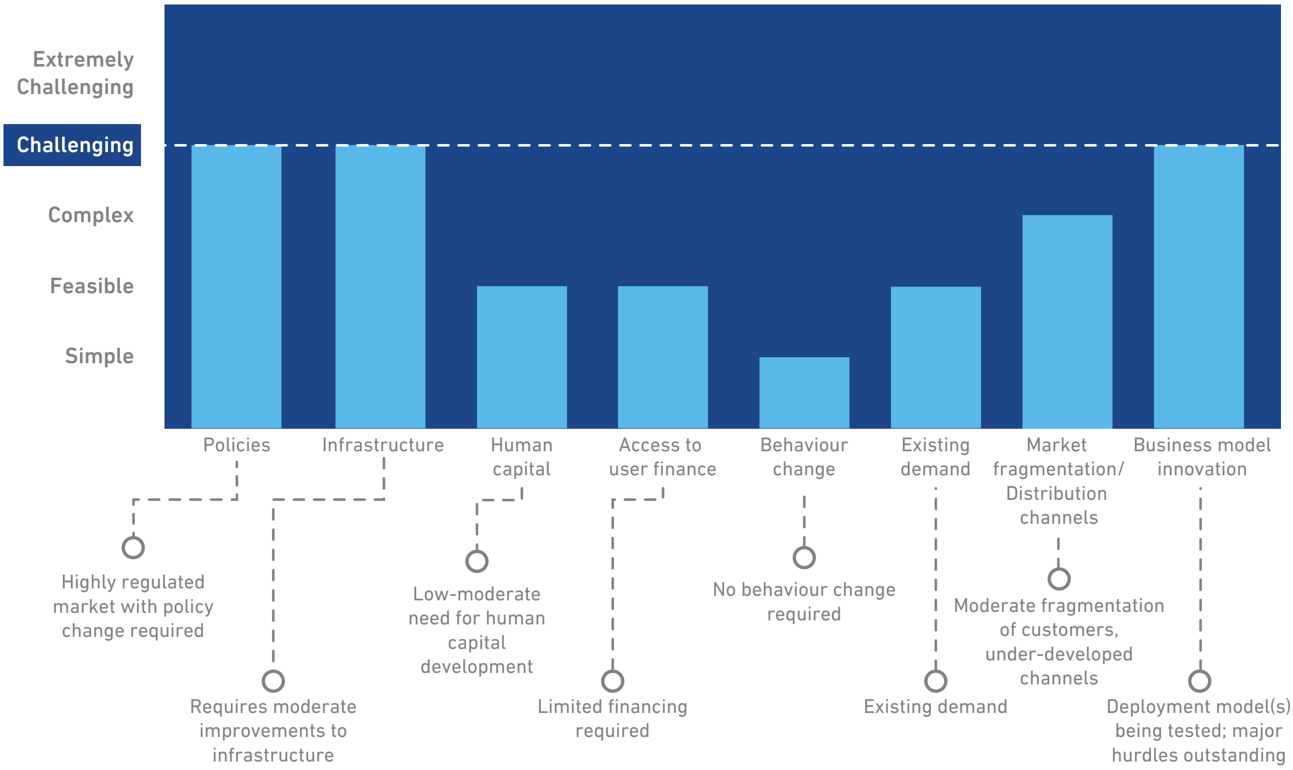
Facebook has also experimented with solar-powered drones at altitudes of about 20 kilometers to provide data connectivity using infrared lasers. Their aircraft Aquila had a successful first test flight in 2016, powered by onboard solar cells.

The drone has a wingspan of 42 meters but weighs only 450 kilograms. However, despite successful technology demonstrations, the project has not been implemented in practice at any locations so far.

Even as such technologies are becoming market-ready, there will be a number of deployment challenges. Many countries have regulatory constraints on the use of the radio frequency spectrum. Some technologies are very capital intensive, with significant risk of failure and loss. Regardless of which technology is used, there is clear need for scaling up the infrastructure and human resources.

In addition, even as the technologies are being developed, there are no proven business models. Therefore, deployment will be CHALLENGING.

Breakthrough 40: Difficulty of deployment



41 Affordable (less than $50) smartphones that support full-fledged internet services and need limited electricity to charge

To be digitally included, low-income populations in developing countries need a fundamentally different set of ICT tools and services, compared with their counterparts in industrialized countries. These services will vary between user segments, as will language and other aspects of information sharing and service delivery.

The ideal device for accessing these services must accommodate a high degree of customizability and should be able to access services and rich information that can be delivered only over the internet. Only smartphones, rather than basic or feature phones, have the platform capabilities to accommodate this.

Access to affordable smartphones will create a virtuous cycle in developing countries—much like the creation of the Worldwide Web did in industrialized countries—by dramatically increasing users' access to many different types of services. This, in turn, will lead to a jump in the sources and types of available applications and information.

Low income users often cannot afford even basic phones. For example, even in South Africa, a middle-income country, fewer than 40 percent of rural consumers own phones. Smartphones, currently costing anywhere from three to 20 times as much, are not a realistic option. It stands to reason, therefore, that smartphones will have to cost considerably less than $50 (the current retail price of the average basic phone) to be affordable.

The biggest challenge in reducing the cost of smartphones is that there are many components and the cost, instead of being concentrated among a few, is fragmented across many components.

Recently, there have been a number of announcements about affordable smartphones. The huge demand for low cost smartphones has driven innovators to produce basic smartphones at the lowest possible cost, such as approximately $25 for a 2G enabled smartphone.

Current State

Development Stage: In-Market Large Scale

Deployment: Feasible

Associated 50BT Chapters

Digital Inclusion

SDG Alignment

Impact

New Income Generated (# of People)

<1M 10M+ 100M+ 1B+

Improved Quality of Life (# of People)

<1M 10M+ 100M+ 1B+

Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- **Attractive for emerging markets (lower profits)**
- Emerging markets potential; requires derisking (sustainable)
- Non-commercial (unprofitable)

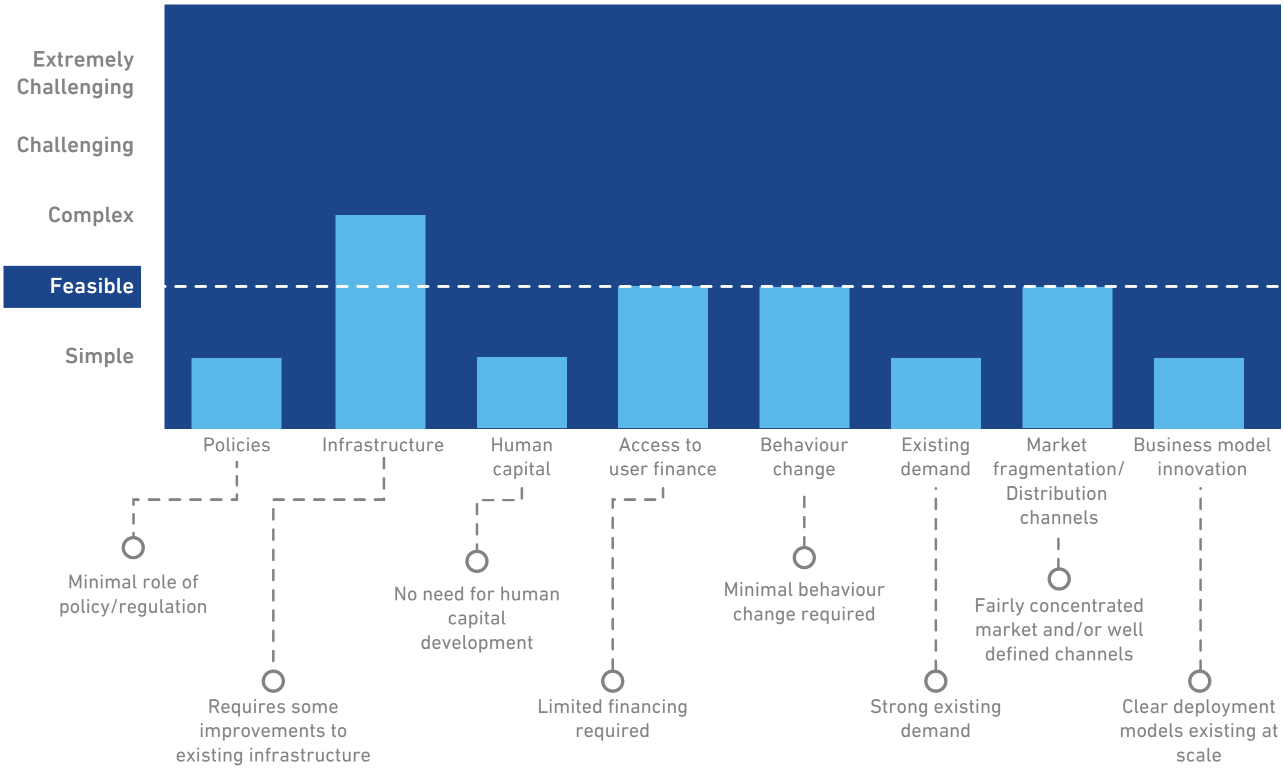
These innovations have drastically improved access to smartphones and thereby internet connectivity. As of 2018 there are close to 2.8 billion people who own a smartphone, and almost 61 percent of these users have access to the internet. These numbers are expected to grow by three to four percent every year.

Google's open-interface Android operating system, combined with increased modularization of the underlying hardware, has been a significant driver of the proliferation of such cheaper devices. Also, prices for key components like flash memory and lithium-ion batteries are falling steeply.

As they are introduced, we do not anticipate major deployment challenges, given the dramatic increases in market penetration of mobile phones. Complementary services, such as broadband coverage, data rates and mobile apps, will influence deployment, as will access to electricity to charge the devices.

All in all, there appears to be a very strong market pull for affordable smartphones. Therefore, we believe deployment will likely be FEASIBLE.

Breakthrough 41: Difficulty of deployment



42 Productized biometric ID systems, linking birth registry, land title registry, financial services, education history, medical history, and other information critical for ICT enabled services

Individuals born in industrialized countries have formal IDs, which are linked to a range of services vital to their wellbeing and empowerment such as birth registries, passport agencies and health care services. This system ensures that all citizens are counted, that their voices are heard and that they receive the public services they are entitled to.

While some developing countries have systems for issuing IDs for their citizens, these are not mandatory. As a result, these IDs are not issued until applied for, nor are they used widely, especially in rural areas. In the absence of IDs for individuals and businesses, and in the absence of a system of services linked to IDs, citizens of those countries continue to live in informal economies. They cannot easily establish citizenship or legal title of land or property and cannot access loans and other formal mechanisms of finance.

Furthermore, if repressive governments so wish, the fact that these citizens ever even existed can be denied. In other words, the absence of formal IDs is a fundamental barrier to economic and human development.

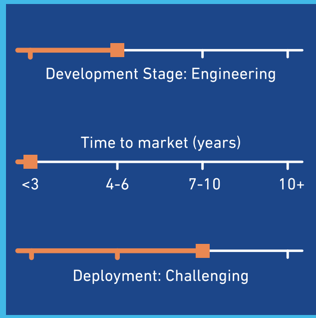
Recognizing the importance of IDs, and the challenges faced by the very poor in verifying their identity, several developing countries have begun bootstrapping effective ID systems. India's Aadhar identification system, for example, is a 12-digit unique identity number that can be obtained by residents of India based on their biometric and demographic data.

Aadhar has now registered around 1 billion Indian citizens making it the largest such database in the world. While biometric sensors and data management systems are used for health records, land registry and other applications, there is still no integrated systems that tie, for example, a unique biometric identifier to a GPS-mapped land parceling and registry system, nor are there systems that link someone's educational or health histories to their ID.

While all the components are already available, creating robust, integrated, productized ID systems will take considerable work. Given the initiatives underway in countries like India and Rwanda, it is likely that a reasonably integrated system will be in place within the next three years.

The challenge will be in creating a productized system of software components that integrates digitally-enabled services across multiple sectors, and can be replicated by other countries. A relevant emerging example of a digital ID system is ID2020, a public-private partnership that uses blockchain and distributed ledger technology to provide digital identity for the displaced.

Current State

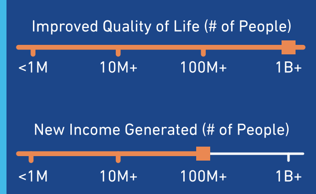


Associated 50BT Chapters

Digital Inclusion

SDG Alignment

Impact



Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- Emerging markets potential; requires derisking (sustainable)
- **Non-commercial (unprofitable)**

It is important to note that there are serious and legitimate concerns about mandatory ID systems, and about biometric IDs in particular. Digitized systems make it possible for governments and other powerful parties to easily access large volumes of information about citizens and communities. This opens the door for easy abuse of information.

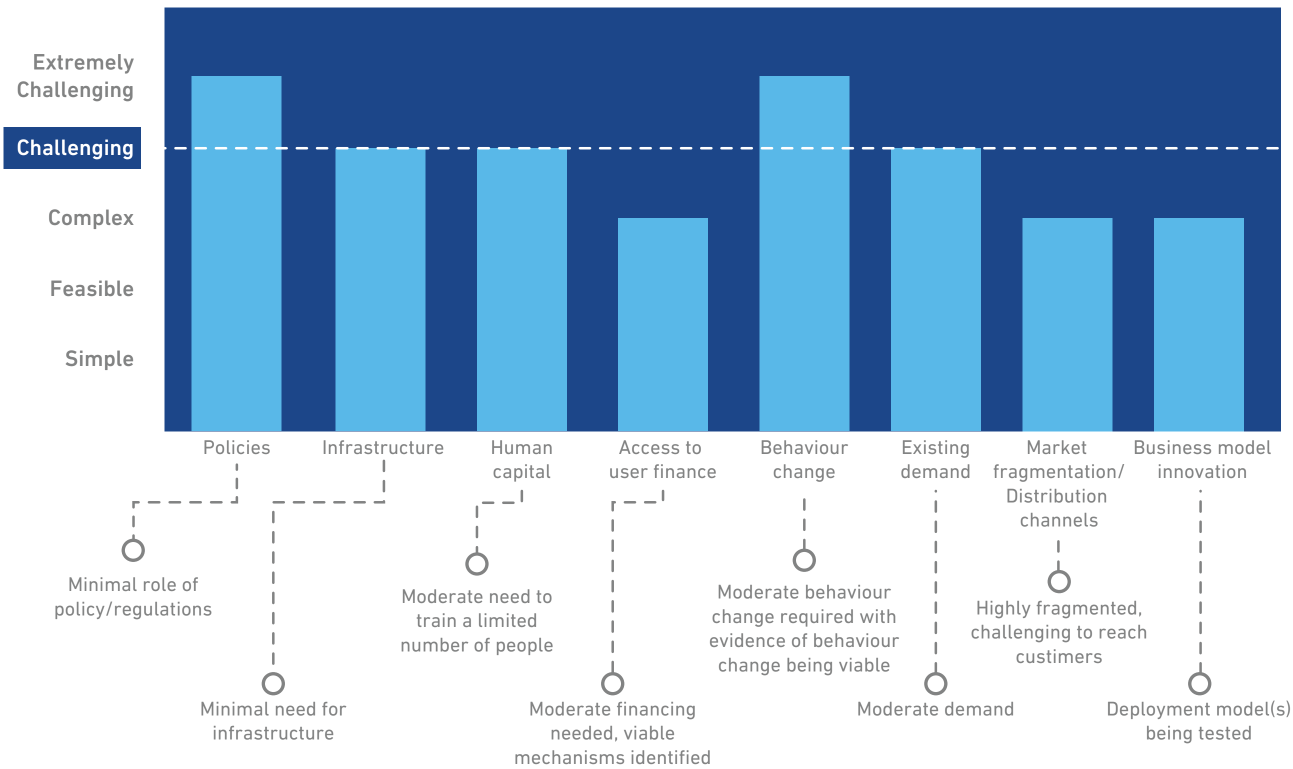
By enabling surveillance of targeted individuals and communities, biometric ID systems can aid the creation and maintenance of authoritarian states. The more integrated the ID systems are with other aspects of life, the easier surveillance becomes. One can imagine the dangers of a system which has facial recognition, GPS-based tracking of mobile phones and any data on ethnic or religious identity. Integration of personal information also exposes people to hacking and theft of personal information.

It will be important that stringent international standards with respect to protection of privacy and civil rights, as well as for data security, are in place before such systems are deployed. Most industrialized countries currently lack comprehensive laws about biometric data, and many developing countries do not meet international criteria for hosting and protecting data.

Beyond the significant regulatory constraints, a national biometric ID system will require the installation of large numbers of biometric sensors, other hardware and related software, which will link the various system components.

It will also take considerable behavior change to implement widely across large and diverse populations. Finally, the logistical challenges involved in reaching remote populations will be daunting. Considering these hurdles, deployment will be CHALLENGING.

Breakthrough 42: Difficulty of deployment



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ACCESS TO ENERGY

Energy is broadly defined as the capacity for doing work.

It may exist in various forms such as potential, kinetic, thermal, electrical, chemical and nuclear. All animals, including humans, require "endosomatic" energy use within their bodies to drive life processes like respiration and reproduction.

Endosomatic energy is released in the body by the metabolism of food, and for adult humans is roughly 2000 kilocalories per day (equivalent to 8.4 megajoules per day, or about 100 watts of continuous power) (FAO, 2001). Children and the elderly need less food energy than adults, and women generally need less food energy than men. Ensuring food supply for sufficient endosomatic energy is discussed in detail in the Food Security and Agriculture chapter.

In contrast to endosomatic energy used within living bodies, "exosomatic" energy is used outside of the body and is the focus of this chapter. Although some animals like cold-blooded reptiles use limited amounts of exosomatic energy by basking in sunlight on cold days, the use of large amounts of exosomatic energy is a defining characteristic of the human species.

Fossil evidence suggests that early hominids used fire to cook food as early as 1.9 million years ago, and controlled use of fire appears in the archaeological record about 400,000 years ago (Bowman, et al., 2009).

Beginning about 50,000 to 100,000 years ago, fire has been routinely used by humans for domestic purposes.

The controlled burning of wood and other biomass has benefited humans in many ways, including protection from predators, warmth in cold climates, modification of ecosystems to improve hunting and gathering, and cooking of foods (which then require less endosomatic energy for digestion).

Over time, people began exploiting other forms of energy, such as using domesticated animals to pull carts and plows, and harnessing the power of moving water and wind for small-scale industrial processing.

Major advances occurred in the 18th century when Thomas Newcomen and James Watt developed practical steam engines that converted wood or coal fuels into mechanical energy. This sparked the Industrial Revolution, powered by abundant coal that was mined in increasingly greater quantities.

Modern internal combustion engines powered by refined oil fuels were developed in the 19th century by Nikolaus Otto, Karl Benz and Rudolf Diesel, which led to the automobile industry and great expansion of oil usage. Natural gas was increasingly exploited in the 20th century to provide heat for industrial processes and electricity generation.

Exhibit 1 shows global exosomatic primary energy use since 1800, which for the last century is increasingly dominated by the three fossil fuels: coal, oil and natural gas.

Use of traditional biofuels has continued at roughly the same level since 1800. Now comprising roughly seven percent of total global primary energy, these biofuels are mainly used for cooking in developing countries.

During the last several decades, a growing amount of modern non-fossil energy is being used, comprising of nuclear energy and modern renewables such as hydro, solar and wind power.

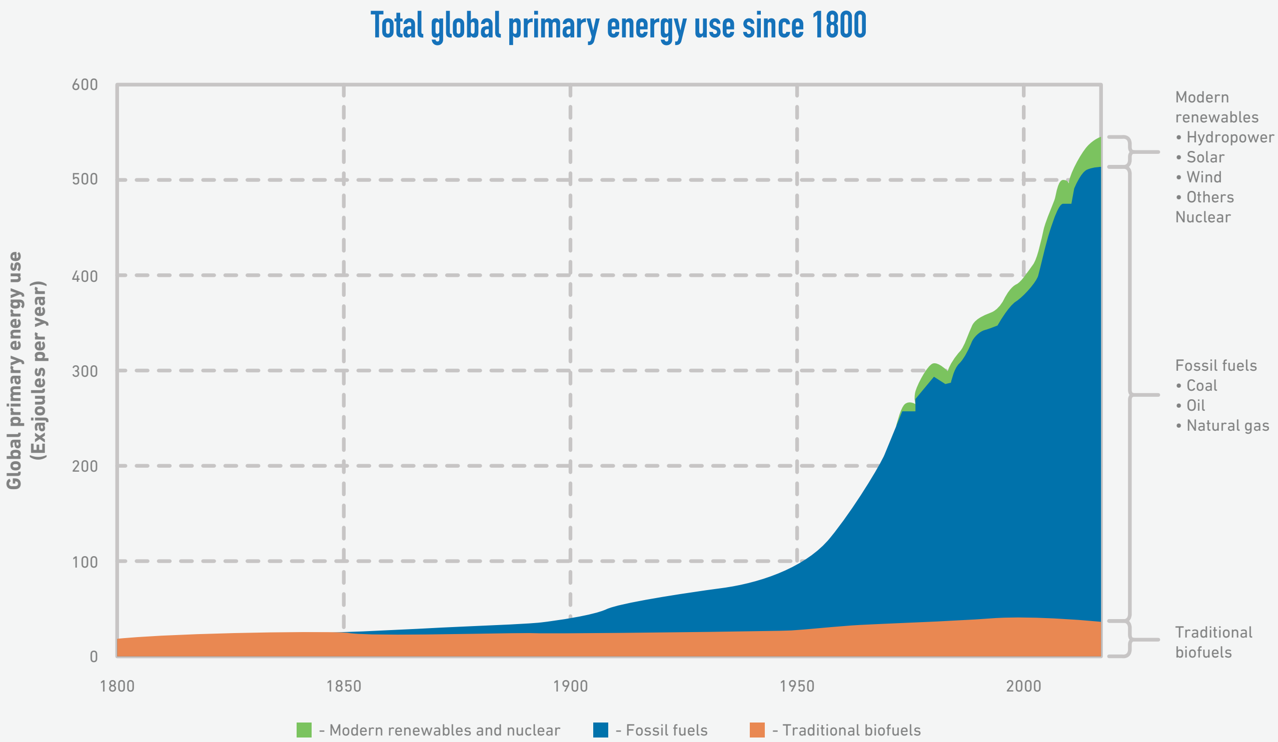

Exhibit 1: Global primary energy use is dominated by fossil fuels. (Source: Smil, 2017; BP, 2018)

There is a very strong correlation between energy use and economic activity, because energy is needed to drive the production and distribution of goods. The relationship between the world's primary energy use and gross domestic product (GDP) has been almost linear during recent decades (**Exhibit 2**).

The notion that technological progress may decouple economic growth from natural resource use is appealing, as it would allow unlimited economic expansion with finite energy use and environmental impacts (UNEP, 2011).

Nevertheless, empirical evidence to date shows such decoupling is not occurring in practice (**Exhibit 2** and Parrique, et al., 2019). Furthermore, physics-based theory suggests it is generally implausible (Baumgärtner & Arons, 2003; Ward, et al., 2016).

This has important implications for global development prospects, because conventional economic development measured by GDP will require vast continued expansion of energy supplies. Development practitioners may use other metrics to inform energy-related decisions, such as the Human Development Index and the Genuine Progress Indicator, which more accurately reflect the goals of global humanitarian efforts (Kubiszewski, et al., 2013).

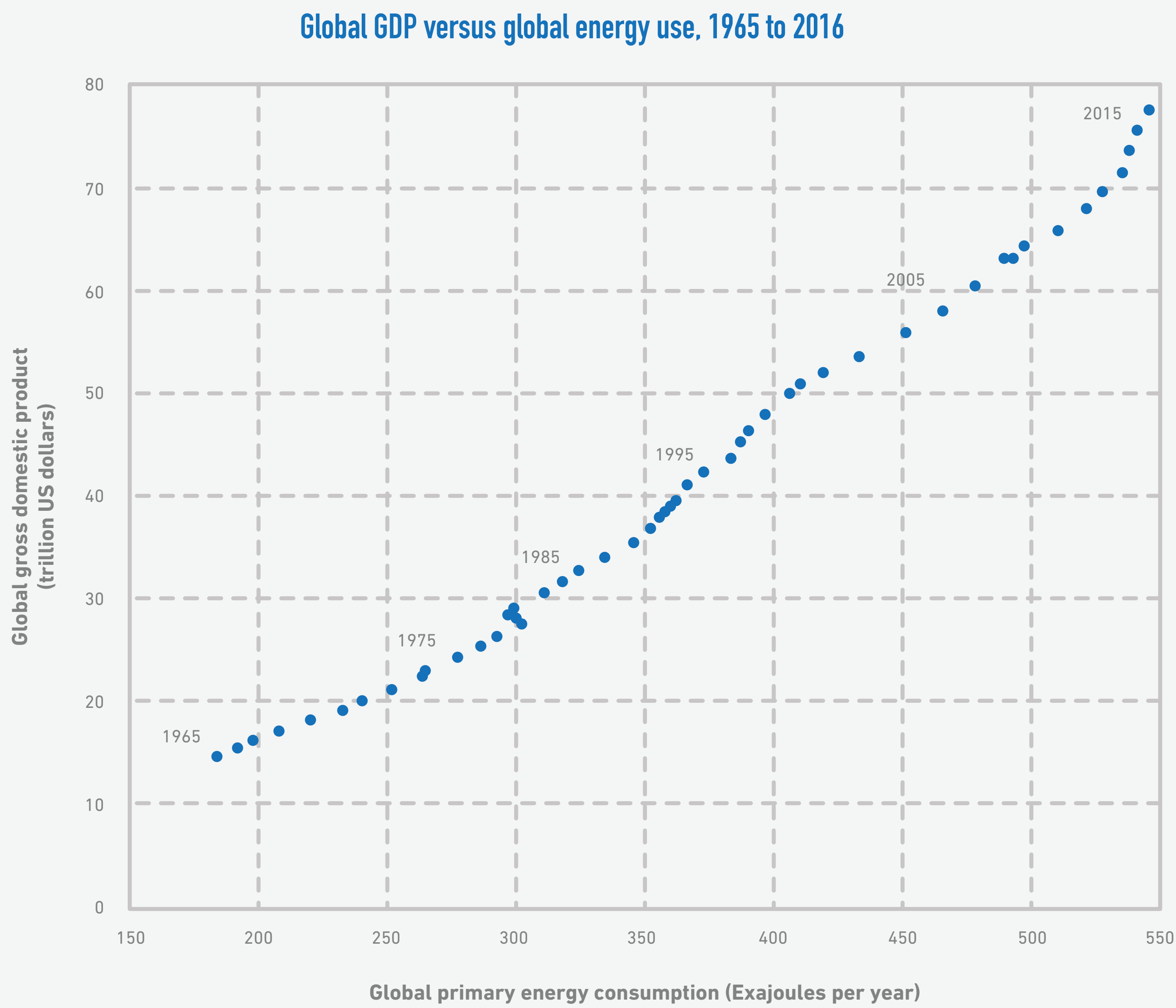

Exhibit 2: There is a strong correlation between energy use and economic production. (Source: energy data from Smil, 2017 and BP, 2018; GDP data in constant 2010 U.S. dollars from World Bank, 2018)

Exhibit 3 shows the global primary energy use on a per capita basis. Per capita energy use increased steadily for over a century until the 1970s, as growth in total energy use exceeded population growth.

Since the 1970s, the human population has risen at about the same pace as energy use, and per capita energy use has remained fairly constant at about 70 gigajoules per person per year.

Current global average per capita exosomatic energy use is about 24 times greater than typical human endosomatic energy use.[1]

This can be interpreted as broadly equivalent to the work of 24 human servants laboring full-time for each person on the planet.

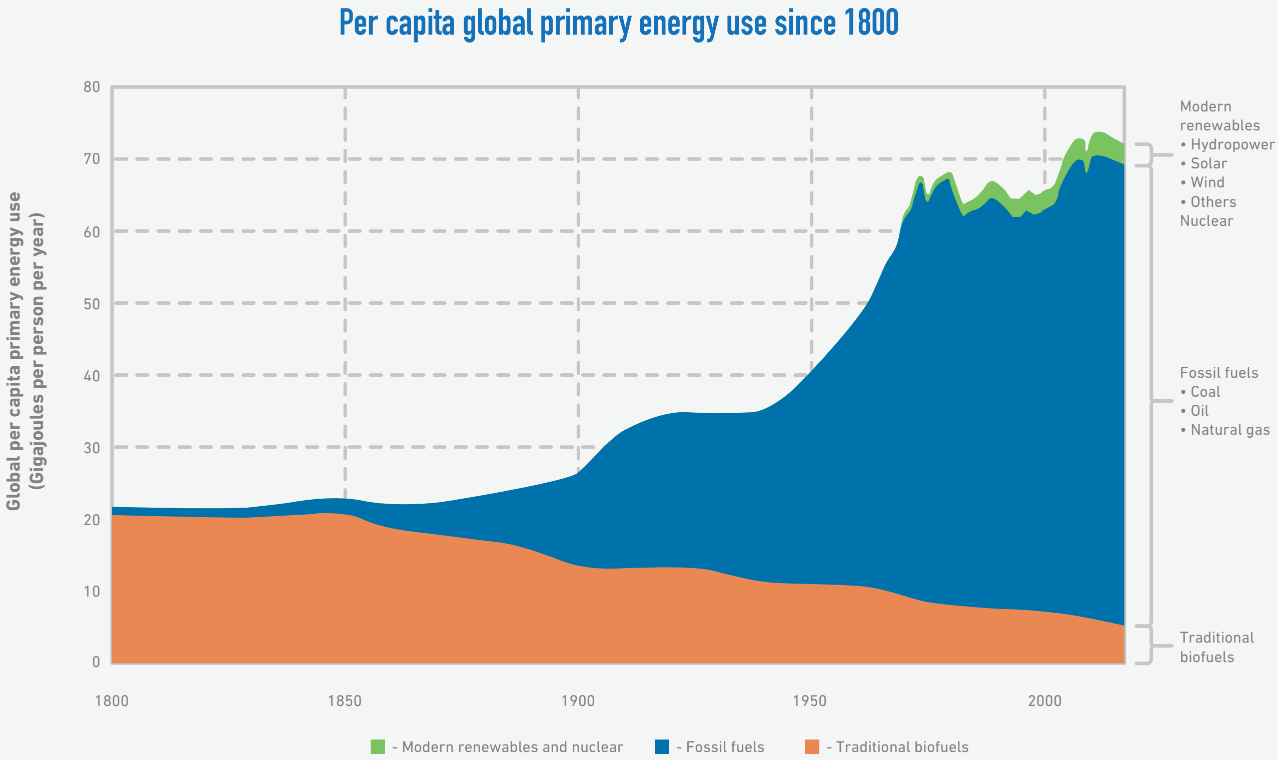

Exhibit 3: Per capita global primary energy use has stagnated since the 1970s, as population and energy use both increase at roughly the same pace. (Source: energy data from Smil, 2017 and BP, 2018; pre-1950 population data from US Census Bureau, 2018; post-1950 population data from UN, 2017)

[1]Human metabolism is about 2000 kilocalories per day, or 97 watts. Global per capita primary energy use is about 73 gigajoules per year, or 2300 watts.

Energy use varies widely across the world, with some people using vastly more energy than others. **Exhibit 4** shows total primary energy use by country and region. Four countries (China, United States, India and Russia) are responsible for almost half of all global primary energy use.

All countries in Africa combined use about six percent of total global primary energy. **Exhibit 5** shows per capita primary energy use for select countries. People in the United States use about 282 gigajoules per capita per year, while those in Bangladesh use only about 10 gigajoules per capita per year.

Comparing to typical human endosomatic energy use, resident of the United States benefit from the equivalent of more than 90 full-time energy servants, while Bangladesh residents use the energy equivalent of only three servants.

In addition to this disparity in average energy use by countries, there is also great disparity within countries, with wealthier population segments using more energy than poorer segments.

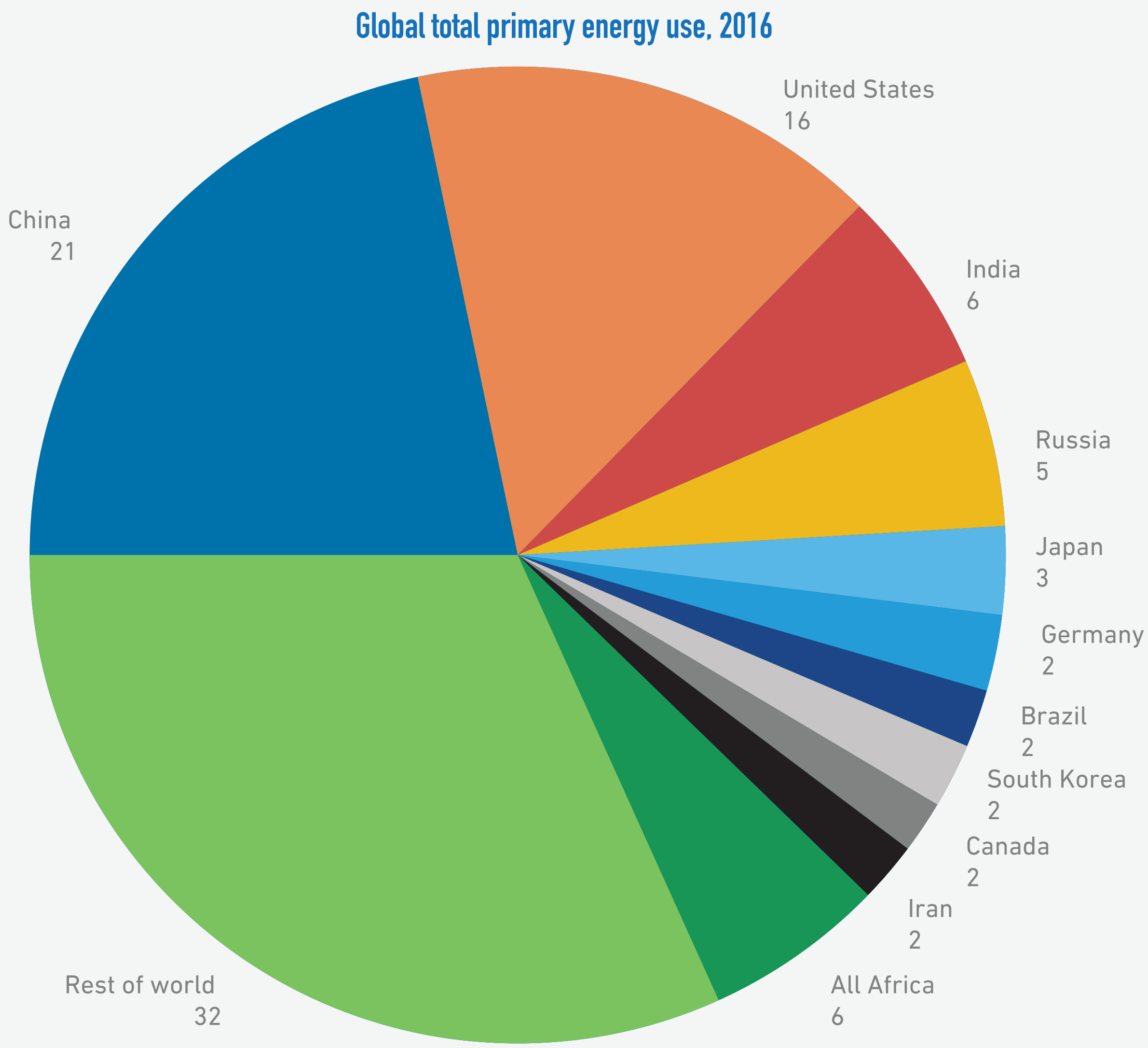

Exhibit 4: China uses more energy than any other country, followed by the United States and India. All African countries in total use only six percent of the world's primary energy supply. (Source: IEA, 2018)

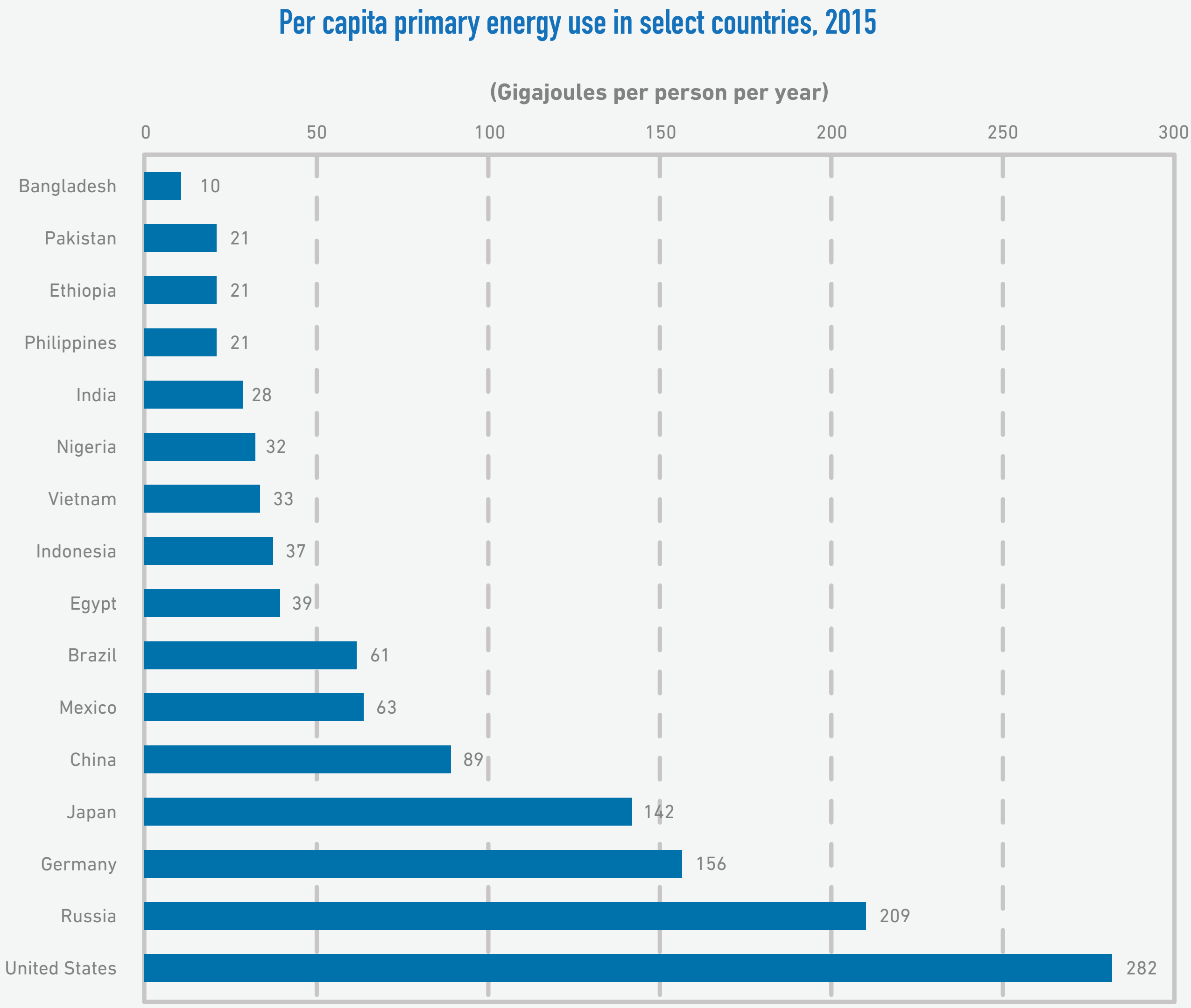

Exhibit 5: There is wide variation in per capita energy use between countries. (Source: energy data from OECD, 2018; population data from UN, 2017)

There is a non-linear relationship between a country's per capita energy use and its level of human development (**Exhibit 6**). As a country's per capita energy use increases up to about 100 gigajoules per person per year, the country's Human Development Index (HDI) tends to increase strongly.

Additional energy use, however, brings limited further improvement in human development. This is in contrast to the linear relation between energy use and GDP (**Exhibit 2**), reinforcing the unsuitability of GDP as an indicator of human development success (Kubiszewski, et al., 2013).

This non-linear relationship has two important energy-related implications for the global development community.

First, development efforts should focus on increasing energy access for poorer populations, to improve their wellbeing.

Second, more affluent populations should be able to intelligently reduce their energy use without impacting their wellbeing.

Per capita energy use versus Human Development Index, 2015

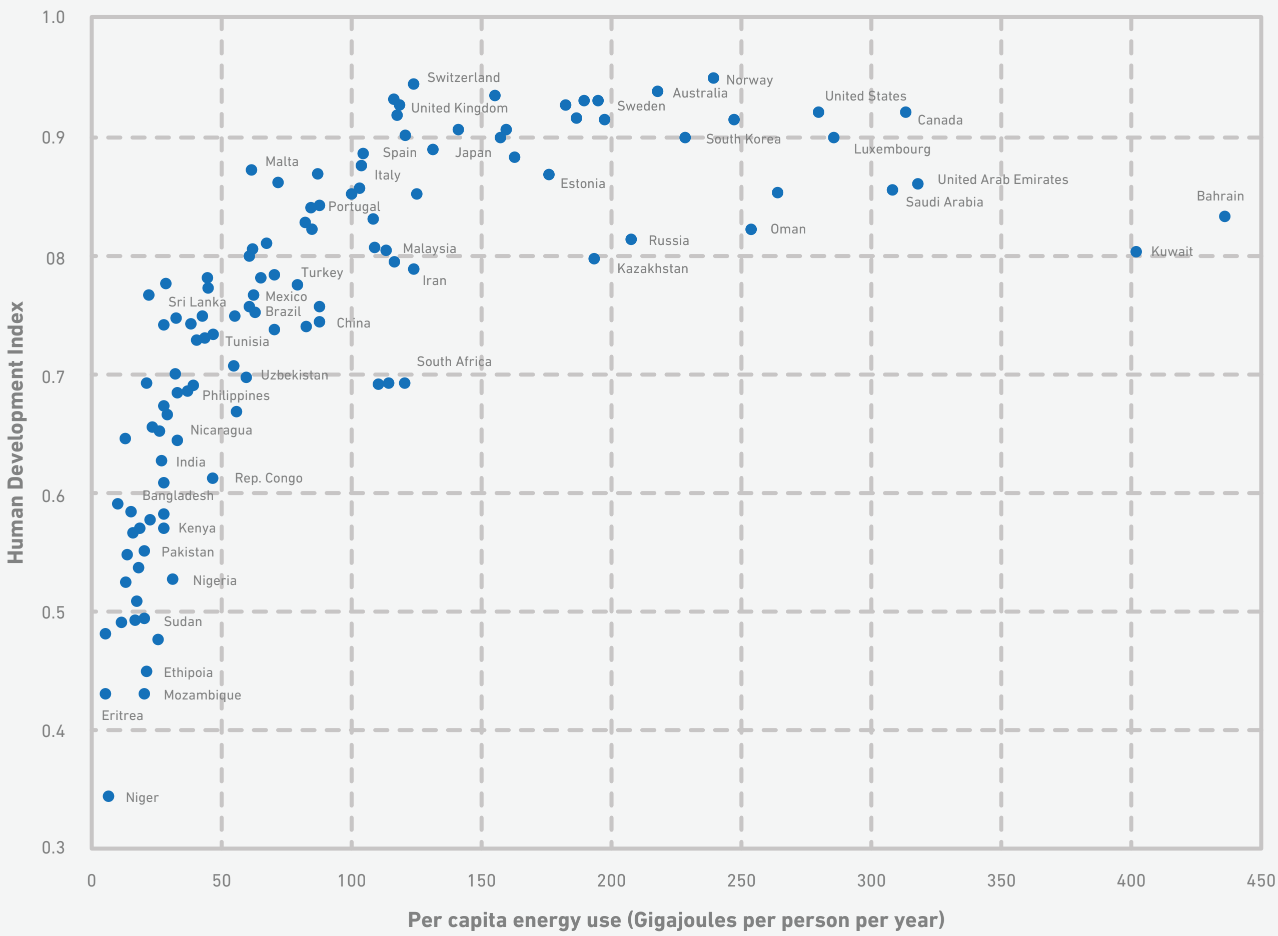

Exhibit 5: Human Development Index increases strongly as per capita energy use increases, up to about 100 gigajoules per person per year. As energy use increases further, there is little additional increase in human development. (Source: energy data from OECD, 2018; population data from UN, 2017, HDI data from UNDP, 2018)

More than 80 percent of current global primary energy supply is provided by fossil fuels (**Exhibit 1**), which are a leading cause of global climate change (see the Resilience to Global Change chapter for further information).

About seven percent of current energy supply is provided by traditional biofuels, mainly used in developing countries for household cooking. These biofuels cause significant health impacts, described in detail in the following section on Clean Cookstoves. The remaining energy supply is provided by a range of modern technologies for electricity generation including hydro, nuclear, solar and wind power.

Electricity is a flexible and versatile form of energy, and global electricity generation has increased strongly in recent decades (**Exhibit 7**). The importance of electricity to human development is discussed in the following section on Access to Electricity.

Globally, about two-thirds of all electricity is produced by burning fossil fuels, primarily coal and natural gas (IEA, 2018). Hydropower is the largest single source of non-fossil electricity, providing about 16 percent of global electricity.

From its early days in the 1880s at Niagara Falls, North America, hydropower facilities have grown to include the colossal Three Gorges Dam in China. Nevertheless, hydropower has been criticized for displacing communities, disrupting river ecology and impacting water quality (Moran, et al., 2018).

Nuclear electricity production expanded rapidly in the 1970s and 1980s, but has faced growing concerns regarding its cost and safety, in part due to high-profile accidents in Ukraine in 1986 and Japan in 2011. Nuclear energy now provides about 10 percent of global electricity.

Global electricity generation, 1971 to 2016

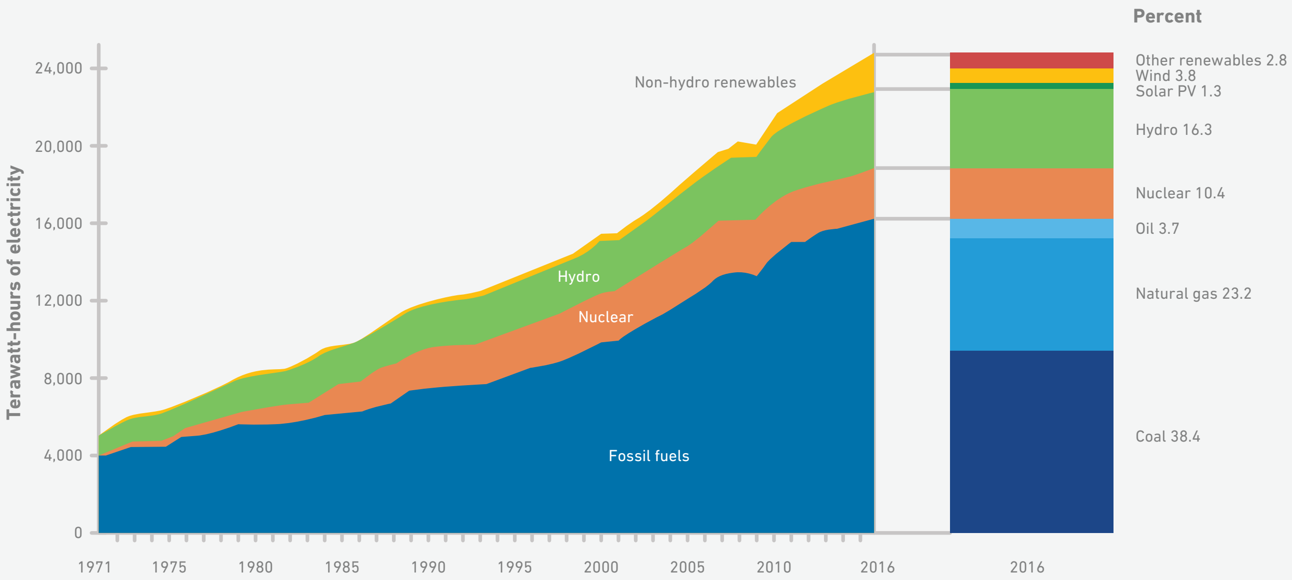

Exhibit 7: Global electricity generation has increased fourfold since 1971. Most electricity is produced by burning fossil fuels, especially coal and natural gas. Hydropower and nuclear also produce a significant share of electricity. Modern renewables, such as wind and solar power, provide a small but growing share of electricity. (Source: IEA, 2018)

Modern renewables such as wind, solar, geothermal and tidal power provide a small but growing share of electricity supply. These electricity sources generally have better environmental performance, across a variety of indicators, compared to electricity from fossil fuels (Masanet, et al., 2013).

Expectations are high, among policymakers as well as the general public, that modern renewable energy sources will rapidly scale up to provide clean, sustainable energy for developing countries.

Nevertheless, energy transitions have historically been slow processes, taking many decades for new energy sources to expand and provide a significant share of total energy use (**Exhibit 8**).

Furthermore, new forms of energy rarely replace older forms, but are instead typically used in conjunction with existing energy supplies.

Major infrastructure is required to capture, convert and distribute significant amounts of usable energy, particularly for intermittent, non-concentrated sources like solar and wind that need extensive collection areas.

Such infrastructure is now being built up, aided by technological advances and rapidly falling costs for capture and storage of renewable energy.

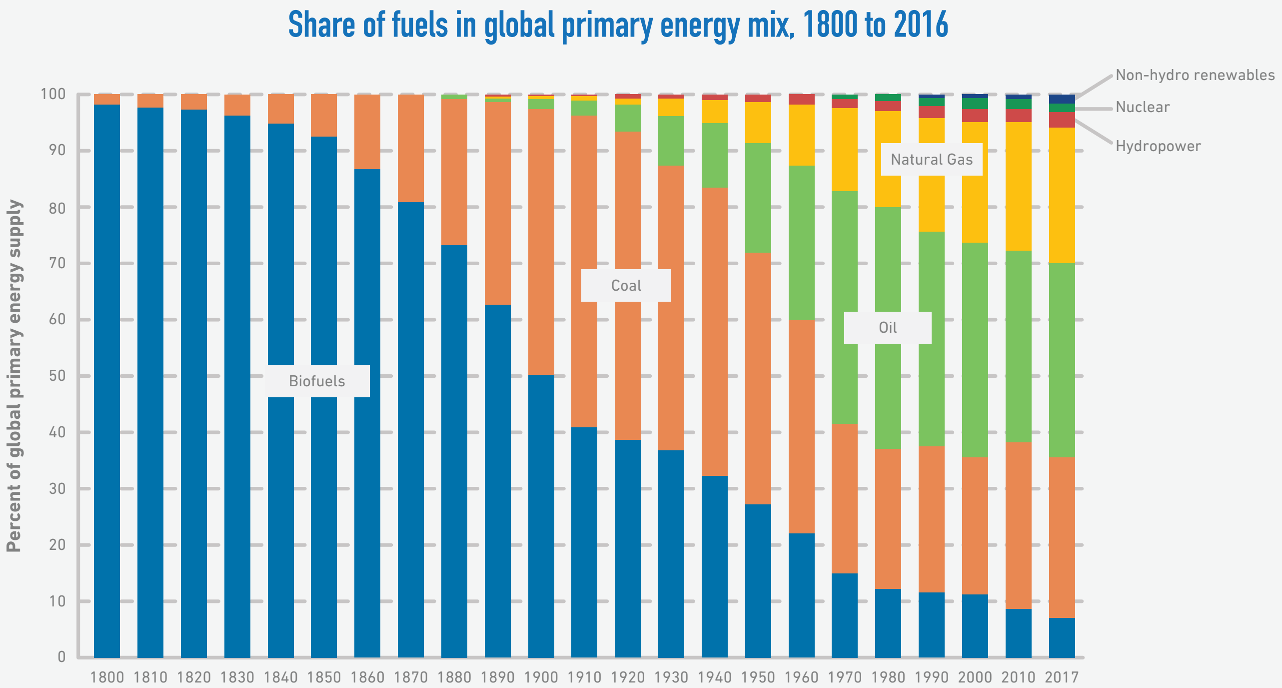

Exhibit 8: Energy transitions occur over time spans of decades to centuries. Clean, modern energy sources currently provide a minor share of global energy, but are expected to increase in scale in the future. (Source: Smil, 2017; BP, 2018)

The future of global energy is uncertain and will depend on many factors affecting both demand and supply. Important energy demand issues include the evolving end-uses of energy for household, industrial, transport, commercial and agricultural purposes, and how much energy efficiency gains can be realized in each sector.

While the supply of clean, renewable electricity is increasing, the limits to electrification of energy services is still unclear, such as in the transport and industrial sectors. There are also demographic uncertainties about regional populations and their economic means to access modern energy supplies like the replacement of traditional cooking fuels by clean fuels.

Important energy supply issues include the future of fossil fuel use, due to concerns about climate change and ambient air pollution, as well as geological resource depletion of high-quality fuels.

Continued use of traditional biofuel cookstoves will depend not only on access to alternative fuels, but also on the sustainability of existing biomass resources. Furthermore, the rate and extent of scale-up of renewable energy sources is quite uncertain, due to potential limits on manufacturing and supply chains.

These include constraints on critical minerals and metals such as lithium, cobalt and vanadium that are used for modern energy capture and storage technologies.

The following sections address in detail two important aspects of energy that are specific to global human development efforts: achieving basic electrification of households and communities, and accessing clean and affordable sources of energy for household cooking.

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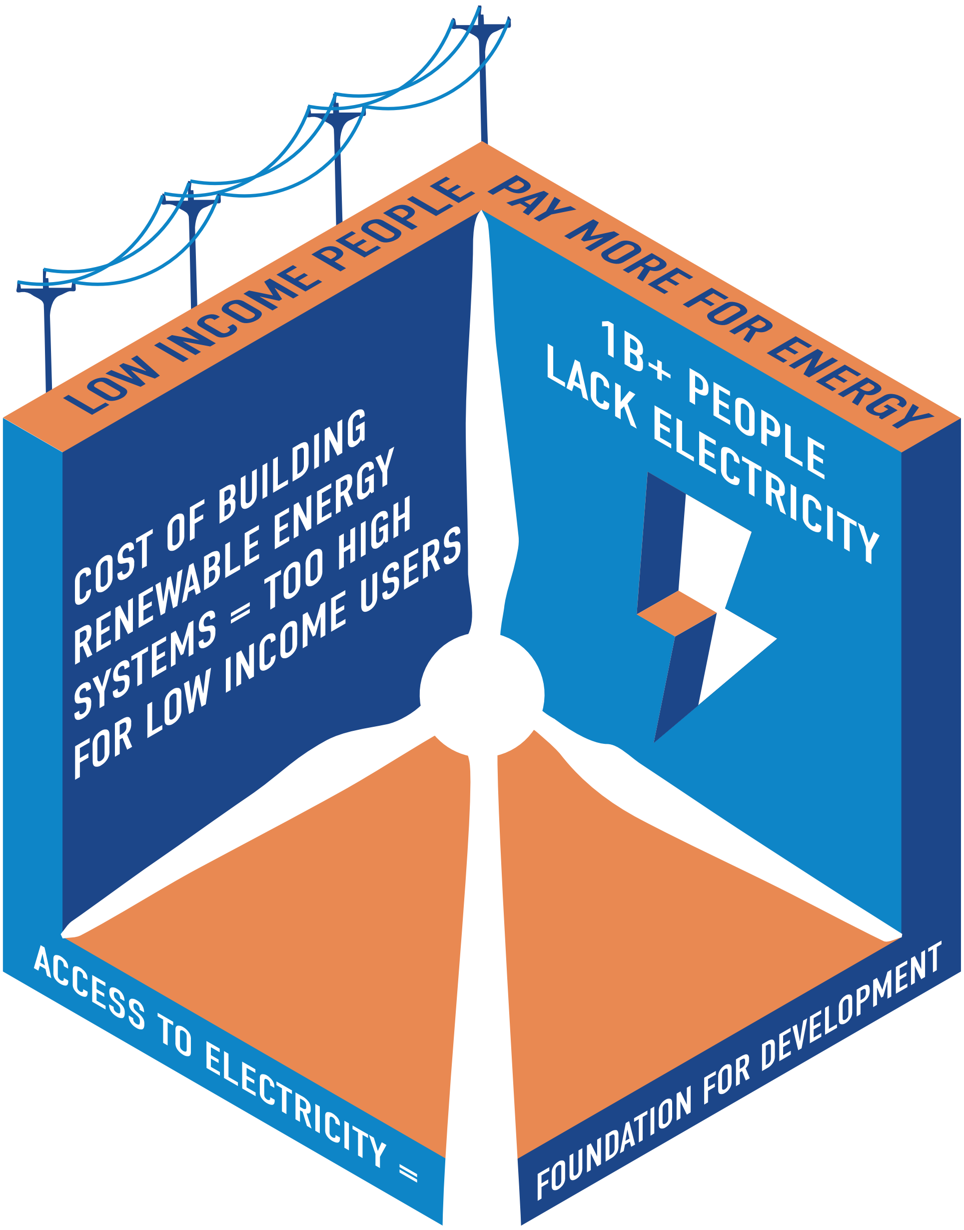


ACCESS TO ELECTRICITY

INTRODUCTION

Access to electricity is fundamental to every aspect of human development. More than one billion people, concentrated mostly in rural Asia and sub-Saharan Africa, lack meaningful access to electricity.

The problem is expected to worsen in sub-Saharan Africa as population growth outpaces the increase in electrification. Even as efforts to improve electrification continue, it is important to recognize that it is not electricity itself that changes lives, but rather, what people are able to do with access to electricity.

In recent years there has been an increase in proliferation of 'pre-electrification' appliances like solar-powered lights and mobile phone chargers. While this has some benefits, low-income households need a number of other appliances, such as refrigerators, televisions (or other ICT devices), fans and tools for improving workplace productivity to improve their overall quality of life. Nevertheless, appliances currently on the market are too expensive for low-income populations, and even if they were affordable, the electricity they consume costs much more than these users can afford.

Two immediate questions emerge when considering access to electricity: How is the electricity generated, and how is the electricity delivered to the user? Globally, the most common form of electricity is produced via centralized fossil fuel-fired generation and delivered to users through a hierarchical grid system.

Much of developing Asia is now gaining access to electricity in this manner. However, there are many people living in large parts of rural Africa and some parts of rural South Asia that are not expected to be reached by grid extension. These populations will need decentralized generation and distribution to gain access to electricity.

Increasingly, renewable energy sources like solar, wind and biomass are the most cost-effective and environmentally sustainable energy sources for decentralized mini-grids. Of these, solar power is the most widely available renewable energy resource.

Currently, solar photovoltaic (PV) mini-grids are relatively difficult and expensive to install and operate, given the resources available in low-income rural populations. While supportive policies and financing mechanisms will need to be a core part of any solution, three technological breakthroughs can improve the lives of low-income rural people across South Asia and sub-Saharan Africa.

- Breakthrough 43: A standardized, solar mini-grid system that makes it simpler, cheaper and faster to set up and operate mini-grids
- Breakthrough 44: Appliances for household use and income generation that are significantly more affordable and energy-efficient than those on the market
- Breakthrough 45: New electricity storage technologies that can be used for decentralized mini-grids, which provide improved performance at a cost approaching that of lead-acid batteries

Electricity is the most versatile way of consuming energy. It can be easily converted to multiple forms of energy for a variety of needs, such as heat, light and mechanical energy. It is relatively non-polluting and loss-free at the point of use, and its use can be controlled easily with the flick of a switch. This makes it ideal for powering appliances for activities and services that are central to human wellbeing, comfort and productivity.

CORE FACTS AND ANALYSIS

1. Access to electricity is a foundation for achieving many aspects of human development

Electricity is vital for human development, but low-income countries and populations do not have enough access to it. The lack of access to electricity forms a vicious cycle with development (**Exhibit 1**). On one hand, low-income countries are not able to invest in the infrastructure to generate and distribute electricity to their citizens, especially in remote areas. On the other hand, lack of access to electricity is a fundamental barrier to human development. These barriers exist in every fundamental aspect of development.

Health

Without electrical power, health facilities cannot operate medical devices, refrigerate temperature-sensitive pharmaceuticals and vaccines, or even light facilities to provide care at night. An estimated one billion people use health facilities that are not electrified (Practical Action, 2014).

Education

Children in low-income families do not get access to quality education because their schools cannot operate computers, access the internet, or operate laboratories for them to learn in (even if they have computers and other equipment). Worse yet, many students do not have access to appropriate lighting at home in order to study after sunset.

Food security, agriculture and economic development

Smallholder farmers and agribusinesses cannot operate powered equipment to grow, preserve and process adequate food for their families, communities and countries. Similarly, small scale businesses in other sectors cannot operate even the equipment needed for offices and factories.

Gender equity

Women are disproportionately affected by the lack of electricity. The absence of appliances leads to significantly more manual household work for women. Without electricity for clean cooking and lighting, women suffer more from indoor air pollution. When outside their homes, women are also exposed to a greater risk of violence due to the absence of outdoor lighting. Similarly, they are at a greater disadvantage compared with men when it comes to operating manual equipment.

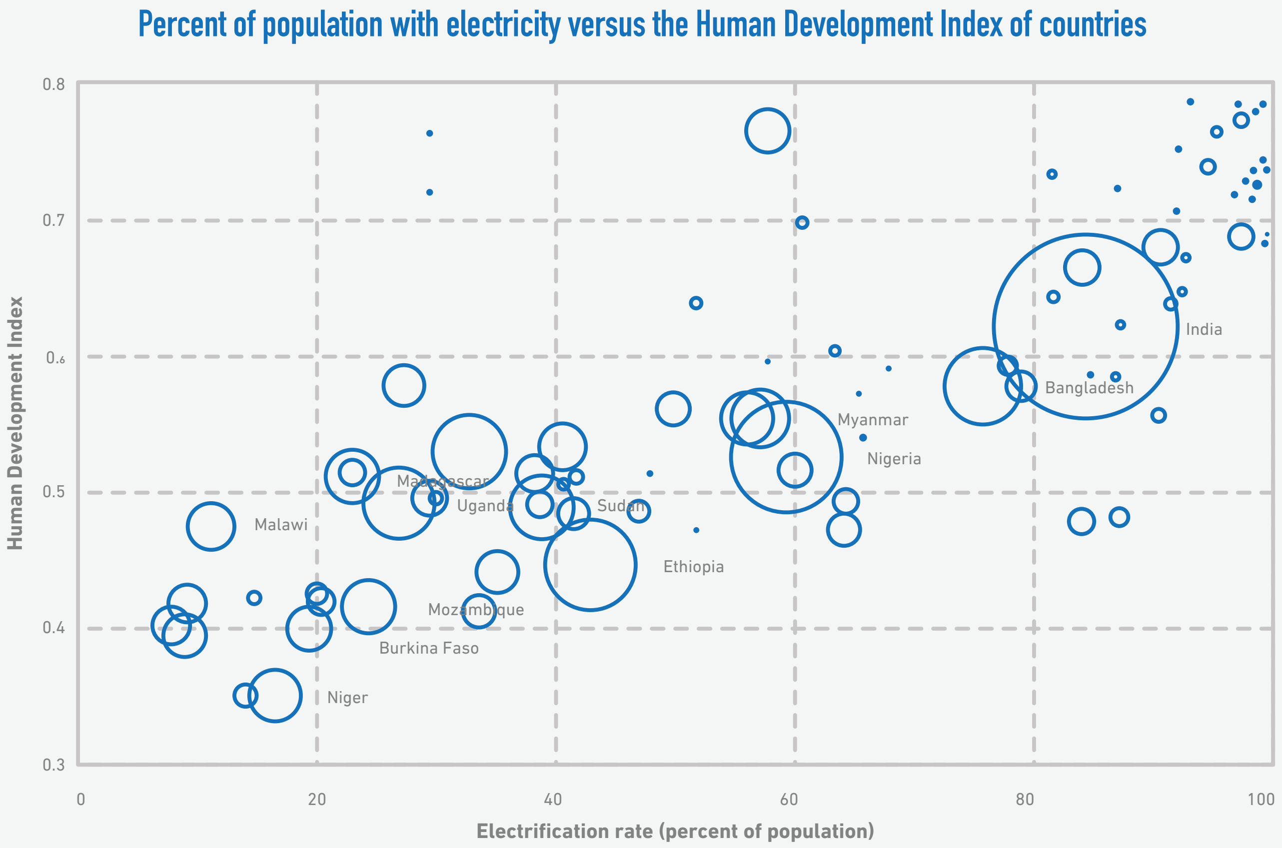


Exhibit 1: There is a strong and direct correlation between electricity access and human development. The size of the bubbles is proportional to the size of the countries' unelectrified population. (Source: ITT analysis based on 2016 electrification data from World Bank, 2018a; 2015 HDI data from UNDP, 2018; 2016 population data from UN, 2017)

2. More than one billion people lack electricity, mostly in rural South Asia and sub-Saharan Africa

Global progress is being made in electrification, with nearly 1.2 billion people having gained access since 2000. The number of people without access to electricity fell from 1.6 billion in the year 2000 to 1.1 billion people in 2016 (**Exhibit 2**).

Great progress has been made in developing Asia, where the number of those who lack access to electricity fell from more than one billion in 2000 to fewer than half a billion in 2016. Progress is uneven, however, and in sub-Saharan Africa there were more people without electricity in 2016 (590 million) than there were in 2000 (520 million).

There is a recent positive trend in sub-Saharan Africa, where electrification efforts have been outpacing population growth since 2014.

Despite the progress that has been made, 14 percent of the world's population still lacks access to electricity, 84 percent of whom live in rural areas. (IEA 2017a). According to estimates by the International Energy Agency, the number of people without access to electricity is projected to fall by 36 percent by 2030, despite an increase in the global population (**Exhibit 3**).

However, this still means that 674 million people (8 percent of the world's population) will be without access to electricity in 2030, 90 percent of whom will be in rural areas.

Population lacking access to electricity in different regions, 2000 to 2016

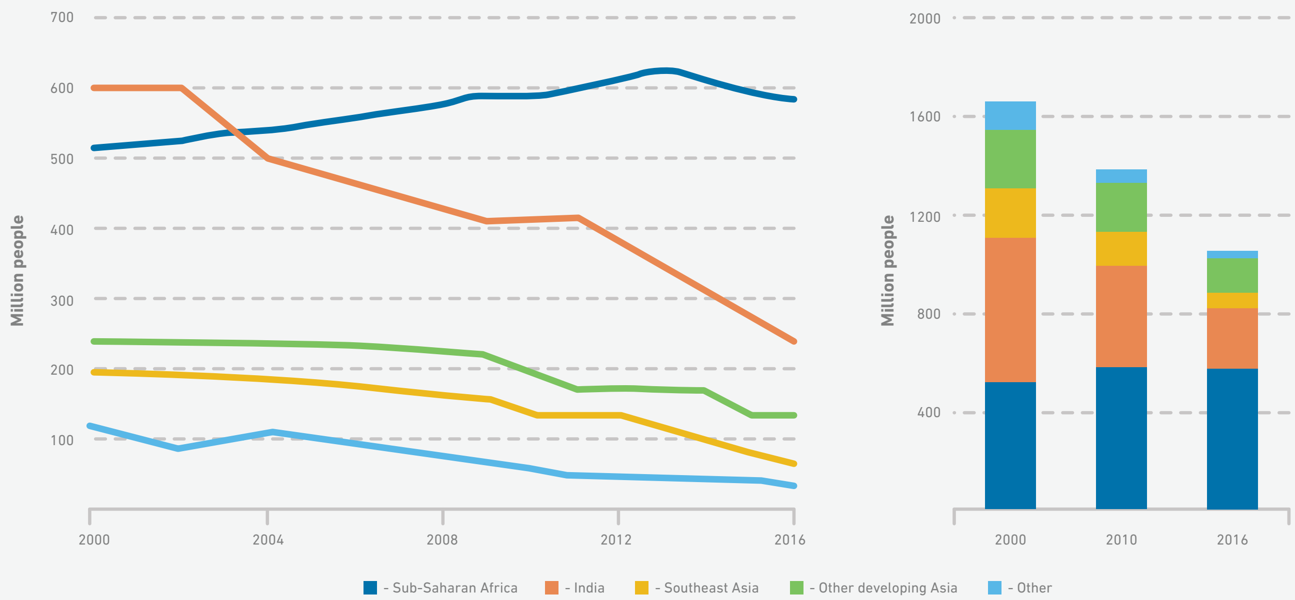


Exhibit 2: In recent decades great progress has been made in providing electricity access in Asia, particularly in India. Sub-Saharan Africa now encompasses the greatest population without access to electricity. (Source: IEA, 2017a)

Projections of electrification through 2030

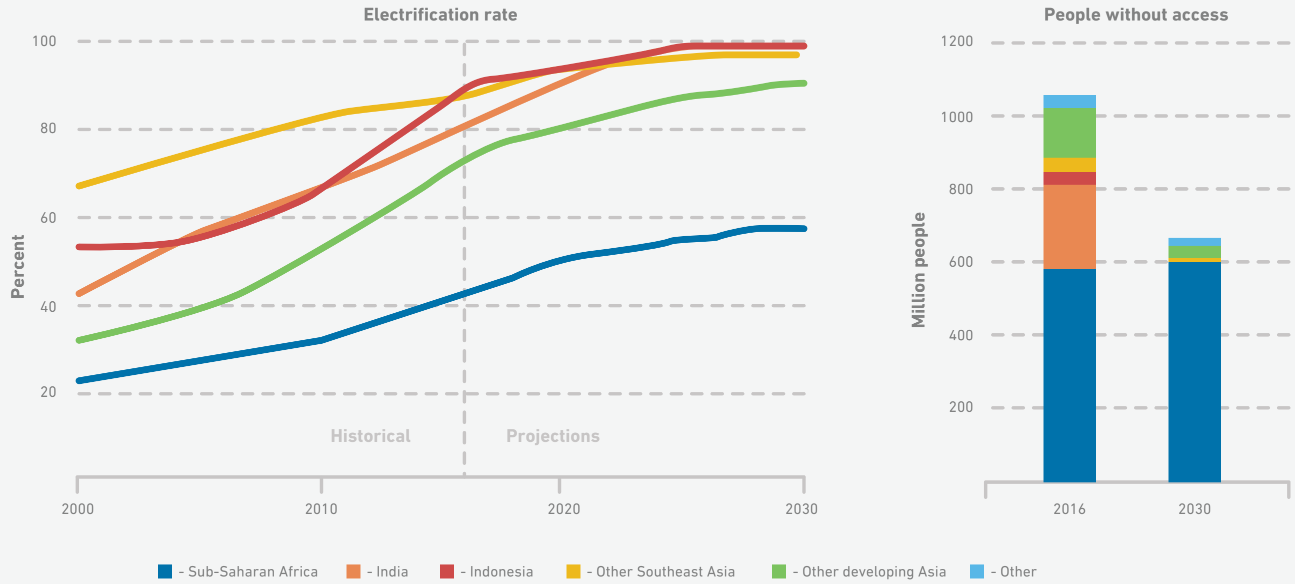


Exhibit 3: In the 'New Policies Scenario' of IEA, the overall access rate in developing countries is projected to increase from 82 percent today to 90 percent in 2030, and many countries in Asia, Latin America and the Middle East achieve or come close to achieving the target for universal electricity access by 2030. (Source: IEA, 2017a)

3. Percent of population with electricity versus the Human Development Index of countries

One unfortunate irony is that people who do not have access to electricity actually have to pay a much higher price per unit of energy—compared with wealthier segments of the population—when they use alternatives to electricity such as kerosene. Energy sources available to low-income populations often cost much more, on a per-output unit basis, than those available to higher-income populations.

For example, kerosene lamps are the norm for unelectrified populations, but cost 15 times more money per hour of operation than their LED counterparts, and cost 1500 times more to produce each lumen-hour of light (**Exhibit 4**). In recent years, however, rural households, even in poor areas, have started to replace their kerosene lamps with non-rechargeable dry-cell battery driven lamps and solar kits.

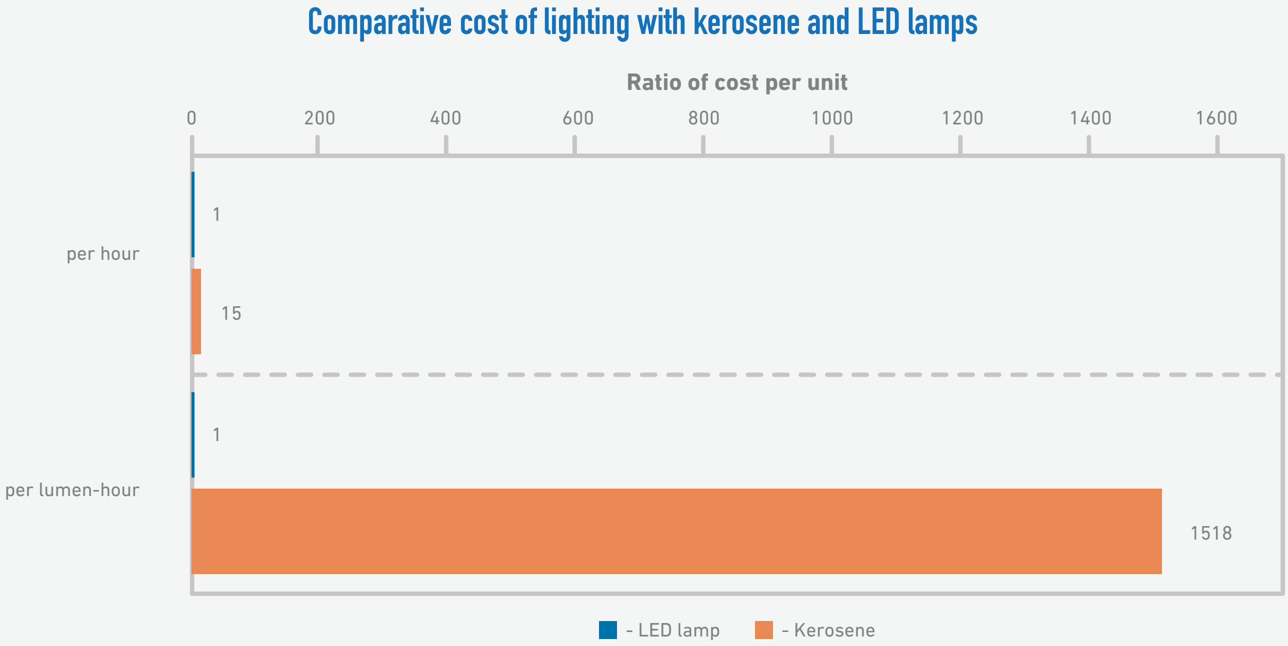


Exhibit 4: Cost of energy for a given amount of light, measured per hour of operation and per lumen-hour of light, using kerosene and LED lamps. (Source: ITT analysis[1])

[1]Based on Indian context: kerosene cost of INR 74 per liter, kerosene consumption of 10 ml per hour of single-wick lamp usage, electricity cost of INR 5 per kWh, electricity consumption of 0.01 kWh per hour of LED lamp usage, and lamp lumen output data from Mills (2003).

4. Electricity improves lives through its end uses, hence there is a need for productive appliances

Access to electricity has been defined differently depending on context. In some it has meant having a connection to the electricity grid, while in others it has meant reliable supply and being able to consume a minimum quantity of electricity.

However, to be meaningful for human development, access to electricity must be measured by the quality and range of electrical usage via appliances to improve quality of life and workplace productivity.

In other words, merely having an electrical connection is not helpful if the consumer does not have the necessary appliances, and if those appliances cannot be powered by the electricity available.

In this context, a multi-tier framework devised by the World Bank in 2017 adopts a more nuanced approach to defining access to electricity, based on six tiers (0 to 5) with progressively greater quantity and quality of electrification (**Table 1**).

This framework acknowledges that electricity access is a spectrum of service levels experienced by households. According to the framework, the tiers correspond to the following service levels:

- Tier 0: Negligible access
- Tier 1: Task lighting, phone-charging and radio
- Tier 2: General lighting and low-power appliances, such as television and fan
- Tier 3: Tier 2 and medium power appliances, such as refrigerators and food processors
- Tier 4: Tier 3 and high-power appliances, such as stoves, irons and light productive use appliances like irrigation pumps and carpentry tools
- Tier 5: Tier 4 and very high-power productive use appliances, such as grain milling, welding and machine shop tools

Having access to just enough electricity to power light bulbs, a fan and a mobile phone is unlikely to lead to substantive improvements in quality of life or economic opportunity. For true social and economic benefits of electrification to be realized, underserved populations must move towards Tiers 4 and 5.

Tier	0	1	2	3	4	5
Attributes of Access						
Peak available capacity (watts)	N/A	>1W	>20W	>200W	>2000W	>2000W
Duration of supply (hours)	N/A	>4 hrs	>4 hrs	>8 hrs	>16 hrs	>22 hrs
Evening supply (hours)	N/A	>2 hrs	>2 hrs	>2 hrs	4 hrs	4 hrs

Table 1: Multi-tiered framework for measuring electricity access. (Source: World Bank, 2017)

5. Most electricity is generated from fossil fuels

Electricity generation is dominated by fossil fuels, with about two-thirds of global electricity produced by burning fossil fuels, primarily coal and natural gas (IEA, 2018a) (**Exhibit 5**). Typically, the fuels are used to boil water to make steam, which drives turbines that generate electricity.

Coal has consistently provided about 40 percent of global electricity since the 1970s, with lesser contributions from gas, oil, nuclear and renewables (**Exhibit 6**). Using oil to generate electricity has become less common in recent decades, while using natural gas has increased and now provides about 23 percent of electricity.

Nuclear electricity production expanded rapidly in the 1970s and 1980s, but has faced growing concerns regarding its cost and safety, in part due to high-profile accidents in Ukraine in 1986 and Japan in 2011. Nuclear energy now provides about 10 percent of global electricity.

An important distinction among power generating sources is their continuity (or the inverse, intermittency). With fossil and nuclear power generation, the energy stored in the fuels is converted into electricity. These processes are dispatchable, meaning that generation can be reliably scheduled according to demand.

Fossil and nuclear generation facilities typically have high capacity factors, which is the percentage of actual generation relative to the full operating capacity. Capacity factors of more than 80 percent are common for dispatchable sources like coal and nuclear, compared to 20 to 40 percent for inherently intermittent source like solar and wind.

Coal, gas and nuclear generation require power plants of significant size (megawatt-scale) to economically produce electricity, reducing their cost effectiveness when it comes to producing electricity for small, dispersed populations.

Fossil fuels are an important source of electricity in most countries. Both China and India, for example, use coal to generate more than 70 percent of their electricity. In discussions of global climate change mitigation, there is legitimate debate on the suitability of using fossil fuels for electrification in developing countries (IEA, 2017a; Nordhaus, et al., 2016).

This is driven by recognition that industrialized countries have used fossil fuels for centuries to power their development process. For example, the United States and European Union countries are responsible for well over half of the total cumulative carbon dioxide emissions from fossil fuels since the beginning of the Industrial Revolution through year 2002 (WRI, 2005).

While acknowledging the continuing contribution of fossil fuels to the electrification and development processes, we note the potential perils that accompany such carbon-intensive actions (see the Resilience to Global Change chapter for more information). We also observe that electricity generation from fossil fuels is a well understood business-as-usual practice, with few opportunities for fundamental advances.

In contrast, emerging renewable energy sources are cleaner and have the potential for transformative decentralization in the electricity sector, thus we focus on renewables for the remainder of this section.

Global electricity generation, 1971 to 2016

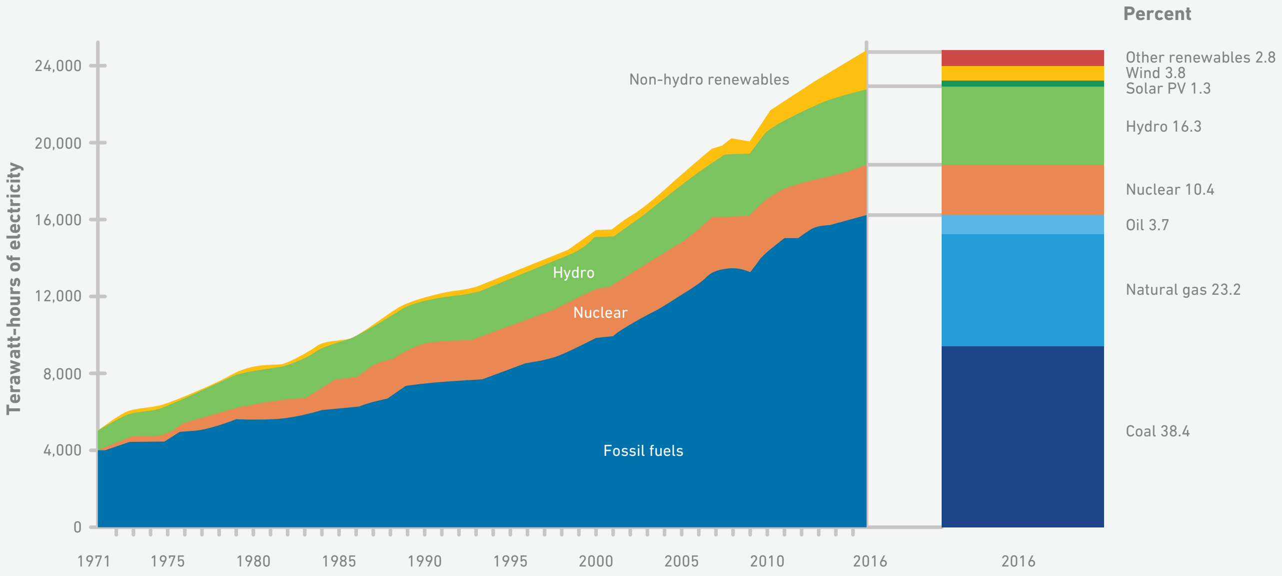


Exhibit 5: Global electricity generation has increased fourfold since 1971. Most electricity is produced by burning fossil fuels, especially coal and natural gas. Hydropower and nuclear also produce a significant share of electricity. Modern renewables, such as wind and solar power, provide a small but growing share of electricity. (Source: IEA, 2018a)

Global electricity generation, 1971 to 2016

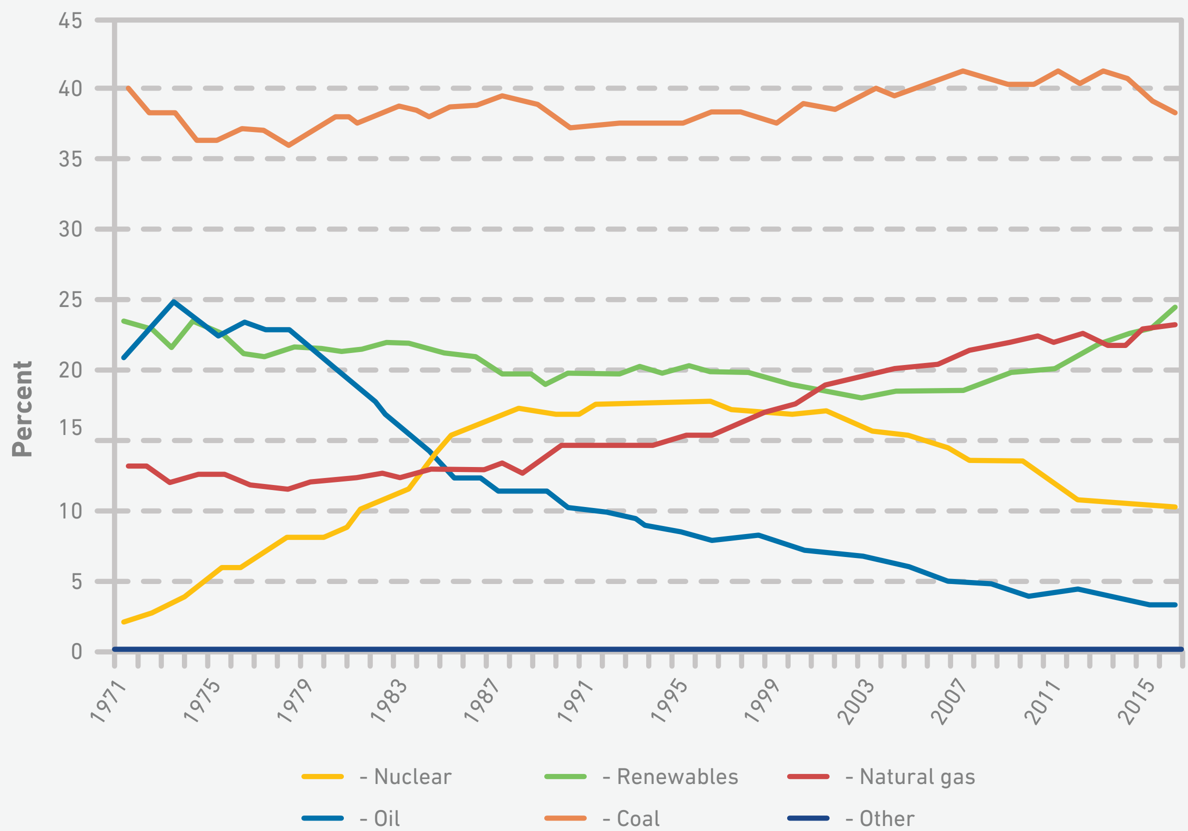


Exhibit 6: Coal is the dominant energy source for global electricity generation. (Source: IEA, 2018b)

6. There is increasing emphasis on renewable sources to meet global electricity needs

Owing to concerns of the polluting nature of fossil fuels and their adverse impact on climate change, there is a growing realization for the need to invest in and move towards renewable energy sources for electricity production.

Renewable energy sources are not only cleaner but also available in abundance as compared to conventional fossil fuels that are dwindling and getting costlier. The Paris Agreement, negotiated in 2015, marked an important milestone in global efforts to limit greenhouse gas emissions to mitigate climate change.

Hydropower is the largest single source of non-fossil electricity, providing about 16 percent of global electricity. From its early days in the 1880s at Niagara Falls, North America, hydropower facilities have grown to include the colossal Three Gorges Dam in China. Nevertheless, hydropower has been criticized for displacing communities, disrupting river ecology and impacting water quality (Moran, et al., 2018).

Other renewables, such as wind, solar, geothermal and tidal power, provide a small but growing share of electricity supply. The environmental performance of these electricity sources is generally better, across a variety of indicators, than electricity from fossil fuels (Masanet, et al., 2013). Since 2015, addition of new capacity from renewable solar, wind and hydro power has outpaced additions of non-renewable coal and gas capacity (**Exhibit 7**).

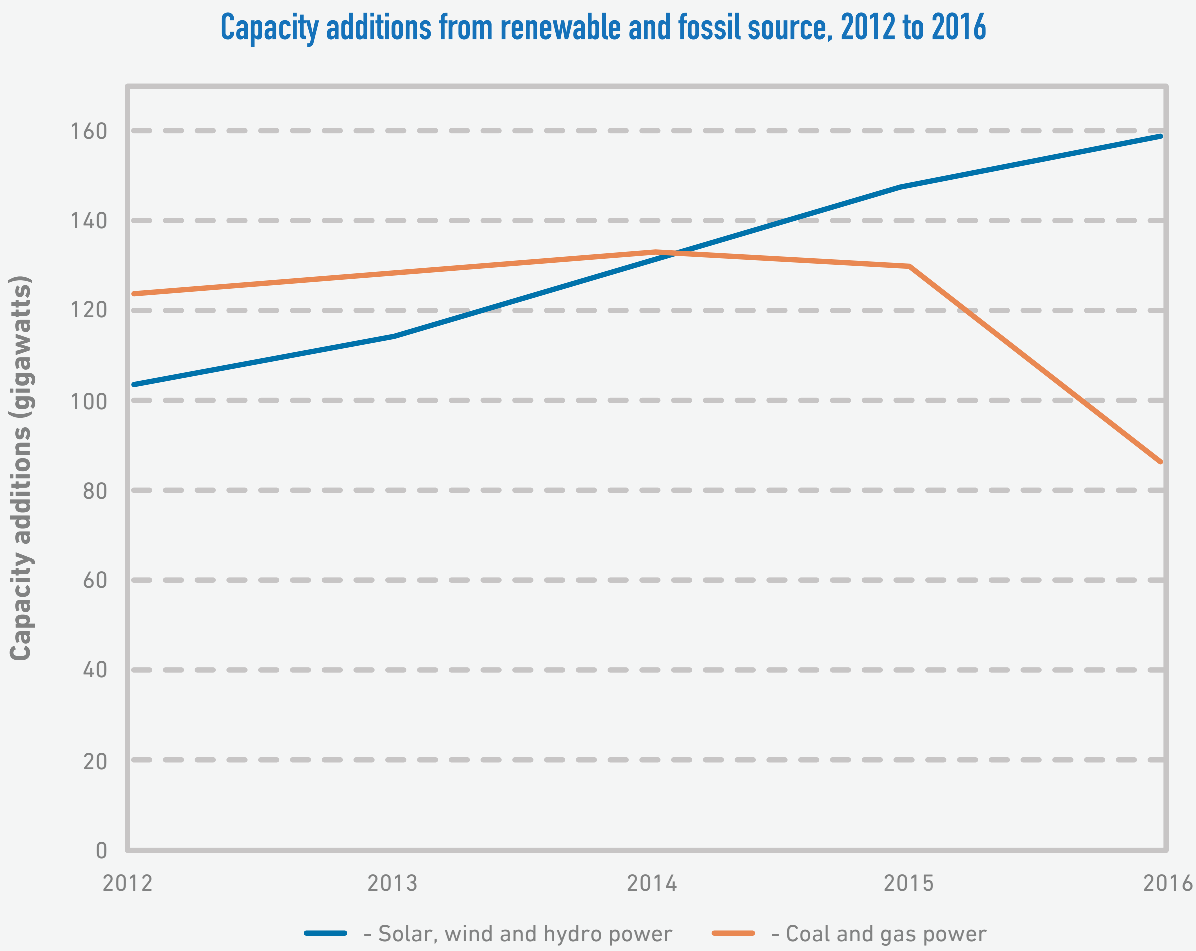


Exhibit 7: Year-wise capacity additions from renewable and non-renewable sources from 2012 to 2016. (Source: IEA, 2017b; IEA, 2018c)

A range of renewable energy sources can be used to produce electricity. Each has a number of strengths and weaknesses in terms of availability, intermittency, complexity, modularity, cost and potential for improvement. These are discussed below.

Availability: Diffuse versus site-specific

The various resources of renewable energy—wind, sunlight, biomass, geothermal and hydropower— are present at different amounts in different parts of the world.

- **Solar:** Solar power has a large scale of application since it is the most widely available resource, and can be produced from many distributed sites rather than isolated resource-dependent locations. With a few exceptions due to extreme rain and cloudiness, solar power can be generated in most of Asia and Africa as seen in **Exhibit 8** (IED, 2013). Solar plants can also be located very close to, or even in the midst of, settlements, significantly reducing distribution costs.

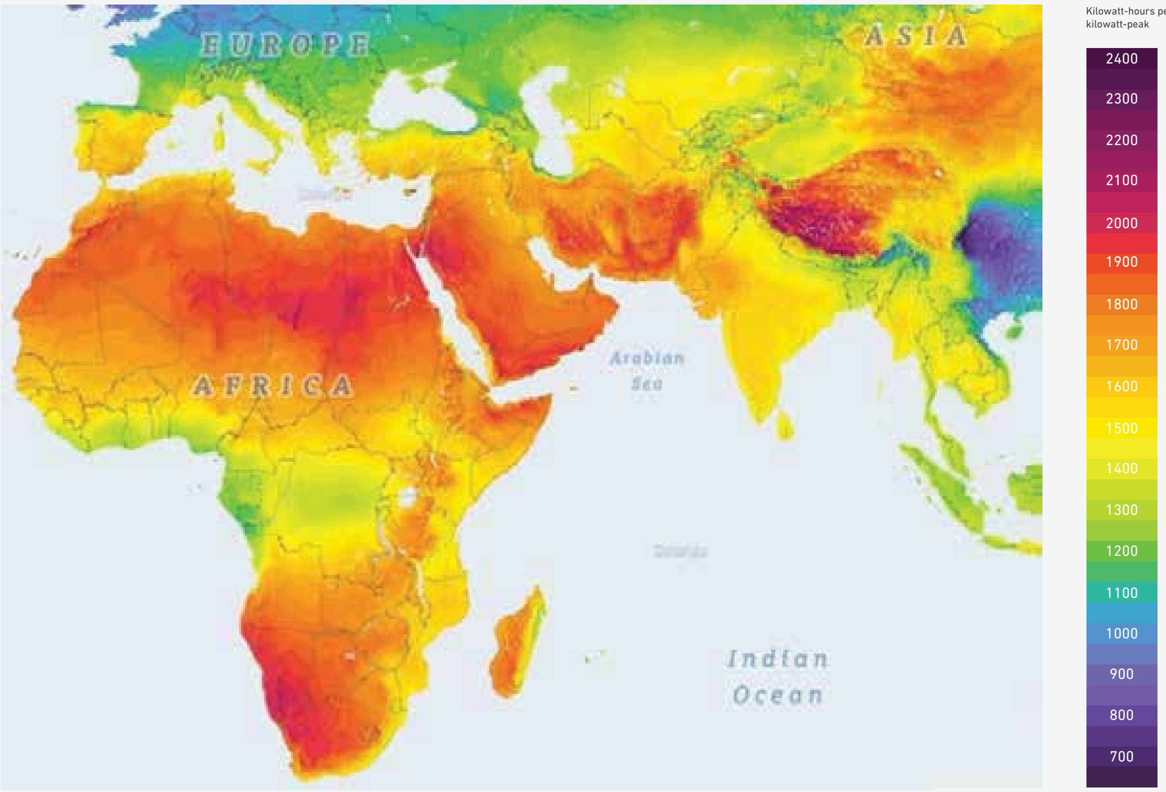
- **Hydroelectric:** Hydroelectric power needs to be close to a perennial water current with sufficient strength. Because of its site-specific nature, distribution costs are highly variable and depend on population density.

- **Wind:** The potential for wind electricity production varies strongly by region (**Exhibit 8**). Sub-Saharan Africa and South Asia have relatively poor potential for wind generation. Wind power is typically greater near shores of water bodies, or at higher altitudes, where winds blow more consistently (IED, 2013; IRENA, 2013). As a result, their distribution costs are slightly variable, depending on population distribution more than any factor intrinsic to the technology.

- **Biomass:** Biomass includes such organic materials as crop or food waste and animal or human manure. It can be converted to electricity in several ways. It can be combusted as a solid fuel to fire a conventional steam turbine generator. It can also be converted to a gas, and the resulting biogas used to power a reciprocating or turbine generator set. Gasification of biomass can take place by high-temperature thermochemical methods, such as pyrolysis or gasification, or by organic biochemical methods like anaerobic digestion. Biomass generators are limited by their dependence on feedstock—locations close to feedstock production are preferred to reduce transportation costs.

- **Geothermal:** In specific locations with favorable geologic conditions, geothermal electricity is a reliable, low cost form of power with low carbon emissions. Steam from deep underground heat sources is used to drive steam turbine generators. Almost half of Kenya's electricity is produced by geothermal energy from the Olkaria region located south of Lake Naivasha. For specific areas that are endowed with this energy source, geothermal offers a clean, inexpensive and reliable source of electricity.

Potential for solar and wind generation



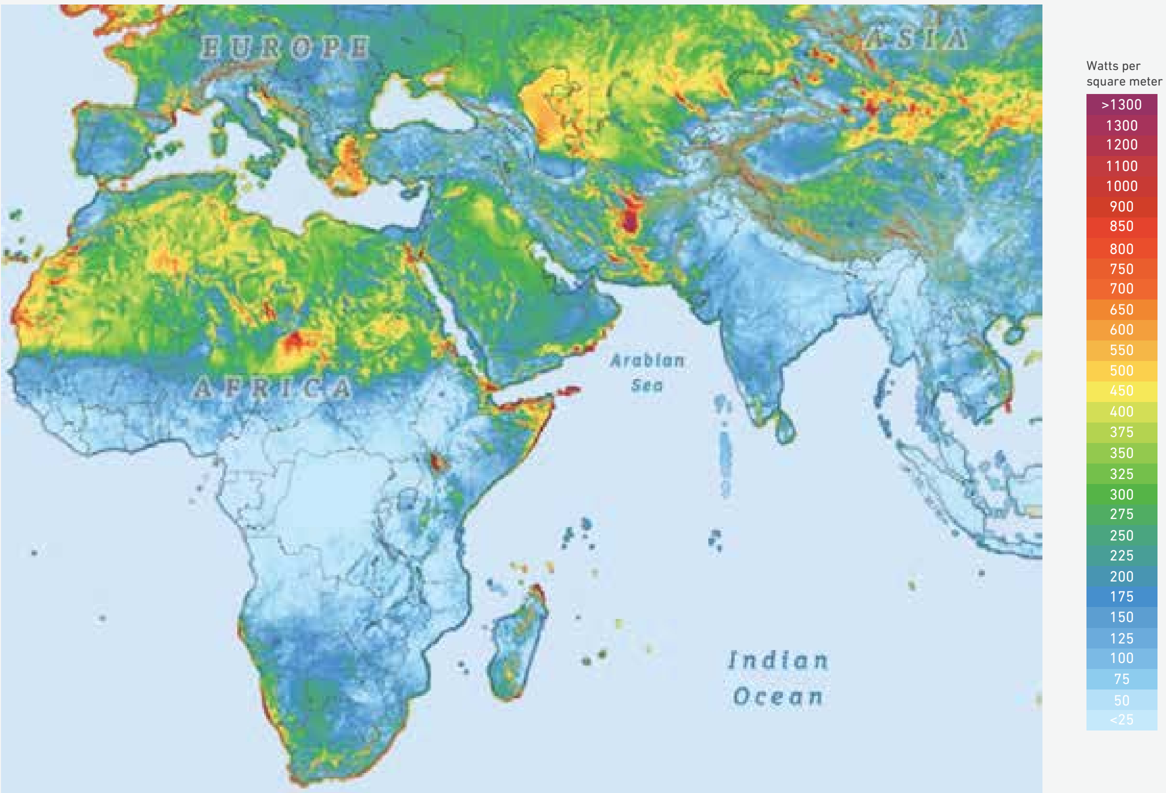


Exhibit 8: The potential for wind and solar electricity production varies strongly by region. Within Sub-Saharan Africa and South Asia, there is generally greater potential for solar photovoltaic generation than wind generation. (Source: Global Solar Atlas, 2019; Global Wind Atlas, 2019; solar map shows photovoltaic electricity output, wind map shows wind power density at 100 meters height)

Intermittency

Renewable sources of energy are, to some extent, unpredictable and vary with a number of diurnal and seasonal factors.

- **Solar**: PV cells produce the best output with uninterrupted, direct sunlight. Though they work with diffused light in cloudy conditions as well, their output varies with season and time of the day. Solar PV cells do not produce any electricity at night.
- **Hydroelectric**: Given sufficient water storage, hydroelectric generators can produce continuous power. Small-scale hydroelectric power is usually dependent on seasonal factors, such as changes in water levels due to seasonal changes or droughts, which can impede generation.
- **Wind**: Given the variability in wind speed with the season and time of the day, the output of a wind system is inconsistent. Optimal locations, such as coastal regions, can provide relatively consistent power.
- **Biomass**: Inconsistency of biomass power is largely a function of biomass supply. Some biomass fuels, such as crop residues, are available only after harvest season. Sugarcane bagasse, for example, is the most widely produced feedstock in sub-Saharan Africa suitable for gasifiers, but is not available for several months a year and cannot be stored for long periods (DFID & IED, 2013).

Operations and maintenance complexity

Complexity of operations and maintenance is an important factor not only in the smooth functioning of the power plant but also in defining the operating costs.

- **Solar**: Solar energy requires minimal maintenance as compared to most other generation sources. However, regular maintenance in the form of cleaning panels, replacing batteries, and monitoring inverter and power electronics data can ensure optimal performance.
- **Hydroelectric**: The complex systems and equipment inside a hydroelectric powerhouse result in specialized operations and maintenance requirements. Routine maintenance of turbine, generator, hydraulic systems and gearboxes is needed.

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- **Wind**: Working on a wind turbine is often difficult because of the need for it to be remotely located and requirement for specialty equipment. Regular maintenance and lubrication of gearboxes, generator and bearings is key to effective performance.
- **Biomass**: Biogas plants today are still operationally complex. Gasification systems, whether thermochemical or biochemical, require skilled operation and maintenance which may be unavailable in some areas (Rajendran, et al., 2012).

Modularity

Rural markets are typically small and vary significantly in size. Because these markets are nascent, demand is hard to estimate at the outset, and systems may need to be scaled up or down with time. Power generators are often best suited for locations with anchor clients, such as small mills and agri-businesses, that have sizable but fixed and predictable power needs (IED, 2013).

- **Solar**: Solar plants are modular in design and capacity can be increased by adding more PV panel arrays. Power electronics capacity must also be matched to array area.
- **Hydroelectric**: Hydroelectric plants once built may be expanded in capacity, depending on geology and topography, but the process is time consuming and costly.
- **Wind**: Wind systems are modular, above a minimum viable unit size, with unit costs of smaller-scale applications significantly higher than large-scale ones. Performance increases significantly with greater scale (height and swept area).
- **Biomass**: Conventional biomass gasifiers are scale-dependent and quite capital intensive. However, prefabricated digesters are being developed that are much less expensive than traditional biogas digester and can be installed in a day without the use of skilled labor (Cheng, et al., 2014).

Levelized cost

One important criterion for comparing the various technologies is levelized cost of electricity (LCOE), which is the ratio of the present value of lifetime system costs (discounted using the rate of capital cost) to lifetime electricity generation. The drivers of LCOE are capital expenses (cost of infrastructure and installation), cost of capital, operations and maintenance (O&M), fuel costs, the lifespan of the system and utilization of the system's capacity.

A comparative analysis of the levelized cost of small-scale and utility-scale renewable energy sources is presented in **Exhibit 9**.

Levelized cost of small-scale and utility-scale renewable electricity sources

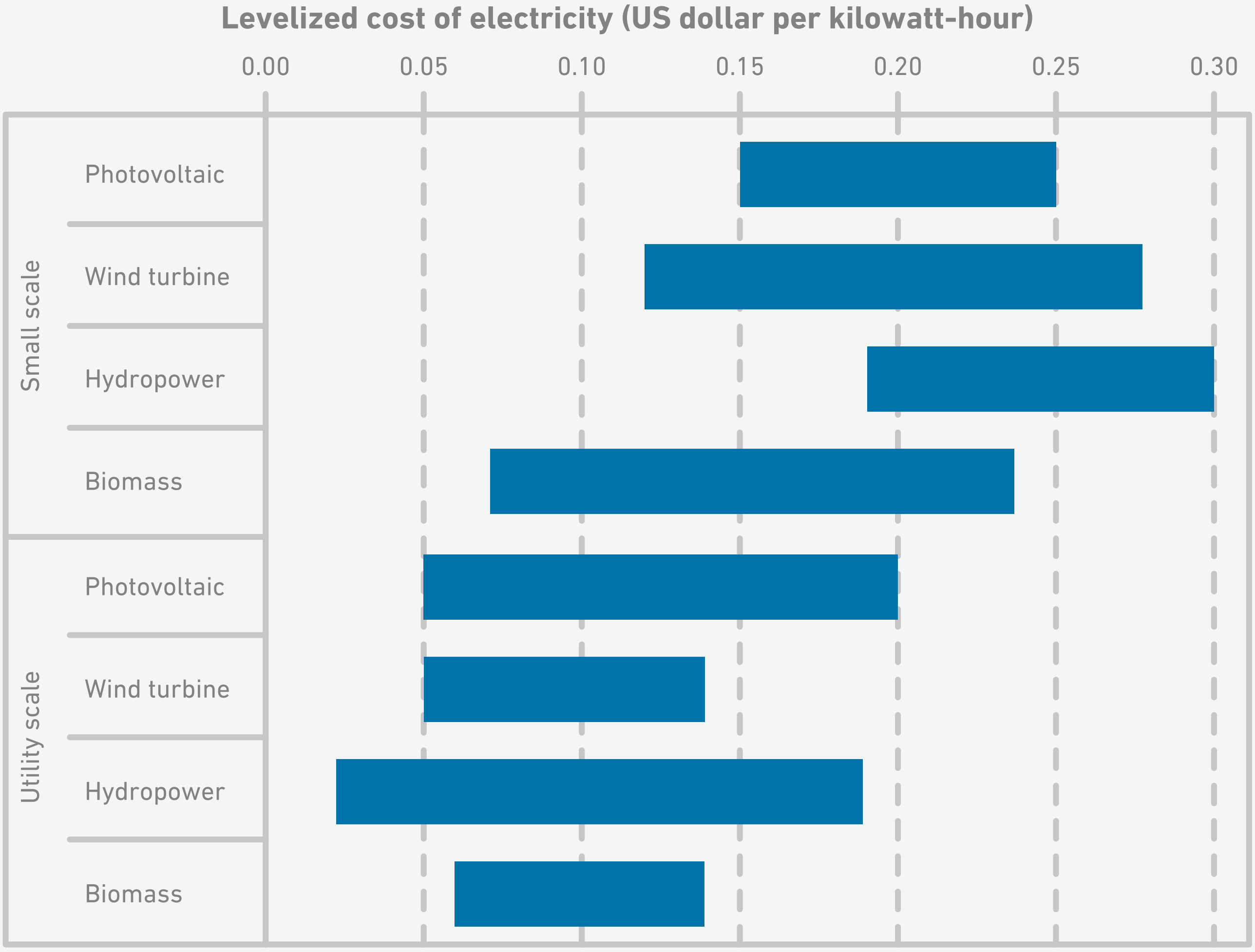


Exhibit 9: Levelized cost of electricity (LCOE) of different renewable electricity sources deployed at small- and large-scale. (Source: IRENA, 2016; IRENA, 2018)

Potential for Improvement

The learning rate of an emerging technology is the cost reduction for each doubling of deployment. Learning rates vary widely among renewable energy technologies.

- **Solar**: Solar PV modules have high learning rates of between 18 percent and 22 percent depending on the period analyzed (IRENA, 2017), the highest among renewable energy technologies. This, matched with the global growth of solar PV, resulted in massive cost reductions which are expected to continue, propelled by concerted R&D efforts in industrialized markets, such as the United States Department of Energy's (DOE) SunShot initiative whose target is to reduce the total installed cost of solar energy systems to $.06 per kWh by 2020.

- **Hydroelectric**: Hydroelectric is a fairly mature technology with low potential for further cost reductions and a very low learning rate.

- **Wind**: Onshore wind has experienced a learning rate of 15 percent for the cost of electricity delivered, as installed cost reductions and performance improvements have raised yields (IRENA, 2016).

- **Biomass**: Biomass gasification technologies are fairly mature, with cost reduction opportunities limited to lowering fuel handling and preparation costs. In general, the learning rate of biomass electricity is fairly low.

Table 2 summarizes the pros and cons of various renewable energy technologies at small- and utility-scale, in the context of electrification in developing countries. Solar PV has advantages over other renewable energy sources because of its widespread applicability, relatively simple operations, high modularity and large potential for improvement.

Characteristics of renewable energy sources

Small scale	Solar PV	Hydroelectric	Wind	Biomass
Diffused vs Site specific	good	very poor	medium	medium
Volatility	medium	medium	poor	poor
O&M Complexity	very good	medium	good	poor
Modularity	very good	poor	good	medium
Levelized Cost	medium	poor	medium	medium
Potential for Improvement	very good	poor	good	medium

Utility scale	Solar PV	Hydroelectric	Wind	Biomass
Diffused vs Site specific	good	poor	medium	medium
Volatility	medium	good	medium	good
O&M Complexity	good	good	good	medium
Modularity	very good	poor	very good	good
Levelized Cost	medium	good	medium	medium
Potential for Improvement	very good	very poor	medium	poor

very good | good | medium | poor | very poor

Table 2: Pros and cons of different renewable energy technologies in the context of both centralized utility-scale generation and decentralized mini-grids in developing regions.

7. Advances in energy storage have enabled intermittent renewable energy sources to provide reliable continuous electricity

Unlike other tangible commodities, it is challenging to accumulate significant stocks or inventories of electricity to cushion differences in supply and demand.

There are, however, various technologies that have been developed to store energy for time periods from seconds to days (**Exhibit 10**). Storage is particularly important for intermittent energy resources in order to bridge diurnal or seasonal cycles.

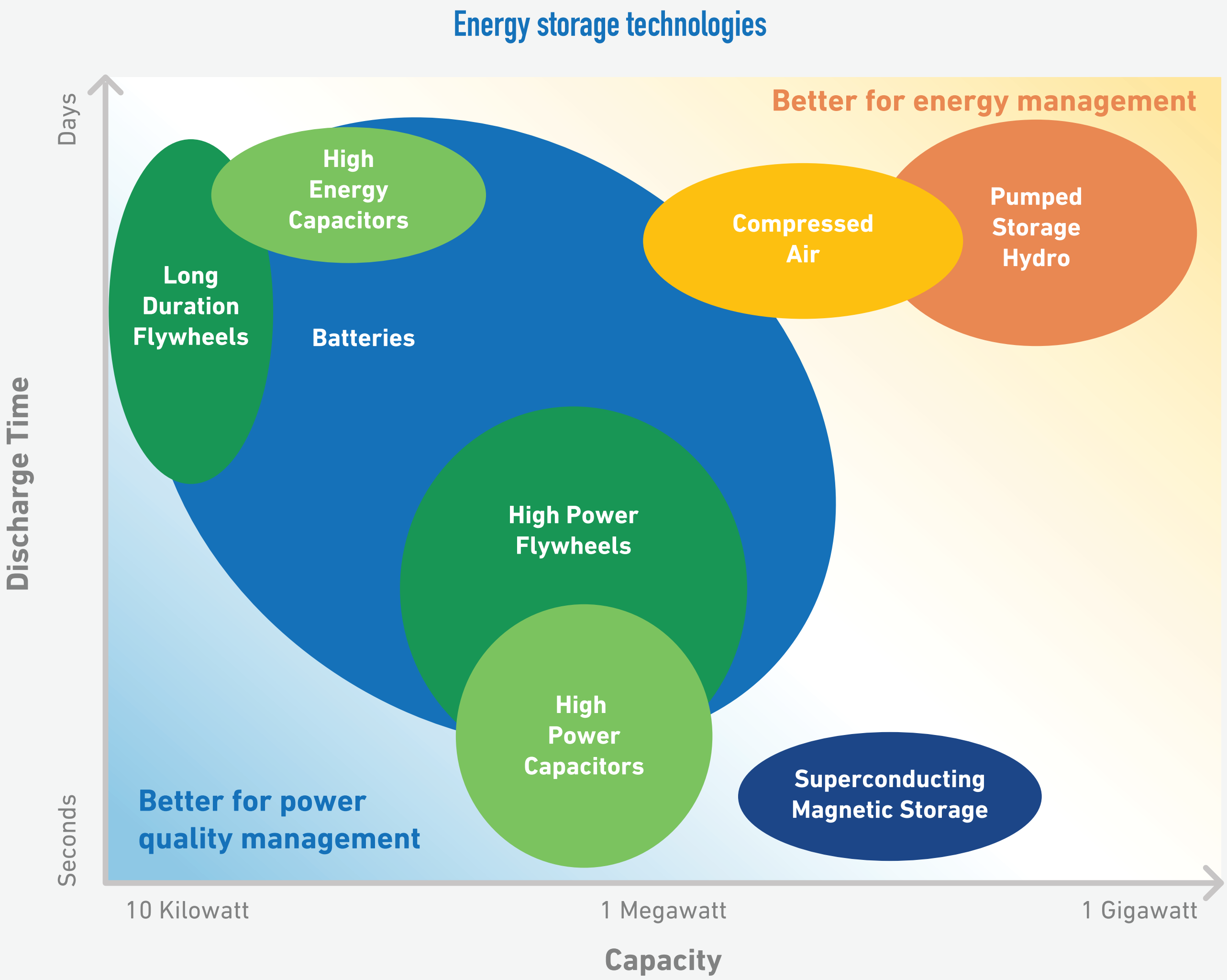


Exhibit 10: A large number of electricity storage technologies exist and are suitable for different conditions of discharge duration and power. The "batteries" category encompasses many different electrochemical types. (Source: US EIA, 2018)

Electrochemical batteries are the most common form of electricity storage with a wide range of types, some of which are discussed below.

- **Lead-acid batteries** are the least expensive commercially available rechargeable batteries, but have low energy density. The operating life of this battery type degrades if used in temperatures above 30 to 35 degrees Celsius and their energy storage capacity degrades if left in a partial state of charge. Additionally, lead-acid batteries cannot recover their original capacity when subjected to occasional deep cycling, a scenario that cannot be avoided when demand for electricity is high or sunlight is sporadic. Furthermore, disposal of lead-acid batteries has environmental and health risks that require careful handling and regulation.

- **Lithium-ion batteries** are one of the most promising battery technologies with very high power density, modularity, no memory effect and high depth of discharge. However, they are expensive and have limited capacity. There are also safety concerns about abnormal heating from overcharging and short circuits. Due to their adoption by the electric vehicle industry, lithium-ion batteries are currently on route to replace lead-acid batteries. However, lithium-ion batteries still require improvements to achieve lower cost, better safety and higher capacity. Costs of these batteries have dropped continuously with increasing commercialization of electric vehicles (**Exhibit 11**). Market trends suggest that EVs are poised to overtake traditional internal combustion engine vehicles in the coming decades.

- **Advanced lead-acid batteries** are a hybrid of conventional lead-acid batteries and super-capacitor technology. This hybridization enables longer life at cyclic operation under partial state of charge compared to conventional lead acid batteries, while operating at high charging and discharging rates. Advanced lead-acid batteries are also less sensitive to temperature rise as compared to standard lead-acid batteries.

- **Sodium-sulfur (NaS)** batteries are made with low-cost, abundantly available materials and offer significant potential for further price reduction. Hence, they are very well suited for large-scale applications in mini-grids. However, they are very bulky (weighing several tons) and operate at high temperatures (300 degrees Celsius). Commercial versions are more expensive than deep cycle lead-acid batteries. They are well suited for storage in megawatt-size, utility-scale mini-grids (village-scale or larger) and are typically available in multiples of 1 megawatt (with installations in the 2 to 10 megawatt range). As a relatively new technology with low production capacity, there is significant potential for cost reductions. Production of smaller batteries is in its early stages.

- **Vanadium redox batteries (VRB)** are highly configurable, with very high depth of discharge and long life, but need pumping and cooling systems. Configuring the battery is extremely simple—both the cell stack size and the electrolyte volume can be easily changed to modify power output and storage needs. They can be fully discharged without any damage, thereby significantly improving operational range, increasing longevity and minimizing the need for maintenance. VRBs are normally considered for relatively large stationary applications (1 kWh to 10 MWh) ranging from a few kilowatts to a few megawatts (Sandia, 2013).

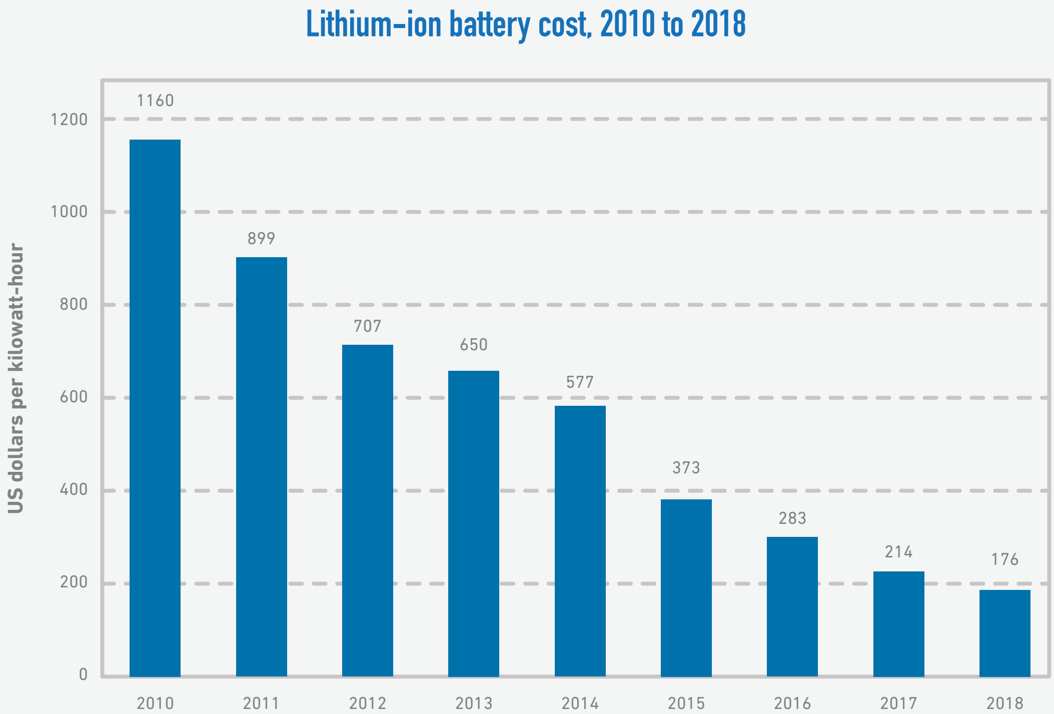


Exhibit 11: The cost of lithium-ion batteries is declining due to increasing scale of production brought on by the proliferation of electric vehicles. (Source: BNEF, 2018)

8. The technology of solar photovoltaics (PV) is rapidly evolving and the cost is dropping significantly

Solar photovoltaics (PV) are electronic devices made with semiconducting materials such as silicon or germanium, which generate electricity from sunlight. Electricity production is roughly proportional to the solar irradiance. The modern form of the solar cell was invented in 1954 at Bell Telephone Laboratories in the United States, and research has continued since then to improve their efficiency and performance (**Exhibit 12**).

The cost of PV power has steadily decreased as the scale of production and deployment has grown (**Exhibit 13**). The learning rate, or the cost reduction for each doubling of deployment, is about 20 percent for solar PV modules, which is the highest among renewable energy technologies.

Since their invention, there have been three generations of solar PV technologies. The first generation, wafer-based crystalline silicon, is mature and commercially available. The second generation is made of thin-film modules which use a fraction of the material (compared to the first generation) by depositing solar cells on substrates like glass, metal and flexible polymers.

Though thin-film PV tends to have low manufacturing and materials cost, the cells have lower efficiency than crystalline silicon (**Exhibits 12** and **13**). As a result, despite being commercially available, they have not captured significant market share, with crystalline silicon holding 90 to 95 percent of the market share. They do, however, have strong potential for further cost reductions.

There are also some emerging third generation PV technologies. Concentrated PV (CPV) uses optical devices to concentrate sunlight on solar cells and a tracking system to optimize for irradiation. Since the efficiency of silicon solar cells drops with higher temperatures, CPV uses semiconductors with very high conversion efficiencies, such as gallium arsenide.

Tracking systems and optical components increase cost and complexity, as do cooling systems in some designs and multi-junction solar cells. This nascent technology appears to have significant potential for gains from the learning curve. Dye-sensitized solar cells (DSSC), another third-generation technology, use photo-electrochemical solar cells which harvest photons from sunlight mimicking photosynthesis.

The efficiency of DSCC is currently low and the technology requires new dyes that can absorb broader spectral ranges. Another issue that needs to be addressed is performance degradation due to UV light.

Lastly, Organic PV (OPV) has solar cells composed of organic or polymer materials. OPV uses inexpensive, abundant and non-toxic materials but needs to become much more efficient and stable (IRENA, 2012).

Photovoltaic conversion efficiencies, 1976 to 2018

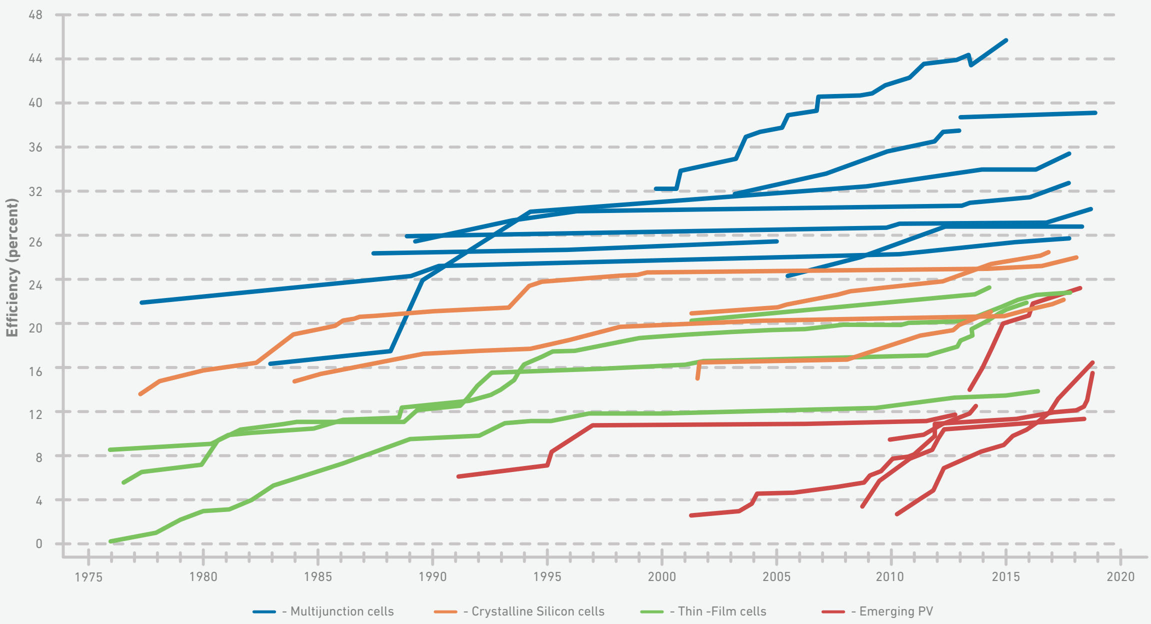


Exhibit 12: The efficiency at which photovoltaic devices convert sunlight into electricity has increased steadily in recent decades. (Source: NREL, 2019)

Photovoltaic experience curve, 1975 to 2016

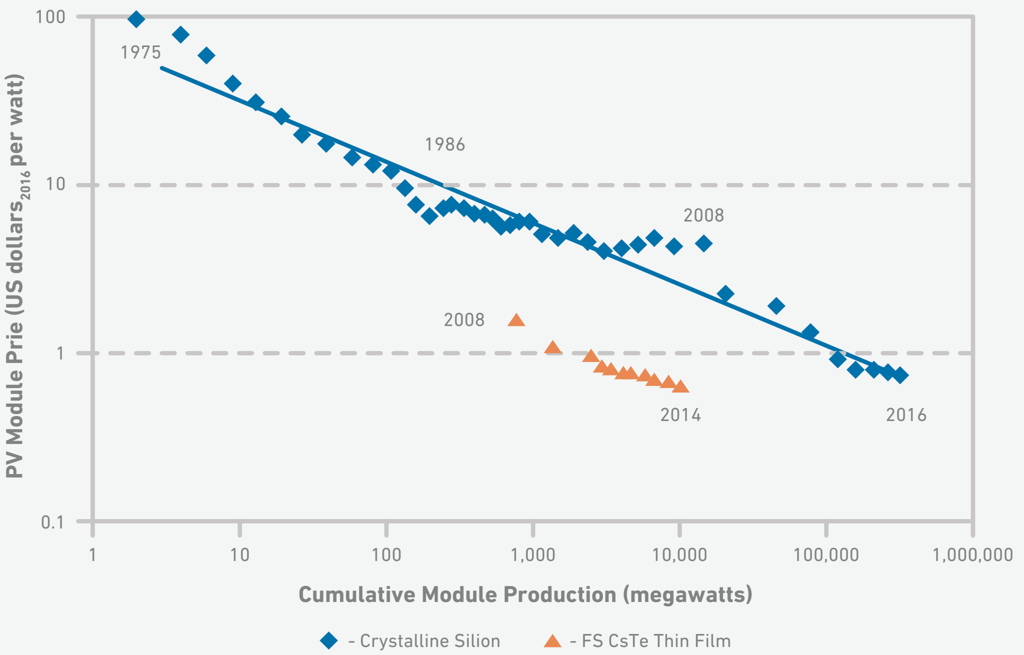


Exhibit 13: The cost of solar PV cells and panels has been dropping as manufacturing experience increases. (Source: JRC, 2016)

Obtaining usable electricity from some renewable energy sources requires the use of power electronic devices to process the power generated. Notable types of power electronics include inverters that convert between direct current produced by PV arrays and alternating current used by many appliances.

Another important device is charge controllers to manage the state of storage batteries. More advanced power electronics can be used to enable smart grid control, such as metering and demand response. The cost of power electronics has declined steadily in recent years (**Exhibit 14**), further improving the competitiveness of renewable electricity (Wood Mackenzie, 2018).

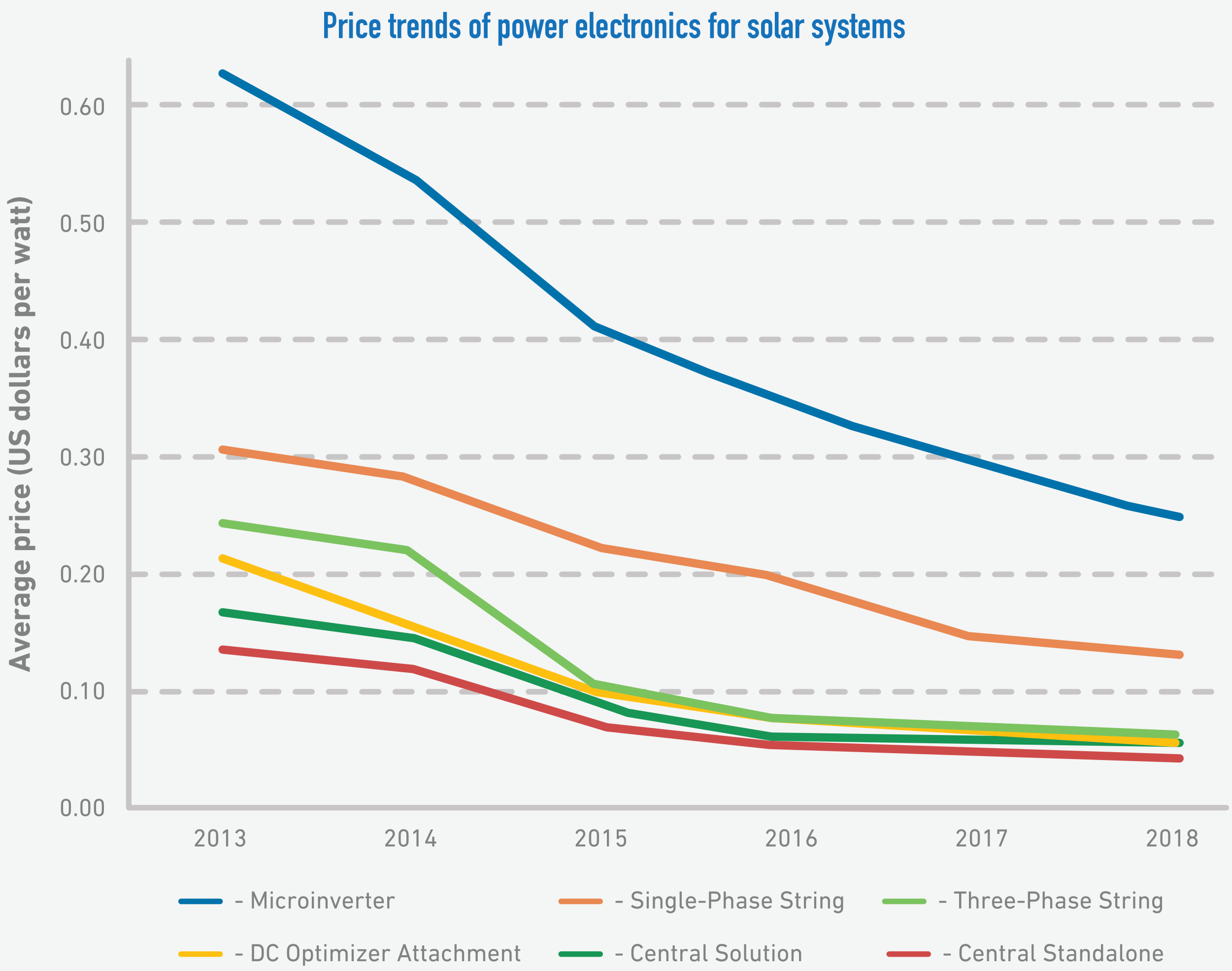


Exhibit 14: Inverters and other power electronics are becoming cheaper and more efficient. (Source: Wood Mackenzie, 2018)

9. Grid extension is the dominant mode of accessing electricity, but there is important need for off-grid and mini-grid devices to enable universal access in remote areas

Main grid

Electricity is typically generated in large power plants and delivered to users across expansive geographical areas through an electrical grid. Transmission lines carry electricity over long distances using high-voltage current to reduce transmission losses.

When the transmission lines reach clusters of users, the voltage is stepped down and distribution lines carry electricity to end users. Transmission of this nature is expensive due to (among other reasons) the cost of infrastructure and comprises roughly 40 percent of the total electricity bill of a power system (IEA, 2010).

In many cases, depending on population density and income levels, it is cost-effective to extend the grid within a range by extending the transmission or distribution lines. This range, known as the grid perimeter, usually includes urban and peri-urban areas where even low-income populations often have access to grid power.

Such main grid architecture has been tremendously successful in providing electricity to populations within its domain, and the vast majority (97 percent) of the new electricity connections made since 2000 have been through grid extensions (IEA, 2017a).

However, grid extension becomes less cost-effective for electrifying remote, dispersed populations and becomes harder to accomplish with increasing distance from the main grid lines (**Exhibit 15**). The feasibility of extending grids to sparsely populated locations is not great, as the cost of transmission (including leakages) becomes prohibitive beyond a certain distance from the generating site.

Populations in these areas must gain electricity, if at all, through off-grid technologies. IEA projects that by 2030, about 150 million people will gain electricity access via mini-grids and another 150 million people via off-grid devices (**Exhibit 16**).

Different modalities of electrification

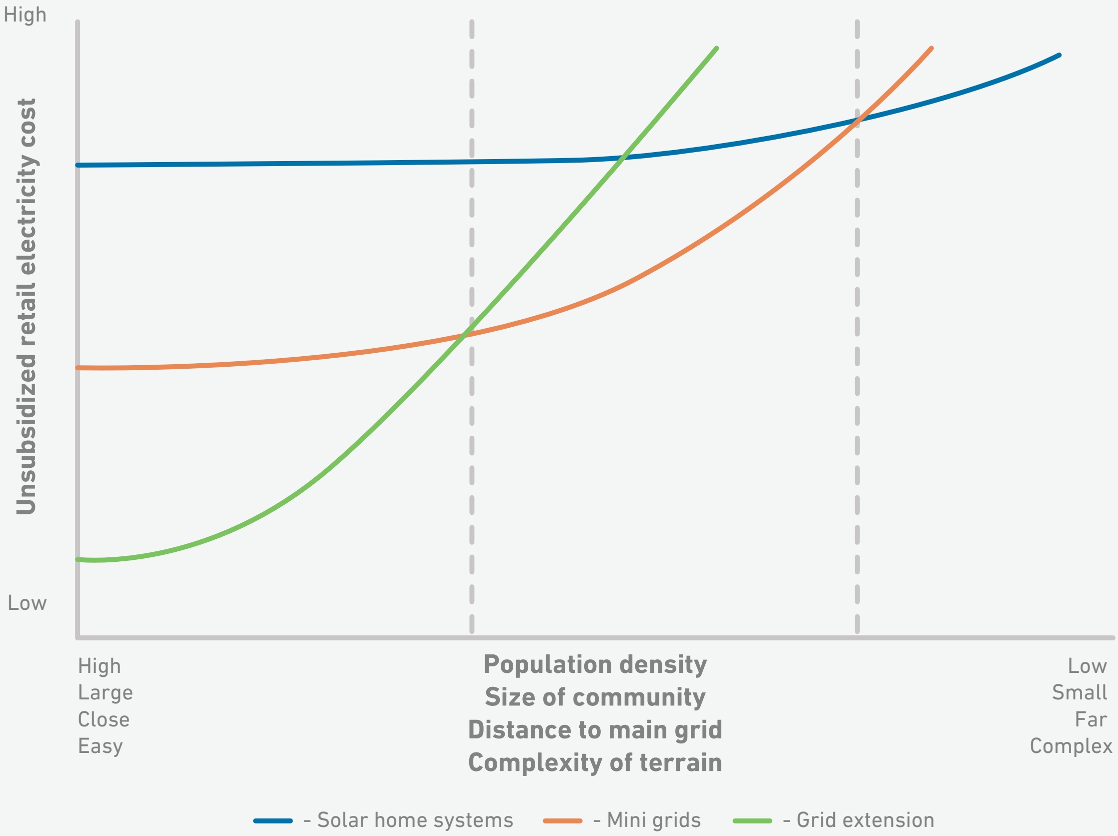


Exhibit 15: Different modalities of electricity provision are most appropriate for various population segments, depending on density of population, size of community, distance to grid and complexity of terrain. (Source: adapted from World Bank, 2017)

Projected modalities of expanding electricity access through 2030

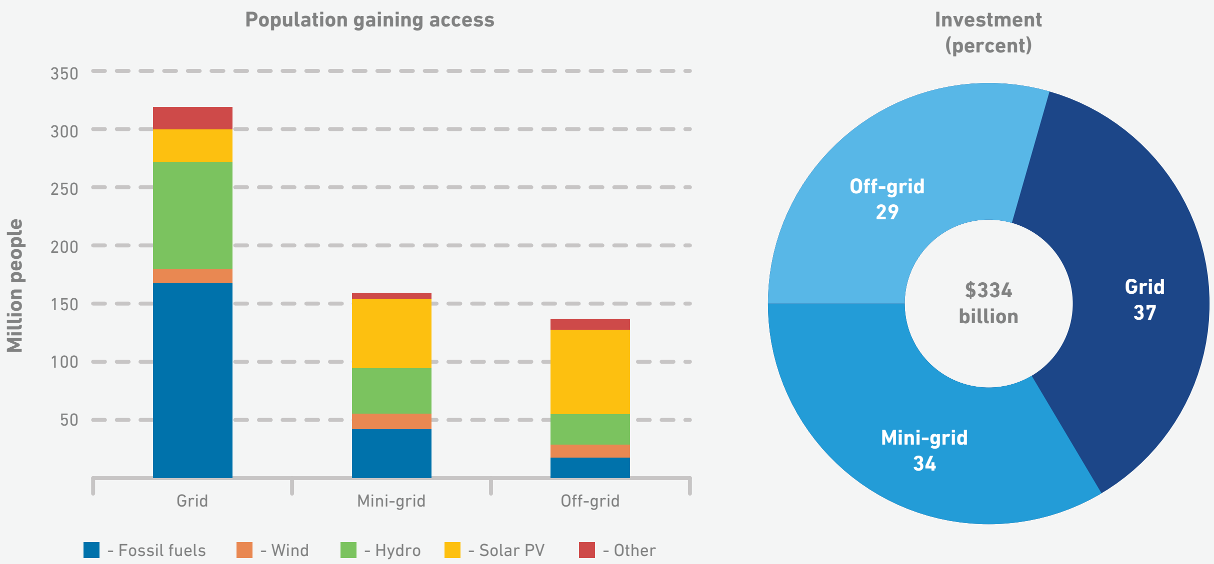


Exhibit 16: Grid extension is projected to reach the greatest number of people, followed by mini-grids and off-grid devices. (Source: IEA, 2017a)

Existing off-grid devices

Through 2017, more than 130 million off grid solar electrical devices have been sold, mostly in sub-Saharan Africa (World Bank, 2018a) (**Exhibit 17**). An estimated 73 million are still in service providing electrical services to households.

Most of the devices sold (about 86 percent) are pico systems that can support limited Tier 1 access. Pico systems are small units that provide up to 11 Watts, and may be comprised of few lights and a mobile charging system.

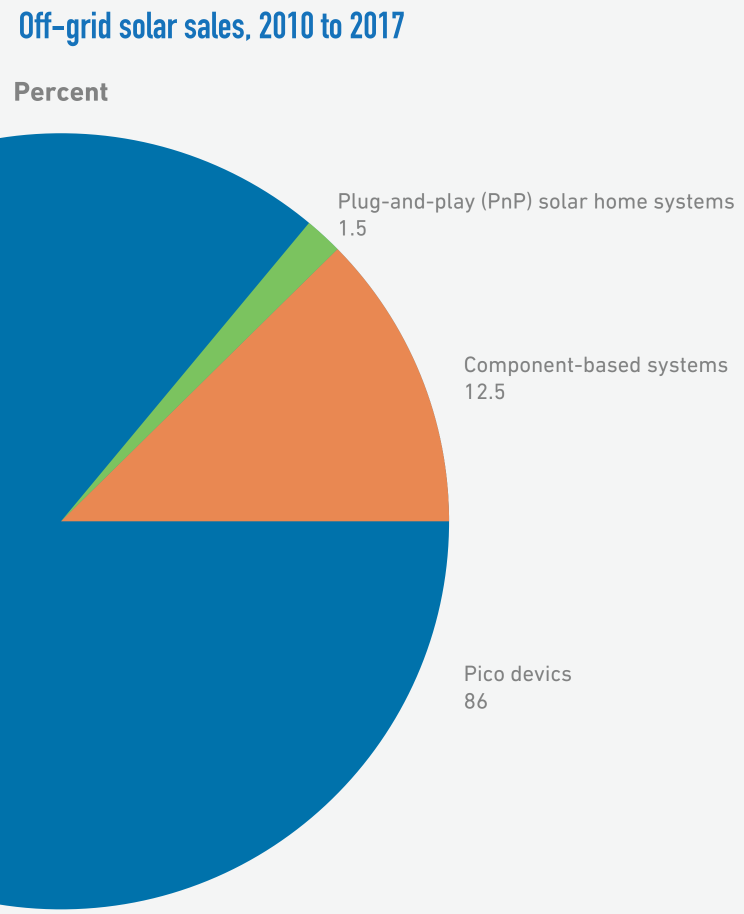


Exhibit 17: Break-down of off-grid solar sales between 2010 and 2017. (Source: World Bank, 2018a)

Plug-and-play (PnP) solar home systems are all-in-one kits that typically enable Tier 2 access. They provide more than 11 Watts, powering fans, energy efficient televisions and some other appliances in addition to lights and mobile chargers.

PnP home system sales have grown rapidly from a small base since 2013. The segment accounts for less than 5 percent of total annual off grid solar devices distribution, yet makes up 20 to 30 percent of annual revenues. This may be attributed to two factors.

First, the proliferation of energy efficient appliances in the market is driven by key innovations including improved brushless DC permanent magnet motors and blade design for fans; improved LEDs, efficient optical films and panel designs that require less lighting for TVs; and improved insulation materials and brushless variable DC compressors for refrigerators.

Second, the pay-as-you-go business model has had considerable success in recent years. PAYGO-based PnP systems had an average annual growth rate of about 140 percent between 2013 and 2016 (World Bank, 2018a).

Component-based systems account for 13 percent of cumulative off grid solar sales. These systems are composed of devices (PV module, battery, lights, inverter, wiring, etc.) that are compiled independently. While initially driven by institutional and government distribution, component-based systems are now dominated by open-market sales.

Consumers are independently assembling open-market component-based systems using PV modules, batteries and other components. Given the decentralized and often informal nature of component sales, conclusive data on these open-market component-based systems remains unavailable, but they are widely considered to enable Tier 2 access to electricity.

Need for mini-grid electrification

It is recognized by experts that electrifying the last 10 to 15 percent of the population, especially in developing countries, is the hardest (IEA, 2017a). Relying on grid extension to electrify these remote populations is not effective for financial and logistical considerations.

Unleashing the life-changing potential of electricity will require access to productive-use, income generating devices corresponding to access of Tiers 4 and 5, which is too energy intensive for pico and PnP solar home systems. It is questionable whether the electricity access enabled by these systems is sufficient to significantly improve the quality of life.

As a result, despite reaching hundreds of millions of people, off grid solar devices have been used for income generating opportunities by very few. For instance, market studies suggest that solar water pumps and refrigeration and cold chain solutions have the most potential for impact (even over LED lighting solutions) with an increasing demand among off-grid consumers (EAC, 2018).

Access to such electricity requires alternative approaches, as conventional off-grid devices are unable to service the loads.

Mini-grids play an essential role in universal electrification, by providing remote areas with reliable electricity supply that is effective for productive use.

Mini-grids can bring economies of scale, thus making electricity more affordable than stand-alone solar home systems. Mini-grids have contributed little to rural electrification to date, but productized mini-grid versions are now approaching the technical sophistication needed to achieve broad deployment, together with the development of appropriate sustainable business models.

Mini-grids are poised to play a major role in expanding access to electricity in the coming decades.

KEY CHALLENGES

1. Rural electrification via main-grid extension faces challenges on three levels: generation, distribution and maintenance

With close to 1 billion people still lacking access to meaningful electricity, there are clearly gaps in the enabling infrastructure.

Grid supply has been the primary mode of electrification thus far, but where it has not achieved adequate service levels, it is because of gaps in generation, distribution or maintenance.

Generation

There is not enough electricity supply in the market due to limited or inefficient generation capacity. This is the case for many of developing countries, especially in sub-Saharan Africa. For instance, Nigeria has about 80 million people living without electricity today (World Bank, 2018b) (**Exhibit 18**). At an electrification rate of about 55 percent, and even lower in rural areas, Nigeria has the largest access deficit in Sub-Saharan Africa and the second largest in the world, after India.

Not only does Nigeria have a capacity of 12,522 MW of electric power from existing plants that is inadequate to spur industrialization and development, but also most days these plants are only able to generate around 4,000 to 5000 MW (World Bank, 2018b).

Electricity access rate of Nigerian states

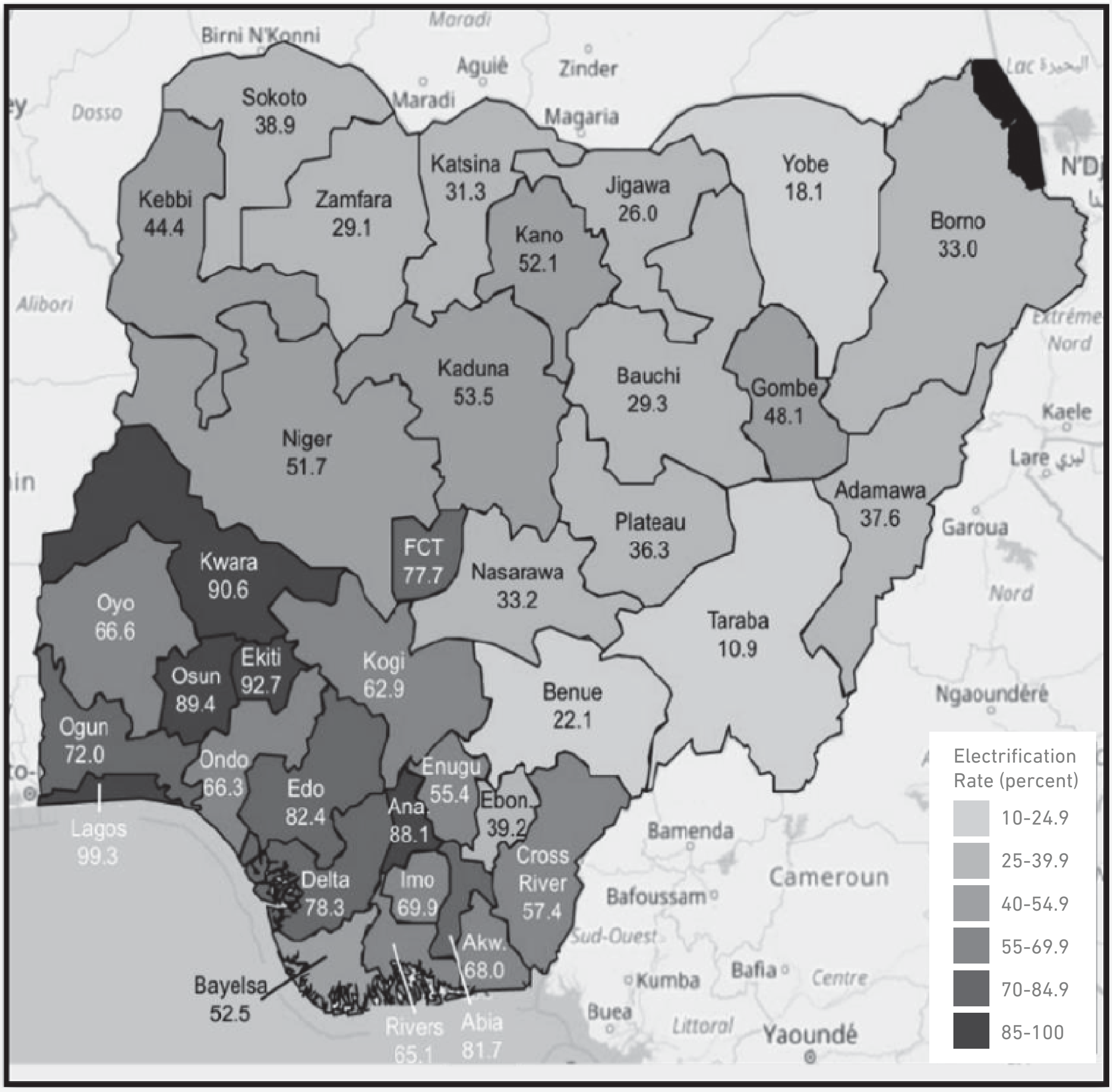


Exhibit 18: Due to its low electrification rates and high population, Nigeria has the greatest number of people without access to electricity in sub-Saharan Africa. (Source: World Bank, 2018b)

Distribution

Where there is sufficient generation capacity, the transmission or distribution infrastructure is lacking. Consider the case of Uttar Pradesh (UP), the most populous and least electrified state of India. Reports suggest that North India has sufficient (if not surplus) energy generation (The Economic Times, 2018).

Yet, UP has the greatest number of villages (close to 30,000 and comprising of 30 percent of the total unconnected villages in India) that are not connected to the main grid distribution network among all Indian states (Indian Ministry of Power, 2018).

Maintenance and management

Where the infrastructure exists for generation, transmission and distribution, either the last-mile infrastructure is inoperable due to poor maintenance or distribution companies are unwilling to supply electricity (IFC, 2012). This is the case for most of un-electrified rural India.

Overall, India is a power surplus state because its installed generation capacity is around 340 GW against the peak demand of not more than 170 GW. The deficit is largely because the distribution companies do not buy the power required to supply consumers, either due to financial stress or because of apprehension about under-recovery of cost of supplied power because of bill non-payment.

2. Powering electric appliances is very costly due to two factors—the high cost of electricity and the low efficiency of appliances

Access to electricity is more than charging a cell phone or lighting a few bulbs. There are a number of electricity-powered services for basic development needs, to reduce the burden of manual labor and physical discomfort, improve overall health and productivity and enhance digital inclusion.

Unfortunately, the poor segment of the population has very constrained energy budgets and cannot afford these services without deep subsidies. This presents a bleak prospect for access considering the large gaps in expanding infrastructure.

While energy efficient lights, fans and televisions have appeared in developed markets, they are designed for urban markets and are priced at a premium. As a result, these appliances have mostly not reached the rural markets. One exception is the success story of the UJALA scheme in India that resulted in more than 300 million LEDs replacing incandescent bulbs and tube lights.

Such concerted efforts are needed across the spectrum of appliances to ensure that electricity becomes affordable for low-income users. In particular, mechanized appliances can benefit from brushless DC motors that are much more energy saving than AC induction motors.

However, their limited proliferation so far has meant that refrigerators and productive-use appliances like irrigation pumps in rural markets still consume a lot of energy. Combined with the high cost of electricity from available solutions like diesel generators, powering even basic appliances can be a very expensive proposition.

In the following analysis, we assume that a portfolio of appliances to meet the basic household needs for a low-income rural family includes lighting, a fan, a refrigerator, an ICT device (like a TV) and an appliance to generate income (like an irrigation pump).

Assuming the energy efficiency levels of appliances currently on the market, the household will consume roughly 105 kWh each month (**Exhibit 19**).

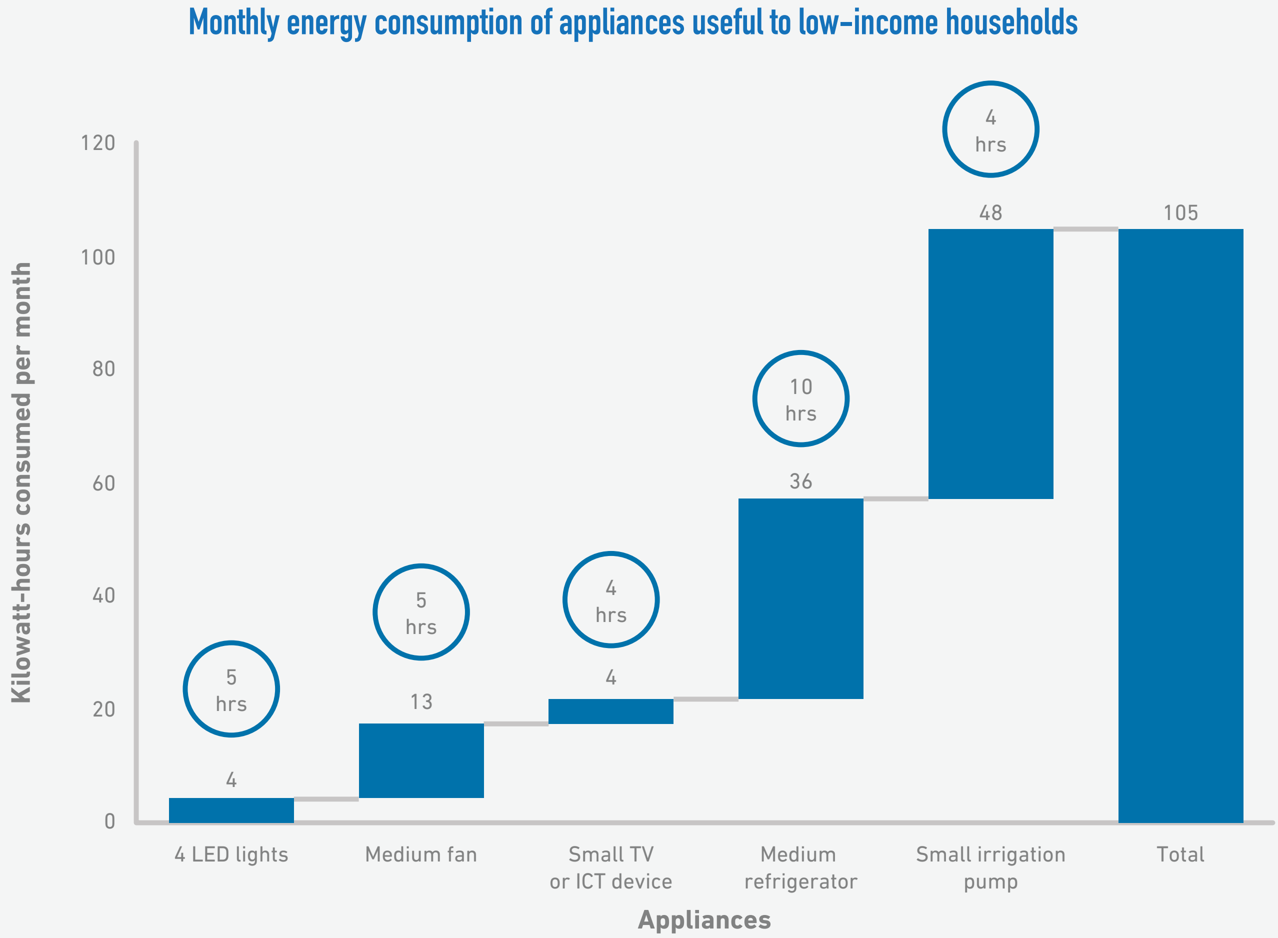


Exhibit 19: A small rural farming household is estimated to consume 105 kWh per month using an essential set of appliances at current energy efficiency levels. (Source: ITT analysis)

Currently, the cost of electricity in solar PV mini-grids is estimated at $0.42 per kWh.[2] At this level, the effective cost of basic services is $44 per month, assuming no subsidies. The question then becomes: how does this compare to what low-income households can afford for monthly electricity bills?

While there is variation by country and region, the poorest 3.3 billion people who make less than $5.5 a day can be grouped into three segments based on World Bank's poverty line definitions[3]— 'low income' (earning $3.2 to $5.5 per day), 'subsistence' ($1.9 to $3.2 per day) and 'extremely poor' (less than $1.9 per day) (World Bank, 2018c) (**Exhibit 20**).

These households typically spend 10 percent of their income on energy, of which roughly half is spent on cooking. This translates to monthly electricity budgets of $8.25, $4.80 and $2.85 respectively, for each of the three segments described above.

Therefore, it appears that the effective cost of electricity for a basic portfolio of appliances—$44 per month—is five times what populations living in the $3.2 to $5.5 per day income range can afford, and significantly more than what populations living at 'subsistence' and 'extreme' levels of poverty can afford.

[2]Based on primary research interviews with Smart Power India (SPI), a Rockefeller Foundation Initiative
[3]International poverty line is at US$1.90 PPP; lower middle-income class poverty line is at US$3.20 PPP; upper middle-income class poverty line is at US$5.50 PPP (World Bank, 2018c)

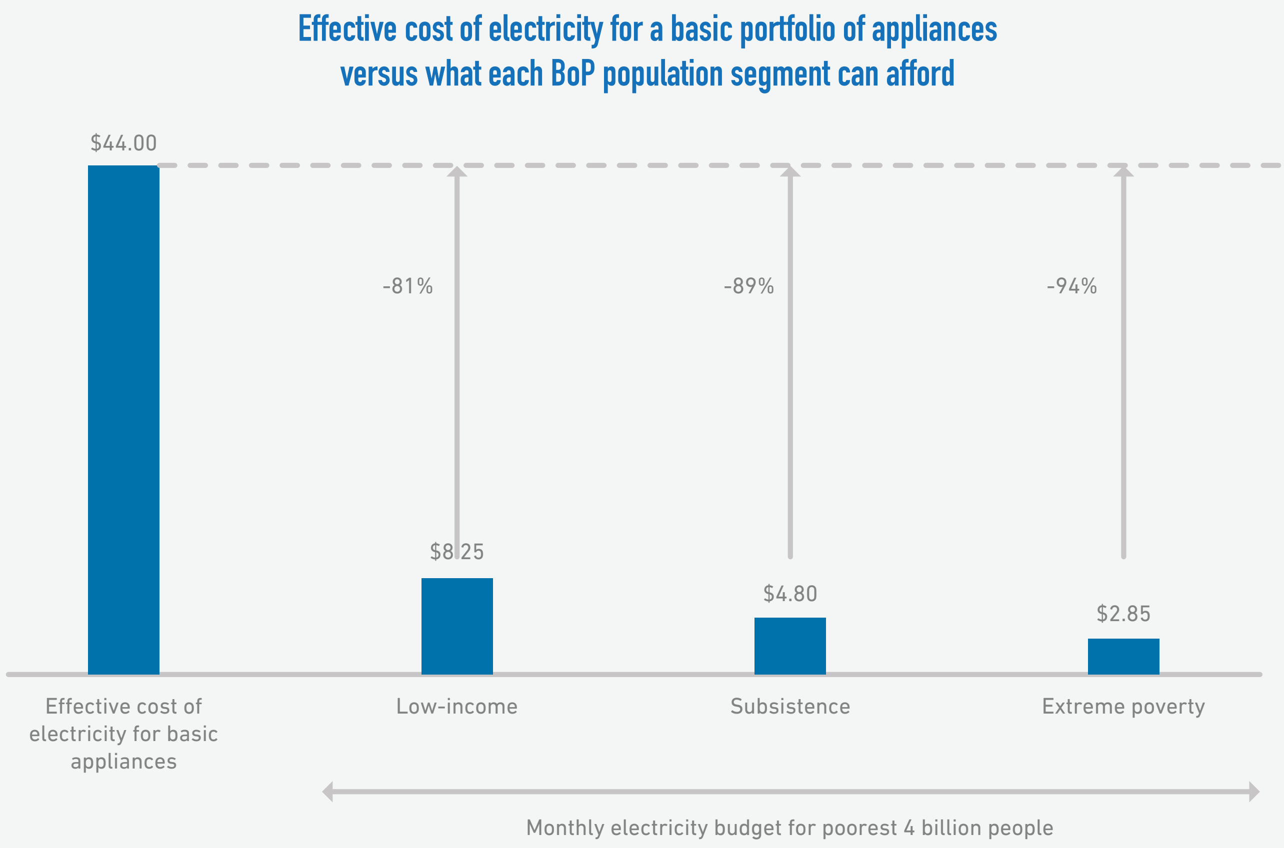


Exhibit 20: The effective cost of basic services in decentralized solar PV mini-grids with storage will have to fall sharply to match the electricity budgets of populations earning less than $5.5 per day. The effective cost of services is driven by the cost of electricity and the efficiency of appliances. (Source: ITT analysis)

For electricity to be affordable for the practical needs of human development, it needs to become less expensive and appliances need to become more efficient. In effect, this relationship between the required decrease in the cost of electricity and the increase in appliance efficiency represents an isoquant, which is shown in **Exhibit 21**.

It is important to note that this is an illustrative analysis using benchmarks and does not represent actual observed data (which may be influenced by a range of factors). For instance, consumption will be influenced by quality of electricity, subsidies and pricing schemes for appliances and electricity.

The cost of electricity will vary widely by installation, availability of resources, cost of capital and subsidies. The purpose of our analysis is not to pinpoint precise numbers, but rather to illustrate the wide gap between effective cost of electricity for basic needs and what low-income populations can afford.

As **Exhibits 19** to **21** demonstrate, improving the energy efficiency of mechanized appliances like refrigerators and other productive-use appliances would be an effective way to make electricity more accessible to low-income populations.

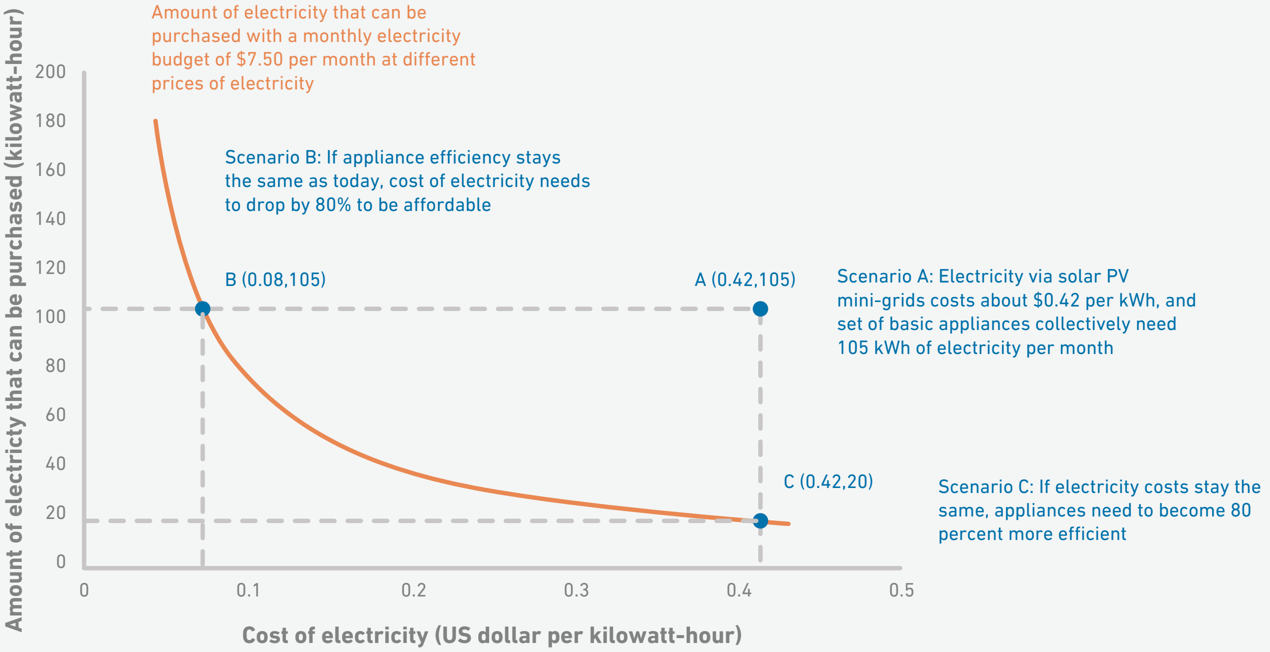


Exhibit 21: The effective cost of electricity can be reduced for low-income populations if the cost of electricity declines and/or if the efficiency of appliances improves. Currently, electricity via solar PV mini-grids costs $0.42 per kWh (including storage) and the illustrative portfolio of basic appliances consumes 105 kWh per month. Based on this, there is an affordability gap of greater than 80 percent (as shown in **Exhibit 20**). Hence, either the cost of electricity needs to be reduced by 80 percent or the combined energy efficiency of the basic portfolio of appliances needs to improve by 80 percent. This is an illustrative analysis, because low-income populations cannot currently afford the appliances. One assumption is that the cost of the appliances themselves will decrease, at which point their energy efficiency will become a significant barrier to adoption. Note that this analysis applies only to the people living on $3.2 to $5.5 per day. The gap for people living on less than $3.2 per day is much higher.

3. Available solutions for stationary electricity storage are too expensive and present challenges providing a continuous supply of quality electricity in renewable energy mini-grids

Environmentally sustainable energy storage solutions are essential for providing continuous and reliable supply of electricity in renewable energy mini-grids. However, neither the cost nor the performance of existing technologies is adequate.

Electrochemical storage, in its current form, is very expensive and significantly drives up the cost of electricity supplied. Even lead acid batteries—the cheapest commercially viable solution—comprise close to 15 percent[4] of the upfront cost of a mini-grid system and are one of the three biggest cost components of the solar mini-grid setup (along with PV panels and power electronics).

Rechargeable batteries need to perform along a range of parameters to be effective in decentralized systems: high depth of discharge (the ability to come as close to being fully discharged, without adverse effects on battery life); memory effect (reduction in the battery's maximum capacity, when it is repeatedly recharged without being fully discharged); round trip efficiency (the ratio of energy recovered from a storage device to the amount of energy put into the device); and operating needs such as cooling, pumping, threshold operating temperatures, and level of technical expertise required for installation and maintenance.

Each family of rechargeable batteries has its unique advantages and challenges (**Table 3**).

[4]Based on discussions with mini-grid experts in India

		Technical/performance parameters							
		Capitial cost (US dollars per kilowatt-hour)	Cycle life	Deep discharge	Partial state-of-charge	High ambient temp.	Maintenance	Environmental footprint	Likely potential for cost reduction via scale/local manufacturing
Mature	Lead-acid	100-150	800-2,000	◔	○	○	◕	◑	○
	Li-ion	300-500	2,000-3,000	◕	◕	Varied	◕	◑	◕
	NiFe	600-800	>7,500	●	●	◑	◕	◕	◔
Emerging	Advanced Lead-acid	300-350	5,500	◑	◑	◑	◕	◑	◕
	Flow	500-1,000	>7,500	●	●	◕	◔	◑	◑
Next generation	Aqueous hybrid ion	350-500	>5,000	●	●	●	●	●	◕
	Zn-hybrid	350	>5,000	◕	◕	TBD	TBD	TBD	◑

● - Favorable ○ - Unfavorable

Table 3: Comparative assessment of different rechargeable battery technologies that are suitable for bulk storage services in mini-grids. (Source: ITT, 2017)

One major reason lead-acid batteries have been the default storage solution is that they benefit from being the battery of choice for automobiles. The rapid global proliferation of EVs is creating a similar large-scale platform based for Li-ion batteries as an option for mini-grids, at least in the long run.

The cost of Li-ion batteries has been in a steady state of decline (**Exhibit 11**) and according to estimates will fall to $100 per kWh by 2026 (BNEF, 2018).

The market for batteries exclusively designed for solar mini-grids is very small, and it will be very challenging for new chemistries to survive on their own, no matter how good their performance.

This challenge was highlighted by the recent bankruptcy filing by Aquion Energy, the manufacturer of a promising sodium-ion battery designed for mini-grids and similar uses. Other early-stage chemistries being explored today, such as zinc-hybrid, flow, nickel iron and solid-state, will face a similar challenge.

SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

Some of the most impactful levers for facilitating universal access to electricity may very well be policy reforms and support for market-based solutions. These solutions include financing mechanisms to improve access to affordable long-term capital for both electricity providers and consumers, stronger regulations to ensure transparency in tariffs and reduce risk for private sector actors, and leveling the playing field for independent power providers (for example, through feed-in-tariffs, power purchase agreements and comparable subsidies for renewable energy systems as are currently provided for fossil fuels).

Because centralized generation and distribution has been the norm since the advent of electricity, the technologies are mature and few breakthroughs are expected to extend the main-grid to remote unelectrified locations.

In contrast, with incremental improvements to solar cell technology and production efficiencies, costs have been coming down at an impressive rate and are putting utility-scale solar power at a competitive price-point with fossil fuel generated electricity. This reduces the need for, and potential of, new breakthroughs in solar capture technology.

Distributed mini-grids, which are projected to play a crucial role in electrifying the last 10 to 15 percent of the global population, can benefit from technological breakthroughs. What is needed is to reduce the upfront cost and complexity of installation and maintenance of mini-grids, and increase efficiencies for production and consumption, to facilitate the creation of self-sustaining markets that can scale up quickly. We believe three breakthroughs can accomplish this.

Breakthroughs:

1	2	3	4	5	6	7	8	9	10
11	12	13	14	15	16	17	18	19	20
21	22	23	24	25	26	27	28	29	30
31	32	33	34	35	36	37	38	39	40
41	42	43	44	45	46	47	48	49	50

43 A standardized, solar mini-grid system that makes it simpler, cheaper and faster to set up and operate mini-grids

Making solar mini-grids inexpensive and easy to install will significantly help scale these systems up. The key drivers of capital expenditures for solar photovoltaic (PV) mini-grids are the PV modules and the balance-of-system (BOS). The BOS comprises both equipment, such as power electronics like inverters and racking structures, and soft costs like labor, site preparation and licensing fees.

BOS costs vary widely by geography, primarily because of soft costs. While PV modules, lithium ion batteries and power electronics are all experiencing steady declines in costs, there exists potential for optimizations in the BOS costs.

Currently, the installation process for solar mini-grids is a time consuming, unpredictable and challenging process involving a highly fragmented supply chain. Many components need to be procured, transported and integrated in hard-to-reach places without supporting infrastructure or adequate skilled labor.

A standardized system, which is easy for technicians (with some training) to install in a few days and simple to maintain on an ongoing basis, will significantly improve the economics of rural mini-grids.

In addition to reducing the balance-of-system costs, a standardized system will minimize the need for technical expertise for operations by simplifying operations and maintenance (which is another major hurdle to the proliferation of mini-grids).

Current State

Development Stage: In-Market Small Scale

Deployment: Complex

Associated 50BT Chapters

Access to Energy

SDG Alignment

Impact

New Income Generated (# of People)

<1M 10M+ 100M+ 1B+

Improved Quality of Life (# of People)

<1M 10M+ 100M+ 1B+

Commercial Attractiveness

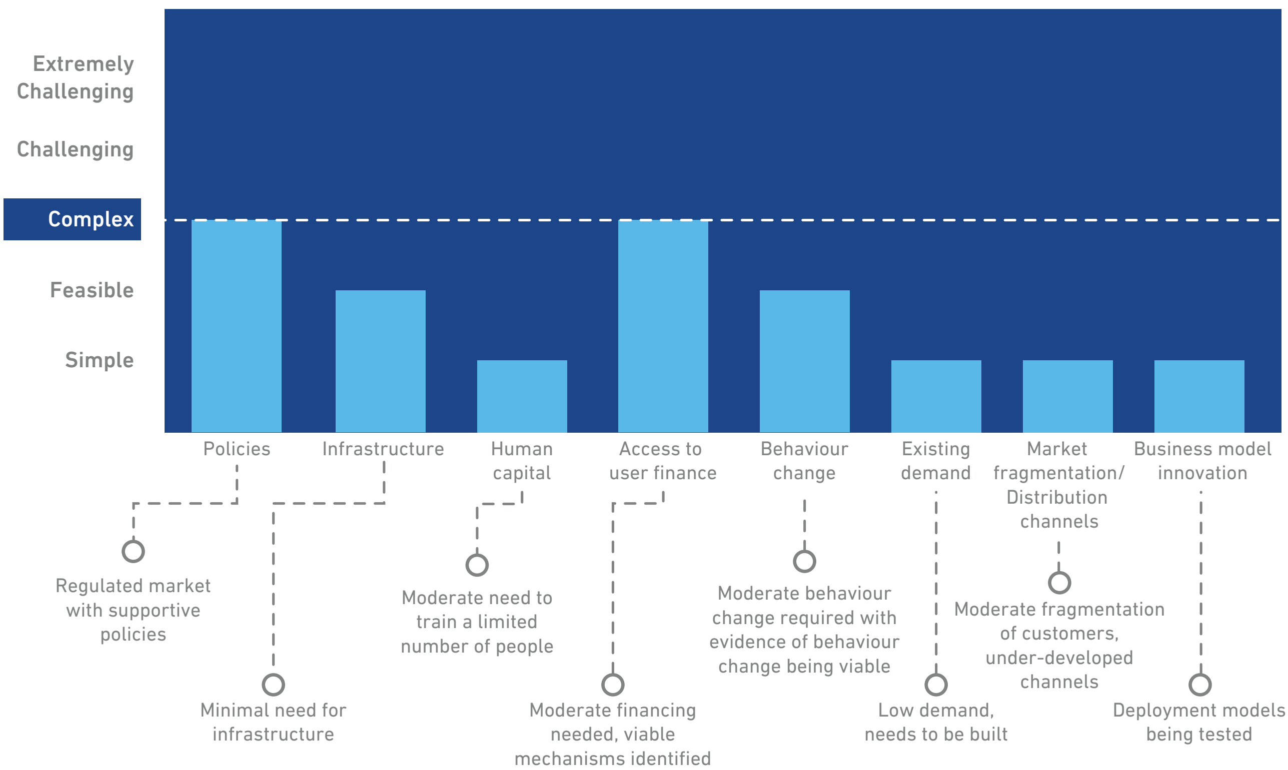
- Attractive for industrialized markets (high profits)
- **Attractive for emerging markets (lower profits)**
- Emerging markets potential; requires derisking (sustainable)
- Non-commercial (unprofitable)

Such a system should include all the key components of a decentralized renewable energy mini-grid for generation, storage and grid management. Standardization and self-help tools for installation, O&M and troubleshooting will be key.

Similarly, modularity and configurability—to meet the specific power demands of a particular installation—will be crucial to ensure adequate capacity and maximum capacity utilization. An early version of such a technology is currently being deployed by ITT after several years of design, integration and standardization of components.

Deployment challenges include limited current demand, challenging market economics and a lack of skilled technicians to install and maintain the systems. As such, deployment will be COMPLEX.

Breakthrough 43: Difficulty of deployment



44 Appliances for household use and income generation that are significantly more affordable and energy-efficient than those on the market

For electricity to have an impact on development and quality of life, users need a range of amenities and services. This requires electrical appliances for reducing manual workloads, physical discomfort and health hazards, increasing the productivity of income generating activities and enabling digital inclusion. These appliances include lighting, fans (or other cooling mechanism for the home), refrigerators (to preserve perishable foods), ICT devices (such as TVs and computers), and income generating appliances (such as irrigation pumps, in the case of farmers).

As things stand, pre-electrification appliances like solar LED lights and systems for charging mobile phones are now common on the market. However, appliances like TVs and refrigerators are currently not an option for low-income rural populations because they are too expensive (by a factor of three or more) and require reliable electricity. There is increasing evidence that there will be strong demand for appliances like these. The strong demand, combined with economies of scale resulting from mass production, will keep pushing down market prices.

Even if these appliances became affordable, the amount of electricity that current appliances consume is more than the available energy budget of the 3.3 billion people living on less than $5.5 per day. While energy efficient versions of some of these appliances are appearing in industrialized markets, they tend to cost more than the energy-intensive versions (even though in many cases, the electricity savings eventually compensate for the higher prices). Improving the efficiency of low-cost versions of these appliances is critical to ensuring that electrification realizes its potential impact. Improving the overall affordability of appliances will also lead to an increase in demand for electricity. Increasing efficiency will reduce the load on mini-grids, in turn reducing the likelihood of power failures and load shedding.

Despite the benefits, businesses have so far been reluctant to invest in developing ultra-low-cost, energy efficient appliances for low-income populations because of market uncertainties and high opportunity costs. In emerging markets, urban middle and lower-middle income users represent a profitable segment where profits are yet to be fully tapped out, and also have better risk-reward profiles than rural low-income markets. To serve the latter with the right kind of energy efficient appliances, businesses need to invest in R&D to design for rural needs and create new distribution channels that are expensive and risky propositions with long payback periods.

Current State

Development Stage: In-Market Small Scale

Deployment: Complex

Associated 50BT Chapters

Access to Energy

SDG Alignment

7 AFFORDABLE AND CLEAN ENERGY

8 DECENT WORK AND ECONOMIC GROWTH

Impact

New Income Generated (# of People): <1M | 10M+ | 100M+ | 1B+

Improved Quality of Life (# of People): <1M | 10M+ | 100M+ | 1B+

Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- **Attractive for emerging markets (lower profits)**
- Emerging markets potential; requires derisking (sustainable)
- Non-commercial (unprofitable)

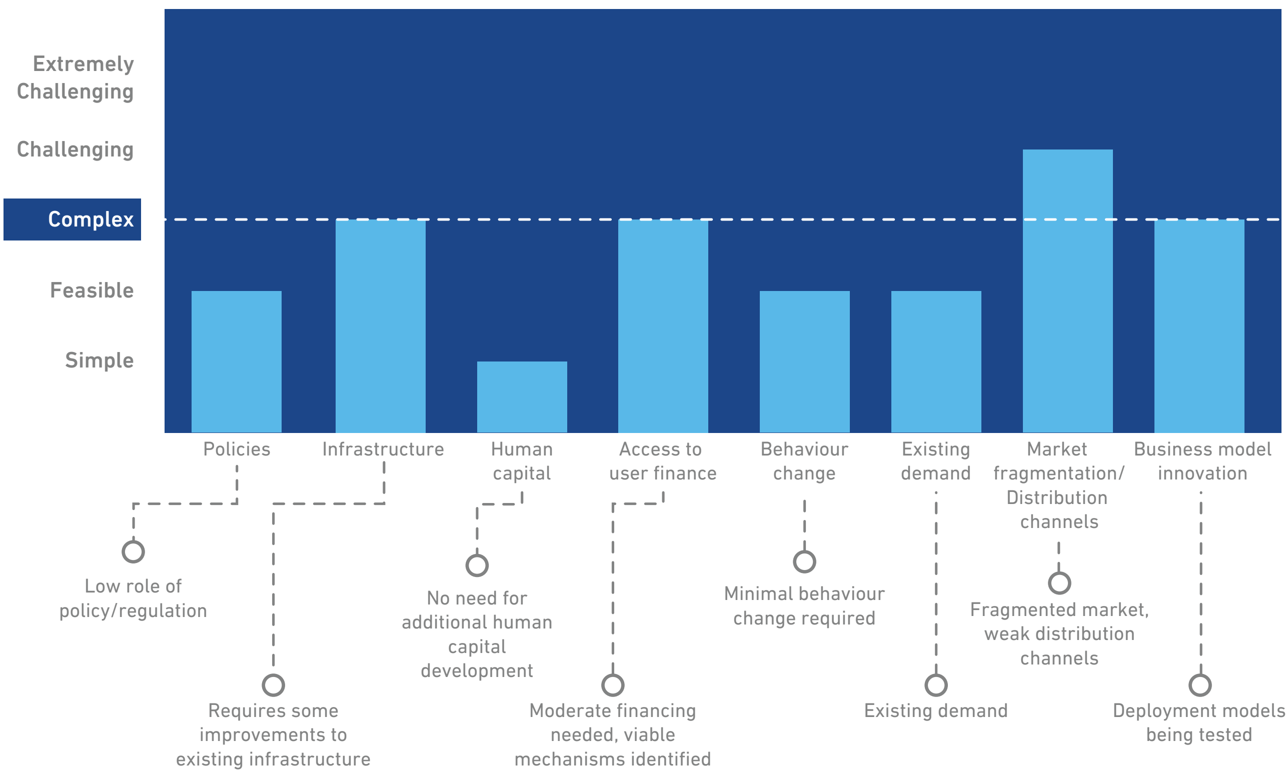
Specific opportunities vary by type of appliance:

- Fans with brushless direct current (BLDC) motors that are twice as efficient as ones with conventional induction motors have entered Indian markets. More efficient blades lead to a two- to four-fold increase in efficiency compared to the US EPA's Energy Star requirements (Sathaye, et al., 2013).
- While BLDC motor driven refrigerators are not yet fully commercial, a new inverter technology allows for variable speed compressors rather than the conventional on/off compressors, thus saving electricity consumption. Refrigerators can also achieve high efficiency gains simply with better insulation and through advances in new refrigerants that improve the efficiency of cooling engines (Shah, et al., 2013).
- Super-efficient televisions that draw a fraction of the power of currently available efficient TVs are also beginning to become commercially available (Cnet.com, 2014).

In general, the observed pattern is that energy efficient appliances with improved technologies have started appearing in urban markets. These innovations are currently focused on the environmental concerns of high-income industrialized markets and are not being designed for the constraints of low-income rural markets. Thus, while affordability may be achieved by mass production, technological advancements will most likely be the driver of energy efficiency.

Still, with rapidly growing markets like India, we believe some of these appliances will begin to appear within the next three years, while others will take five years or more. The key deployment challenge will be distribution, as is typical for rural markets, especially for products that require post-sales technical support. The upfront cost of appliances will also be a barrier but could potentially be addressed using financing schemes. User support services will be crucial as most target customers will be first time users, and these products will be significant investments for them. Overall, deployment will be COMPLEX.

Breakthrough 44: Difficulty of deployment



45 New electricity storage technologies that can be used for decentralized mini-grids, which provide improved performance at a cost approaching that of lead-acid batteries

Consumers use appliances at different times of the day, based on their specific household and livelihood needs, rather than limited by the availability of power. In the case of distributed solar PV mini-grids, for example, users need lighting precisely when sunlight is not available. Similarly, refrigerators need to run continuously through the night and day.

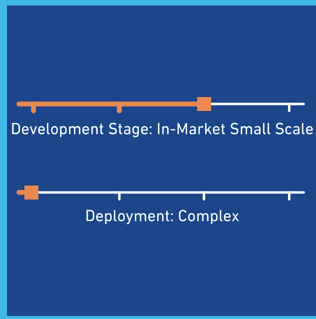
To enable such usage, a continuous and reliable supply of electricity will be required, without which the value of electricity will be limited, as will the willingness of users to pay for it. Some appliances, such as refrigerators, will not be very usable without continuous power. This makes bulk electrical energy storage services essential for renewable energy mini-grids in off-grid locations, where sources are intermittent and backup power from main grids is not an option.

Whereas large-scale storage solutions, such as pumped water, are practical in some locations for main grid, there are major gaps in current storage technologies usable for mini-grids. In fact, one of the main challenges limiting decentralized solar mini-grids is the absence of cost-effective, reliable and high-performance energy storage solutions. In general, the useful life of a battery is dependent on the operating depth of discharge (DOD), environmental conditions like ambient temperature, charge-discharge rates and the operating voltage range. The current standard—lead acid batteries—faces serious performance limitations causing early degradation of battery capacity, especially at high ambient temperatures.

Lithium ion batteries present a promising alternative; however, even with rapidly declining costs, they are presently too expensive for mass adoption in mini-grids. It is estimated that stationary storage systems cost close to 50 percent more than those used in electric vehicles because of lower volumes and associated cost of battery management system (BMS) design. In addition, concerns around safety hazards from overheating need to be addressed. Still, it is widely believed by experts that lithium-ion batteries will be the solution for mini-grids at some point in the future, as the growing global market for electric vehicles is driving down the cost.

Other rechargeable battery technologies with improved cost and performance are beginning to appear on the market at small scale. Each emerging technology faces its own set of challenges. Flow batteries—relatively easy to configure and scale with limited technical expertise and with a long life—have low energy densities and need cooling mechanisms as well as safeguards for potentially toxic chemicals that are needed to make them. Sodium-sulfur batteries appear promising with respect to cost and performance, but are very bulky and corrosive and operate at very high temperatures.

Current State

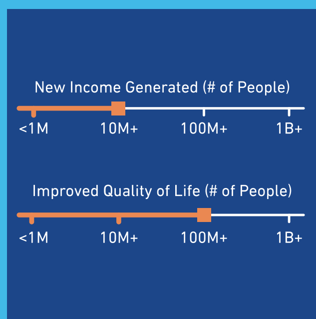


Associated 50BT Chapters

Access to Energy

SDG Alignment

Impact



Commercial Attractiveness

- **Attractive for industrialized markets (high profits)**
- Attractive for emerging markets (lower profits)
- Emerging markets potential; requires derisking (sustainable)
- Non-commercial (unprofitable)

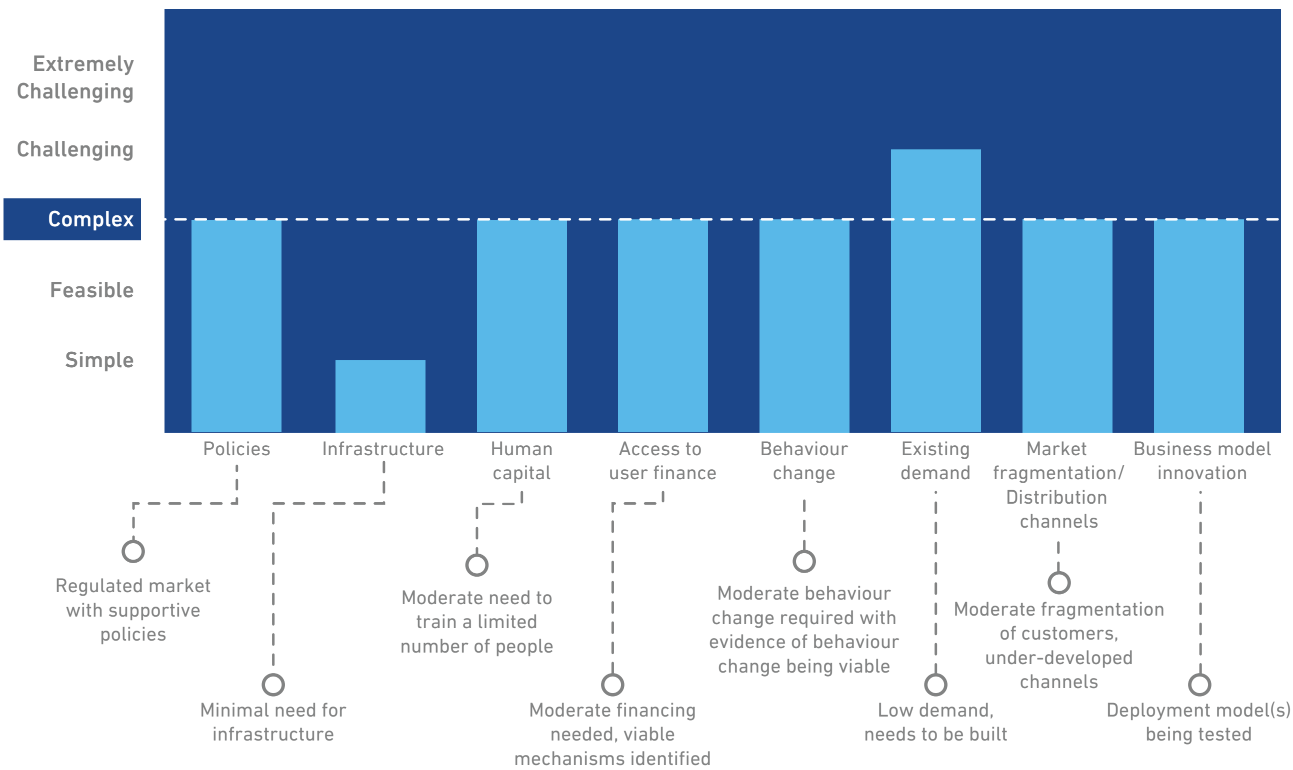
Beyond low cost, a suitable technology will also need to be robust, durable, compact, easy to transport and easy to install. It should also be modular and configurable, with the ability to scale up or down based on usage levels. Operation and maintenance should require minimal technical expertise and limited additional infrastructure.

The two battery chemistries that have so far been commercially successful in mini-grids have catered to the much larger automobile industry. There is a lot of research dedicated to developing suitable energy storage systems for the main-grid infrastructure that could also prove useful at the mini-grid scale. As such, it will be very difficult for a new chemistry to be financially viable while catering to mini-grids alone given the small (in terms of kWh needed) and dispersed nature of the market.

Batteries are an essential component of decentralized rural mini-grids. Hence, the deployment challenges will be those associated with mini-grids overall. These include limited demand, very difficult market economics of a nascent market, and a dearth of technical skills required to install and maintain the systems.

In addition, a number of safety issues will need to be addressed for technologies like sodium-sulfur, and to a lesser extent, lithium-ion. While slightly varying depending on the specific battery technology, deployment will be COMPLEX.

Breakthrough 45: Difficulty of deployment



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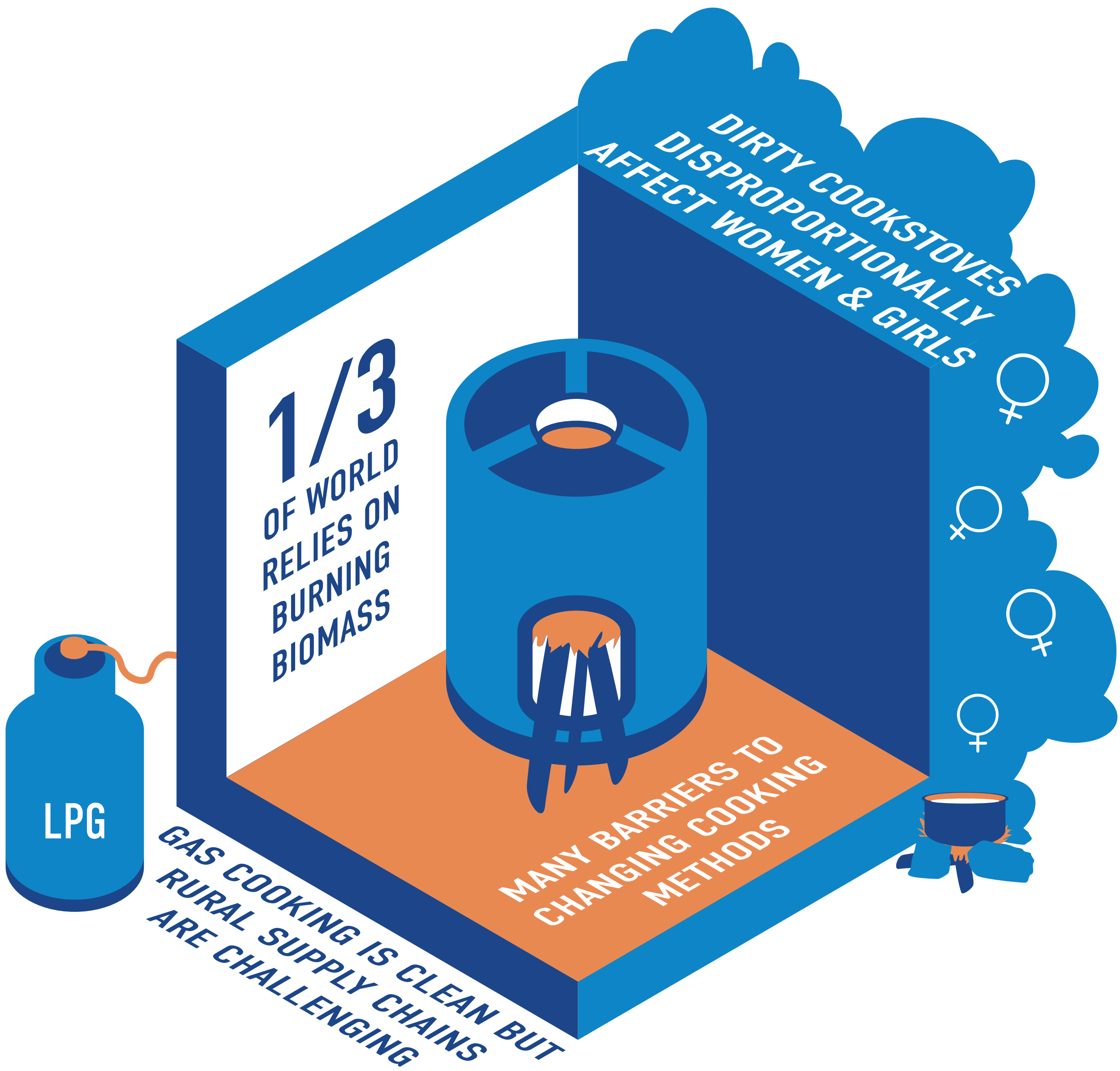


CLEAN COOKING

INTRODUCTION

Cooking is an indispensable activity practiced by virtually all households, rich and poor alike.

It is typically the most energy intensive activity conducted by low-income households in developing countries. Solid fuels like wood and coal are often burned inside homes for cooking and heating, creating household air pollution that contributes to respiratory disease and other health problems, as well as contributing to ambient air pollution. Women and girls, who often carry the responsibility of cooking and collecting fuel, are disproportionately affected by dirty cookstoves.

Current efforts to improve access to clean cooking vary widely by region in terms of technological approach, implementation strategy and scale. Many urban areas continue to expand infrastructure for electricity, liquefied petroleum gas (LPG) and natural gas. Their rural counterparts are left with fewer viable options, because utility infrastructure challenges are greater when population density is lower.

There is growing interest in developing and deploying improved biomass cookstoves that burn organic matter, such as wood, charcoal, dung and crop residues, with higher efficiency and less harmful emissions.

While a number of improved stove technologies now exist, widespread diffusion and use remains elusive due to technical, cultural and economic challenges, and about 2.5 billion people, or a third of the world's population, rely on traditional burning of solid biomass for cooking.

Development and implementation of future clean cooking solutions must involve close collaboration with local communities, particularly women who are the primary users of cookstoves. Communication and user-centered-design is essential to ensuring that proposed solutions meet the operational capabilities, cultural practices and financial limitations of intended users. We have identified two technology breakthroughs that can have a direct effect in improving access to clean cooking:

- Breakthrough 46. Advanced biomass cookstoves that are desirable, affordable, robust and very clean
- Breakthrough 47. Novel ways of converting household or village waste products into clean cooking fuel or electricity

Lack of access to clean cooking fuels and stove technologies are a major barrier to human development in many parts of the world. While virtually everybody in industrialized countries uses clean electricity and gas for cooking, about 2.5 billion people in developing regions still burn traditional solid fuels such as wood, charcoal, coal, crop residue and dung to cook meals. These fuels are often burned with low efficiency and large amounts of harmful emissions, inside poorly ventilated homes, creating a plethora of problems for users and their communities.

CORE FACTS AND ANALYSIS

1. Cooking is both indispensable and energy intensive

Cooking food is a defining characteristic of the human species, shared by all societies and not practiced by any other species. Cooking is part of our long human roots. Fossil evidence suggests that early hominids used fire to cook food as early as 1.9 million years ago, and controlled use of fire appears in the archaeological record about 400,000 years ago (Bowman, et al., 2009).

Beginning about 50,000 to 100,000 years ago, fire has been routinely used by humans for domestic purposes. The controlled burning of wood enabled the cooking of foods, which gave early humans an advantage over other creatures because cooked food required less endosomatic energy for digestion, allowing more net food energy to be used for beneficial purposes.

Continuing up to the present, cooking is an indispensable human activity. Virtually all households, no matter their social or economic status, cook food every day, and often multiple times per day. The daily cooking process is, by far, the most energy-intensive activity in typical households in developing countries.

Exhibit 1 shows the energy used by various components of a typical low-income household. Basic electrical appliances, such as lighting, fan, refrigerator and television use, in total, roughly 0.21 gigajoules of electrical energy per month. An electric cooker, by contrast, uses more energy than all these other appliances combined—roughly 0.32 gigajoules per month.

Even more energy is needed if a wood-fueled cookstove is used instead, due to the lower efficiency of converting the biomass energy to useful cooking. A traditional biomass cookstove uses roughly 2.4 gigajoules of thermal energy per month, while an improved biomass cookstove uses about 1.4 gigajoules per month.

By comparison, the endosomatic energy use of human metabolism by a five-person household corresponds to about 1.3 gigajoules per month. In the parlance used in the Overview section of this chapter, this means that cooking uses the energy equivalent of at least one full-time energy servant per person.

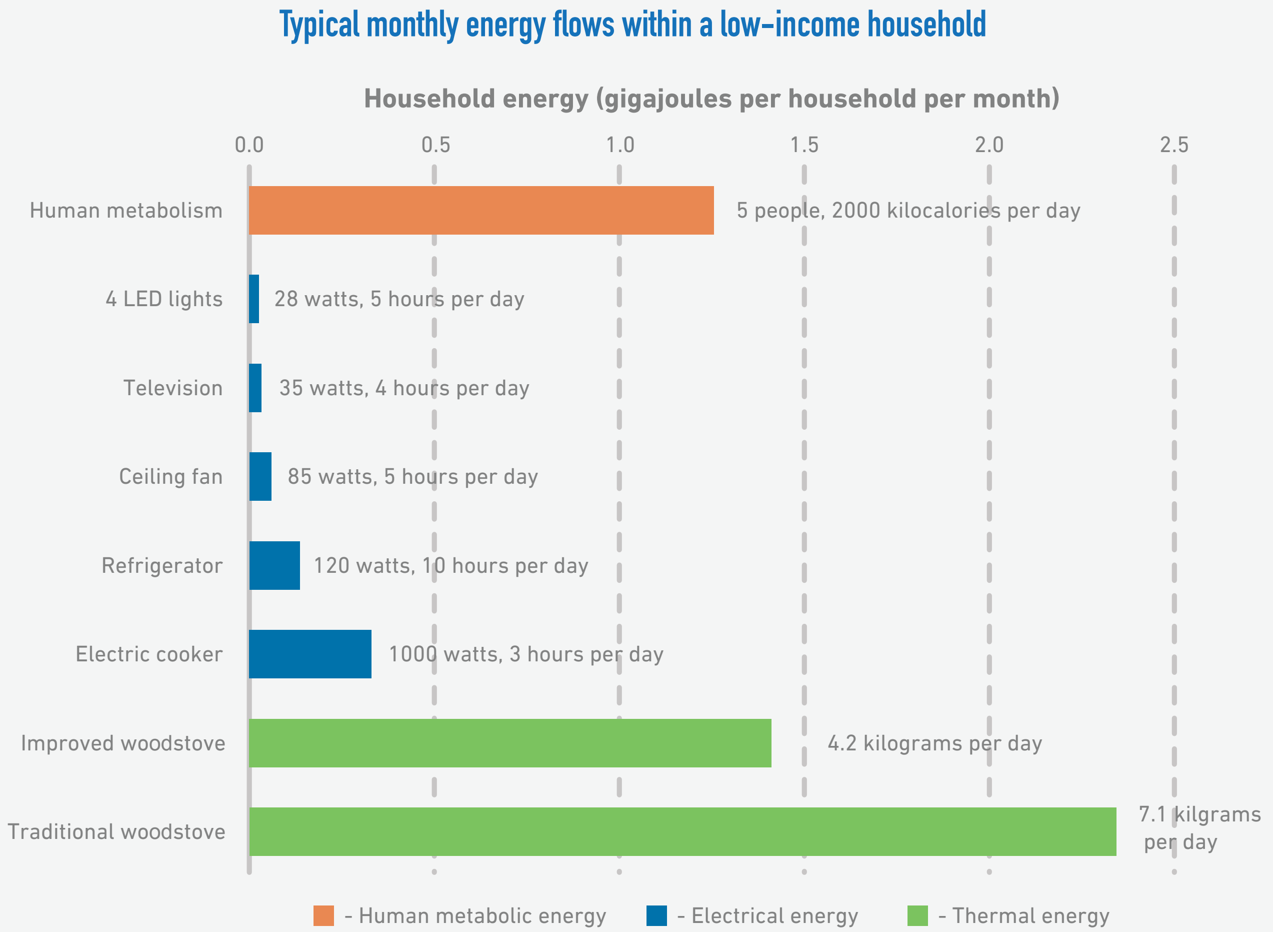


Exhibit 1: Cooking is the single most energy intensive activity of a typical low-income household. (Source: ITT analysis)

2. Many different household cooking methods can be used, with a wide variety of performance characteristics

A wide range of techniques can be used for cooking food. Beginning with open wood fires that have been used for thousands of years, many types of stoves have been developed to provide more controlled cooking conditions.

While wood is still widely used for cooking, a number of other fuels such as coal, gas, kerosene and electricity are also used.

Different fuel and stove combinations have varying characteristics in terms of health and environmental impacts, costs and complexities. **Table 1** provides an overview of the range of household cooking options, and these options are described in more detail in the following pages.

Legend:		good	fair	poor	bad		
Category	**Type**	**Health Impact**	**Environmental Impact**	**Initial cost**	**Operating cost**	**Fuel availability**	**Installation and maintenance complexity**
Traditional Biomass Stove	Wood	High PM, medium CO emissions	Ambient air pollution, GHG emission	Very low	Fuel collection or purchase	Wood fuel usually easily available	Simple and traditional
	Charcoal	Medium PM, high CO emissions	Ambient air pollution, GHG emission	Very low	Fuel collection or purchase	Requires charcoal supply chain	Simple and traditional
Coal Stove	Coal	Medium PM, high CO and carcinogen emissions	Ambient air pollution, GHG emission	Low	Fuel purchase	Mostly used in coal abundant areas	Simple and traditional
Improved Biomass Stove	Basic	PM, CO emissions	Ambient air pollution, GHG emission	Very low	Requires less fuel than tradition stove	Wood fuel usually easily available	Simple and traditional
	Intermediate	Medium PM, CO emissions	Ambient air pollution, GHG emission	Low	Requires less fuel than tradition stove	Wood fuel usually easily available	May require chimney or maintenance
Advanced Biomass Stove	Fan Gasifier	Current versions have inconsistently low emissions	Generally reduces emissions	Medium	Requires less fuel than tradition stove	May require processed fuels	Typically requires maintenance
Modern Fossil Fuel Stove	Kerosene	Medium/low emissions, poisoning, burns	GHG emissions, ambient air pollution	Medium	Fuel purchase	Requires kerosene supply chain	Simple
	LPG	Very low emissions	GHG emissions	Medium	Fuel purchase	Requires LPG suply chain	Requires installation
	Natural Gas	Very low emissions	GHG emissions	Medium	Fuel purchase	Lack of supply chain infrastructure	Requires installation
Electric Stove	Electricity	No emissions	Depends on electricity source	Medium	Typically high cost	Electricity supply often lacking or irregular	Requires installation
Renewable Fuel Stove	Biogas	Very low emissions	Recycles waste	Very high	Very low cost if digestible material is available	Requires supply of digestible biofuel	Requires skilled installation and operation
	Solar	No emissions	Clean, renewable	Low	Free sunlight	Depends on weather	Requires installation
	Ethanol	Very low emissions	GHG emissions	Medium	Fuel purchase	Requires ethanol supply chain	SImple

Table 1: Overview of cookstove types and their performance characteristics.

Standard metrics for testing cooking methods are typically measured for the end use of a fuel and cookstove technology pair. These metrics include carbon monoxide emissions, particulate matter emissions and thermal efficiency (the percentage of energy stored in a fuel that is transferred to the pot or cooking dish), and are analyzed using a series of standardized tests such as boiling water in a controlled environment.

These metrics are then synthesized into standardized tier-based performance levels published by the International Organization for Standardization (ISO). Previously comprising five tiers (Tier 0 to Tier 4), the current standards released in 2018 comprise six tiers (Tier 0 to Tier 5) (ISO, 2018).

Higher tiers correspond to improved efficiency and safety and to reduced emissions of pollutants. **Exhibit 2** shows illustrative emissions levels of various combinations of stoves and fuels, and their correspondence to ISO tiers (Berkeley Air Monitoring Group, 2012).

These cookstove performance tiers are used to compare different cooking methods, but it is important to consider these tiers within the context of the proposed implementation area. While the ideal cookstove would rank Tier 5 in all measurement categories, in real life there are tradeoffs in performance characteristics, and a host of non-technical factors that affect outcomes.

Metrics outside of ISO standards are also important in determining the suitability of a particular cooking solution and should also be given significant weight. These include, for example, compatibility with local customs, reliability, ease of maintenance, employment potential, and overall costs and benefits in a life cycle perspective over the entire supply chain.

Improved cooking solutions can be loosely defined as cooking systems (fuels, stove technology and supply chains) that provide improvements over the current health, environmental, social and economic effects of established cooking methods.

While a general goal is the adoption of clean cooking methods, there is no definitive threshold that separates clean from non-clean cooking systems. Rather, each cooking solution has measurable metrics which lie on independent spectrums and have different implications for users, the environment and communities.

Air pollutant emissions of selected cooking methods

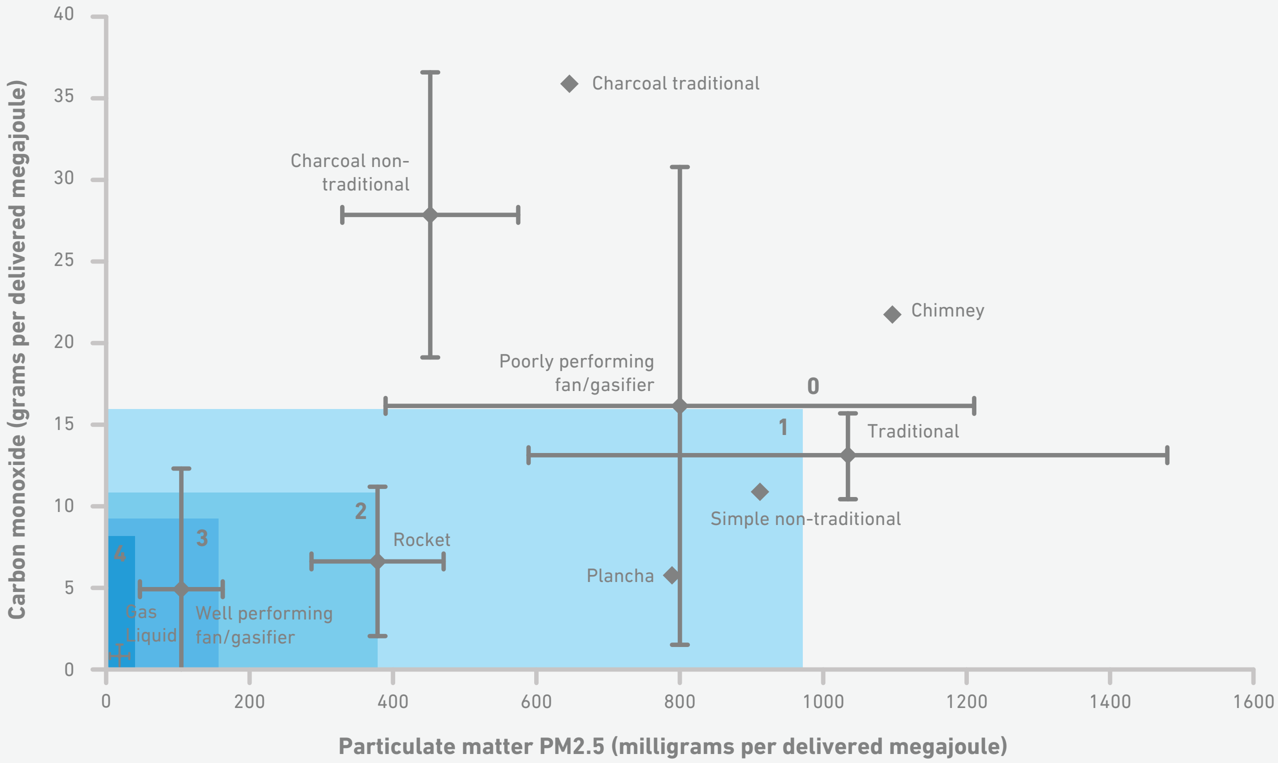


Exhibit 2: Comparison of particulate matter (PM2.5) and carbon monoxide (CO) emissions of a variety of cookstoves and fuels tested in laboratory conditions. Error bars represent plus/minus one standard deviation of the available test sets. Data points without error bars are based on two or fewer tests. Blue shading and numbers indicate tier levels based on previous ISO five-tier rating system. (Source: Berkeley Air Monitoring Group, 2012)

3. There is great variety in cooking methods used in different regions, and traditional solid fuel is still widely used in developing countries

There are strong geographical differences in the types of cooking methods utilized (**Exhibit 3**). In sub-Saharan Africa, more than three-quarters of households use solid cooking fuels, mainly wood (IEA, 2017).

Similarly, more than half of Indian households use solid fuels. Gas fuels are more commonly used in Latin America, North Africa and the Middle East. Chinese households use a wide range of fuels, including gas, wood, coal and electricity.

In the United States, the most common cookstove is electric (61 percent of household stoves), followed by natural gas ((33 percent) and LPG (5 percent) (EIA, 2018a). In addition to variation between countries, there is also a strong difference in cooking fuel type between urban and rural populations (**Exhibit 4**). Rural populations tend to use more wood fuel, while urban populations use more gas.

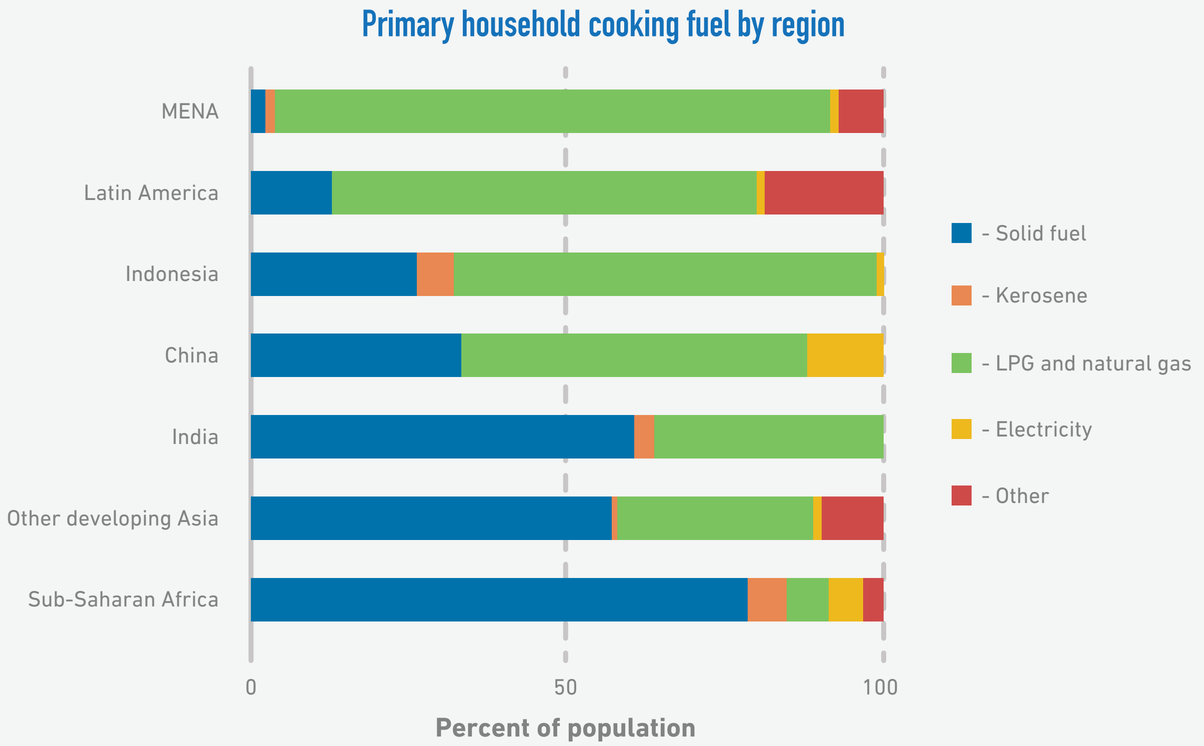


Exhibit 3: The type of cooking fuel used by households varies widely by region. Most households in Sub-Saharan Africa and India use solid cooking fuels, mainly wood. Gas is the most common fuel used in many other regions. (Source: IEA, 2017)

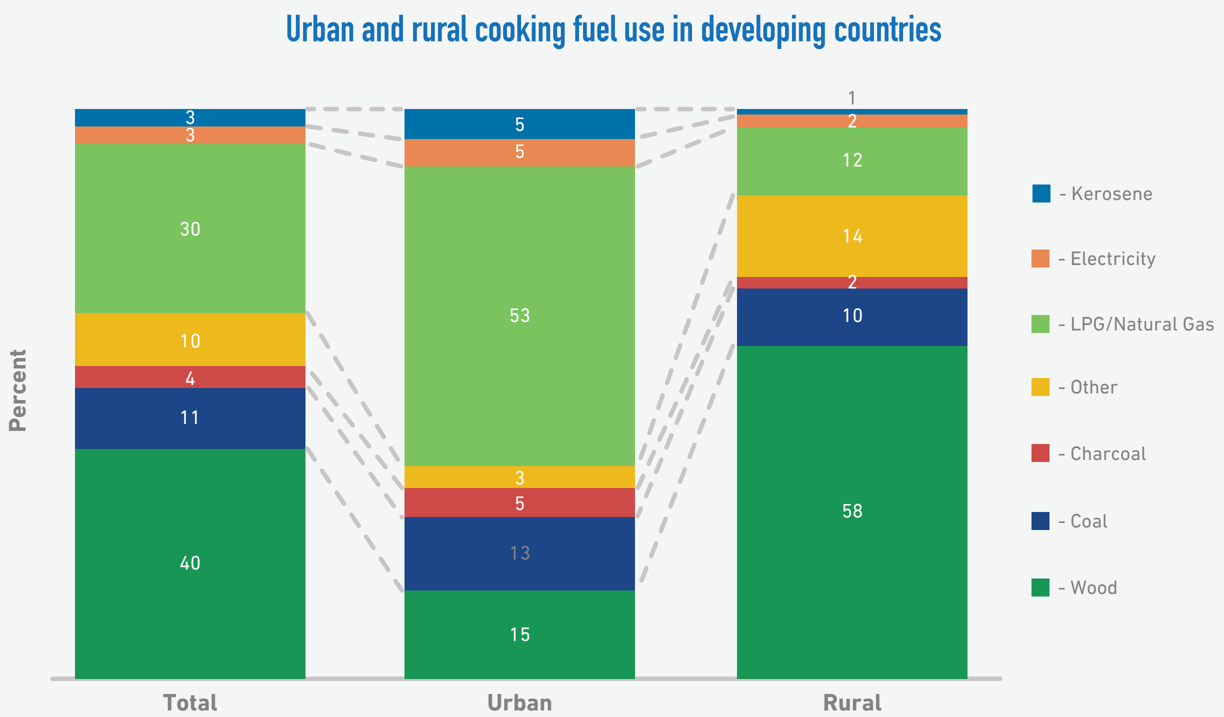


Exhibit 4: There is a strong difference in cooking fuel type between urban and rural populations in developing countries. In general, rural populations use more wood fuel, while urban populations use more gas. (Source: Putti, et al., 2015)

Trends in many developing regions during recent decades have shifted away from solid fuels and kerosene and instead moved towards cleaner fuels like gas and electricity. Between 2000 and 2015, the number of people using clean cooking fuels increased by 60 percent, and the number of those using coal and kerosene for cooking decreased by more than 50 percent (IEA, 2017). Several Asian countries, such as China and Indonesia, have made significant reductions in solid fuel and kerosene use during recent decades.

Despite trends toward cleaner cooking in many regions, about 2.5 billion people, or a third of the world's population, continue to use solid biomass fuels (which includes fuels like wood, charcoal, dung and crop residue) to cook their meals (IEA, 2017) (**Exhibit 5**). Another 170 million people, mainly in China, use coal for cooking. Although the percentage of total population that uses solid fuels continues to slowly decrease, more households currently use solid fuels for cooking today than at any time in human history, due to growing population size (Chafe, et al., 2014).

Between 2000 and 2015, the number of people cooking with biomass increased by 400 million people (IEA, 2017). This is mainly due to the growing population of sub-Saharan Africa, which continues to rely largely on solid fuels for cooking. Cooking with solid fuels is limited to developing regions, as the populations of industrialized countries now cook almost exclusively with clean fuels like gas and electricity (**Exhibit 6**). A relatively small number of people in industrialized country choose to use solid wood fuel for cooking and heating, but typically do so in modern appliances with chimneys to avoid household air pollution.

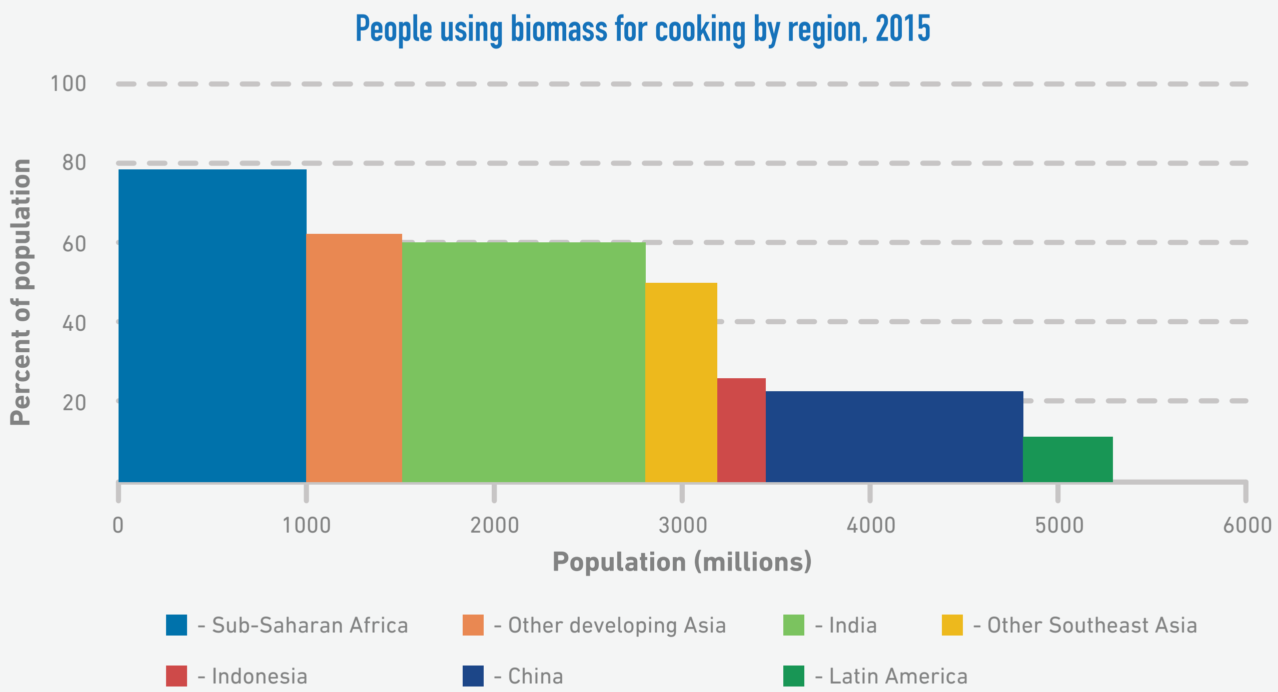


Exhibit 5: About 2.5 billion people, or a third of the world's population, rely on the traditional use of solid biomass for cooking. (Source: IEA, 2017)

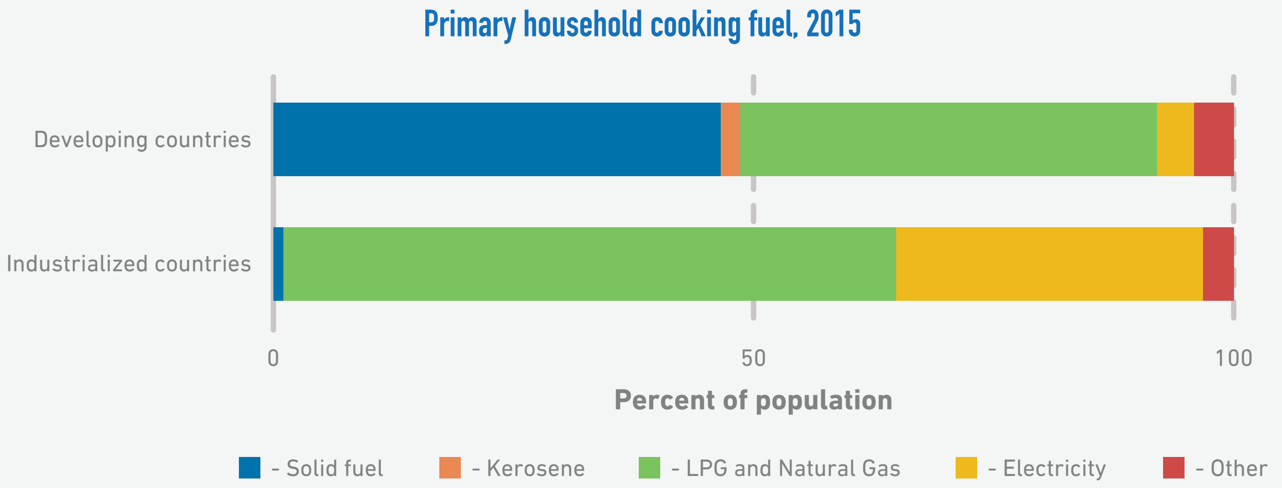


Exhibit 6: There is a stark division in household cooking fuels between regions. While clean fuels, such as gas and electricity, are dominant in industrialized countries, dirty biomass fuels are widely used in developing countries. (Source: IEA, 2017)

There are various types of solid fuels, such as wood, dung, crop residue, charcoal and coal, that are used for cooking. These fuels are burned in different types of stoves with little to no treatment or improvement in combustion techniques to increase efficiency or reduce harmful emissions. These stoves have typically been used for hundreds or thousands of years and have strong roots in cultural history (Kshirsagar & Kalamkar, 2014).

The most basic example is the three-stone fire, which is built by assembling three stones in a triangle, burning a solid fuel in the center, placing a pot on the stones, and then cooking over the open flame. A slightly more sophisticated example is the traditional chulha stove used in India, which is a U-shaped platform made of local clay, within which a fire is made.

The disadvantages of traditional solid fuel stoves are primarily the high air pollution emissions and low thermal efficiency. However, such stoves are still widely used in developing regions because they are easily accessible, require very low upfront costs, low maintenance, and are deeply rooted in established cooking practices and customs. Using solid wood as fuel for traditional stoves is most common in rural areas due to its availability.

Charcoal is a common cooking fuel in urban areas, because its logistics and supply chains into the cities are easier compared to wood. Charcoal is created from the process of carbonization, where wood or other biomass is heated in the absence of air to break it down into liquids, gases, and charcoal (NL Agency, 2010).

This process gives the charcoal properties that make it preferable to wood fuel in many cases (Kshirsagar & Kalamkar, 2014). Charcoal is more energy dense, as a kilogram of charcoal can have double the energy content of the same mass of wood fuel. It is also more convenient, as charcoal is easier to transport than wood fuel and can be stored for long periods of time without rotting.

Although charcoal has some health benefits over wood fuel, as it creates less smoke and particulate matter emissions when burning, the carbon monoxide emissions from charcoal stoves are typically very high (MacCarty, et al., 2010) (see **Exhibit 2**).

Traditional charcoal stoves are used predominantly by those in urban areas without access to electricity or other forms of cleaner cooking. Charcoal use is especially high in sub-Saharan Africa, with roughly 27 percent of the urban population using charcoal as their primary cooking fuel, compared to 6 percent of the rural population (Putti, et al., 2015).

Burning coal in traditional stoves is common among both rural and urban populations of East and Central Asia. Coal is burned unprocessed, and also in the form of processed briquettes. The World Health Organization (WHO) strongly discourages using coal as a cooking or heating fuel in households. Coal often contains toxic elements that are not eliminated during combustion, and indoor emissions from combustion of coal have been deemed carcinogenic by the International Agency for Research on Cancer (WHO, 2014).

4. Use of solid cooking fuels causes health and other problems in developing countries

Health

Household air pollution from solid fuel combustion affects global development because of chronic health impacts on affected populations. The smoke that causes household air pollution contains particulate matter (PM), carbon monoxide, benzene and other harmful agents.

Particulate matter, which consists of a complex mixture of solid and liquid particles of organic and inorganic substances suspended in the air, contains sulfates, nitrates, ammonia, sodium chloride, black carbon, mineral dust and water. Generally, smaller particles are more dangerous than larger ones. Coarser particles tend to be captured in the nasal cavity, upper airways or thoracic cavity.

Smaller particles, such as those with a diameter of 2.5 microns or less (PM2.5), can enter deep inside the body and deposit on the alveoli, the tiny sacs in the lungs where oxygen is exchanged with carbon dioxide in the blood.

Household air pollution from burning solid fuels indoors can cause severe health conditions, such as lower respiratory infection, lung cancer, ischemic heart disease, stroke and chronic obstructive pulmonary disease.

WHO (2016b) estimated that household air pollution is responsible for large portions of disability-adjusted life years (DALY) from several diseases, namely, 33 percent of global DALYs from acute lower respiratory infections, 26 percent from stroke, 24 percent from chronic obstructive pulmonary disease, 24 percent from cataracts, 18 percent from ischemic heart disease and 17 percent from lung cancer.

Additional health issues related to solid fuel use include birth defects, burns from wood fires and injuries related to fuel collection.

While there remains some uncertainty about the exact extent of health impacts of household air pollution, by all accounts they are substantial.

Each year, household air pollution is estimated to cause more deaths than many other high-profile killers including malnutrition, alcohol use, road accidents, war and murder, tuberculosis, malaria and AIDS. Landrigan, et al. (2018) estimated that 2.9 million deaths in 2015 were the result of household air pollution.

WHO (2016b) estimated that exposure to household air pollution resulting from the use of solid fuels caused 4.3 million deaths in 2012. The difference in estimated deaths can partly be explained by different approaches in quantifying exposure-outcome associations.

In South Asia and sub-Saharan Africa, almost 6 percent of all deaths in 2017 were attributed to household air pollution from using solid fuels (IHME, 2018) (**Exhibit 7**).

In India, an estimated 0.48 million deaths in 2017 were attributable to household air pollution, with the worst-affected states being Chhattisgarh, Rajasthan, Madhya Pradesh and Assam in north and northeast India (Balakrishnan, et al., 2018). In China, households that regularly cook with solid fuels have a 20 percent higher mortality risk from cardiovascular disease than those that use clean cooking methods (Yu, et al., 2018).

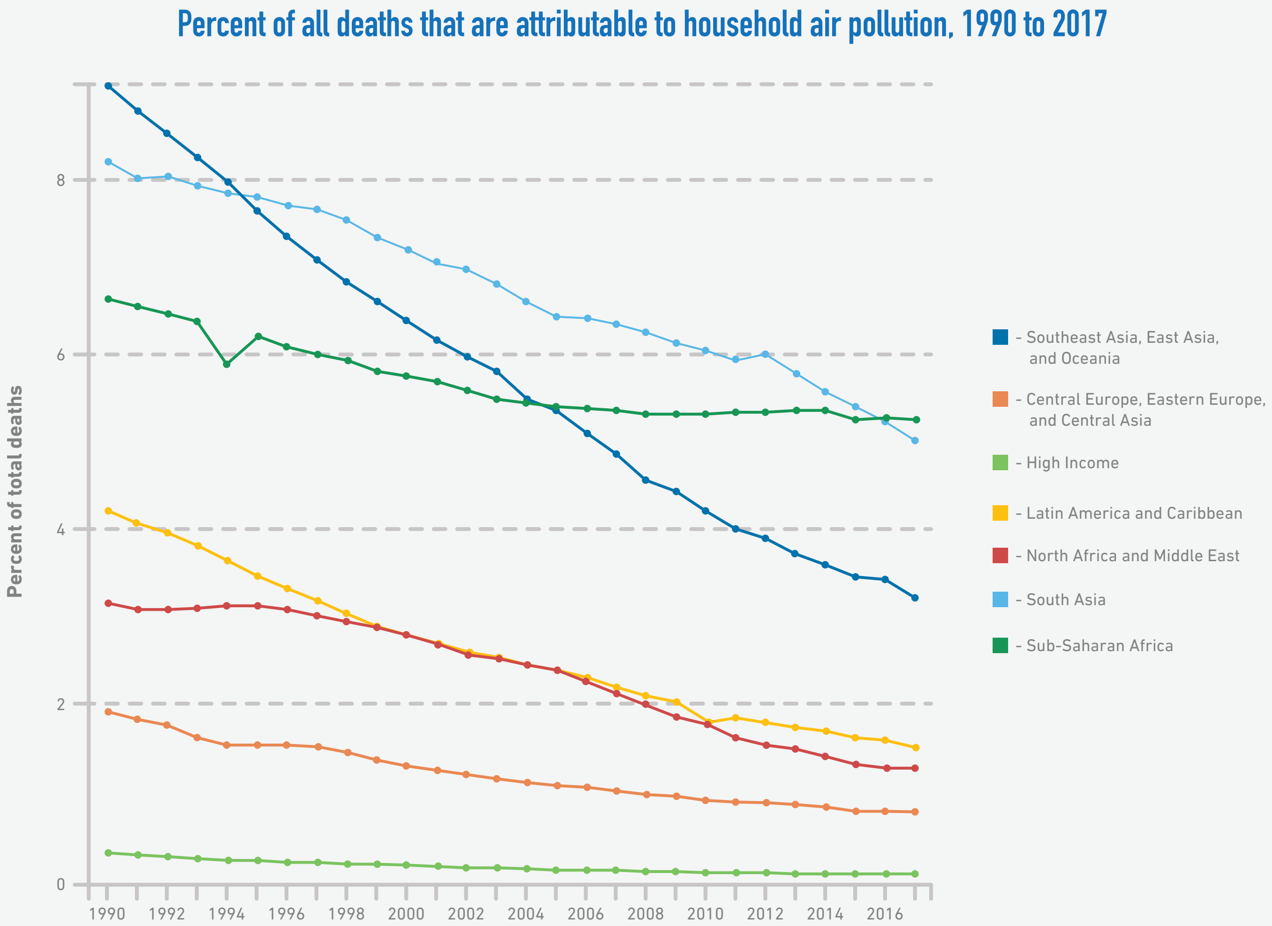


Exhibit 7: The percent of deaths attributable to household air pollution is declining in all regions, but is still significant. Almost 6 percent of all deaths in South Asia and sub-Saharan Africa in 2017 were due to household air pollution from using solid fuels. (Source: IHME, 2018)

Environment

Cooking processes can be responsible for a range of environmental impacts including ambient air pollution, forest degradation and climate change.

Ambient air pollution

While smoke from indoor cooking fires directly causes household air pollution and associated morbidity and mortality (discussed above), the smoke then escapes from the houses and contributes to ambient (outdoor) air pollution.

Although most ambient air pollution is caused by outdoor sources, such as power plants, vehicle exhaust and crop burning, an estimated 12 percent of global fine ambient particulate pollution (PM2.5) is caused by cooking fuels, which escapes from houses and pollutes the outside air (Chafe, et al., 2014). The percentage ranges from zero percent in richer countries to 37 percent in sub-Saharan Africa.

Within India, an estimated 39 percent of all PM2.5 pollution comes from residential sources, primarily solid cooking fuels (Sharma, et al., 2016) (**Exhibit 8**). The percentage varies from a low of 7 percent in urban Delhi to a high of 54 percent in predominantly rural Uttar Pradesh state.

Sources of fine particulate matter (PM2.5) in India

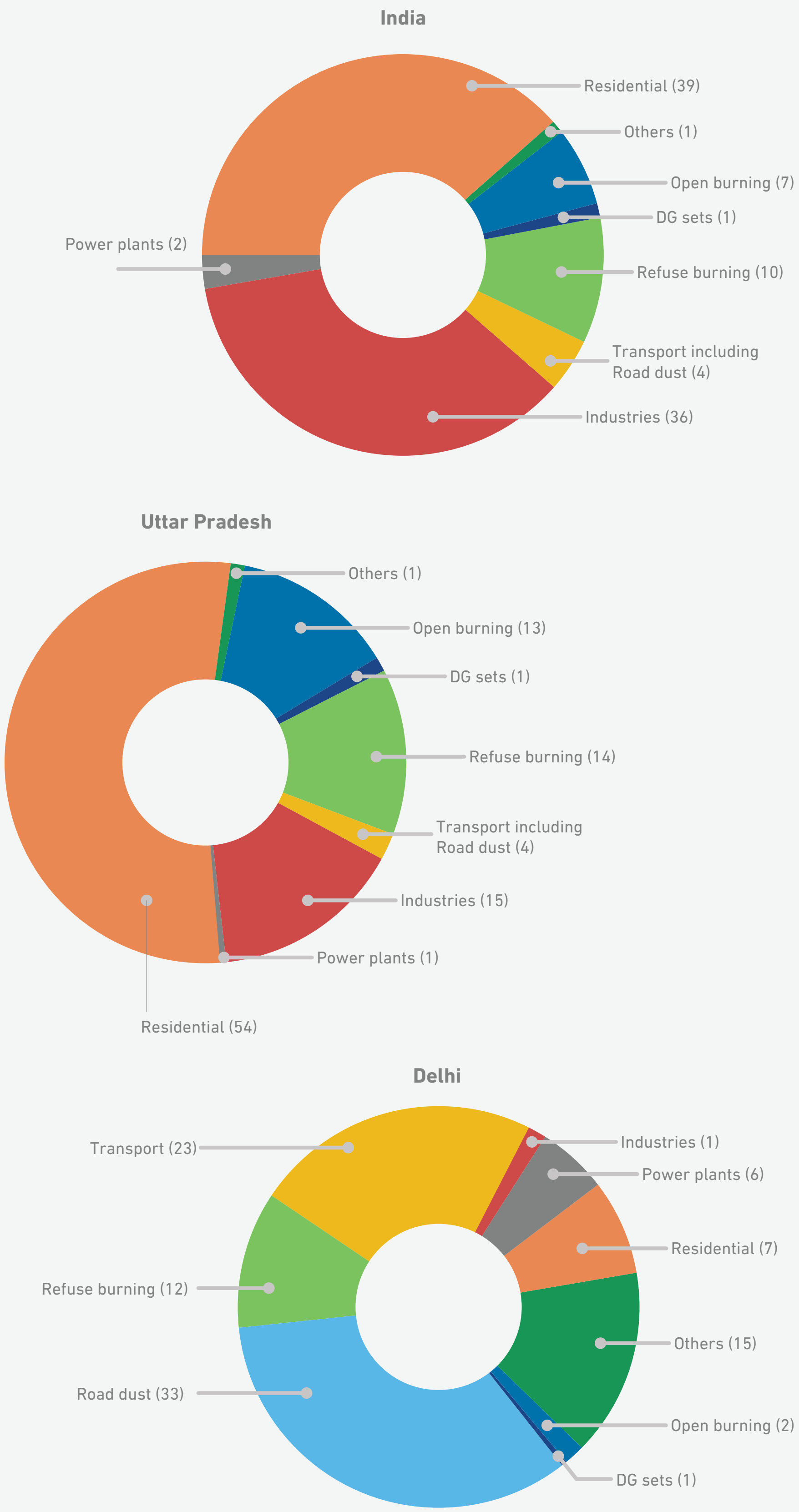


Exhibit 8: Solid fuel use in households (here termed "Residential") contributes more than half of PM2.5 emissions in Uttar Pradesh state in India and more than one third in all of India. (Source: Sharma, et al., 2016)

Forest degradation and deforestation

Wood fuel can come from many different sources, such as the felling of live trees, trees that have died naturally and trees that were cleared for agricultural land. Because of this, it is often difficult to attribute forest degradation or deforestation directly to wood fuel collection, and the sustainability of wood fuel use varies strongly from place to place.

Bailis, et al. (2015) estimated that between 27 and 34 percent of all harvested traditional wood fuel is non-renewable, defined as annual harvest levels that exceed incremental growth.

There are large geographic variations in woodfuel sustainability (**Exhibit 9**), and unsustainable wood use is concentrated in certain areas of South Asia and East Africa.

They report that about 275 million people—60 percent in Asia, 34 percent in Africa and 6 percent in Latin America—live in regions where more than half of harvested fuelwood is non-renewable.

In East Africa, unsustainable wood fuel use extends from Eritrea through western Ethiopia, Kenya, Uganda, Rwanda and Burundi. In Asia, such harvesting occurs in parts of Pakistan, Nepal, Bhutan, Indonesia and Bangladesh (Bailis, et al., 2015).

Collection of woodfuel can contribute to forest degradation in areas already experiencing heavy deforestation, but the production of charcoal represents a larger threat to forest degradation and possibly deforestation.

Studies suggest that wood harvesting for charcoal production is an important cause of forest degradation (Sedano, et al., 2016; Mwampamba, 2007).

Charcoal demand continues to increase in Sub-Saharan Africa and other regions (Putti, et al., 2015). Charcoal production in low- and middle-income countries is typically inefficient and can require four to six times as much wood to produce the same amount of end-use energy as burning unprocessed wood (Mwampamba, 2007), through there is a wide range of charcoal production techniques with varying efficiencies.

Most interventions in the charcoal cooking sector have focused primarily on the demand side, for example improved charcoal stoves.

There have been fewer supply side interventions, for example increasing kiln efficiency or improving sustainability of forest management for charcoal production (Mwampamba, et al., 2013), though such efforts could bring long-term benefits of resource conservation.

Non-renewable fuelwood harvest

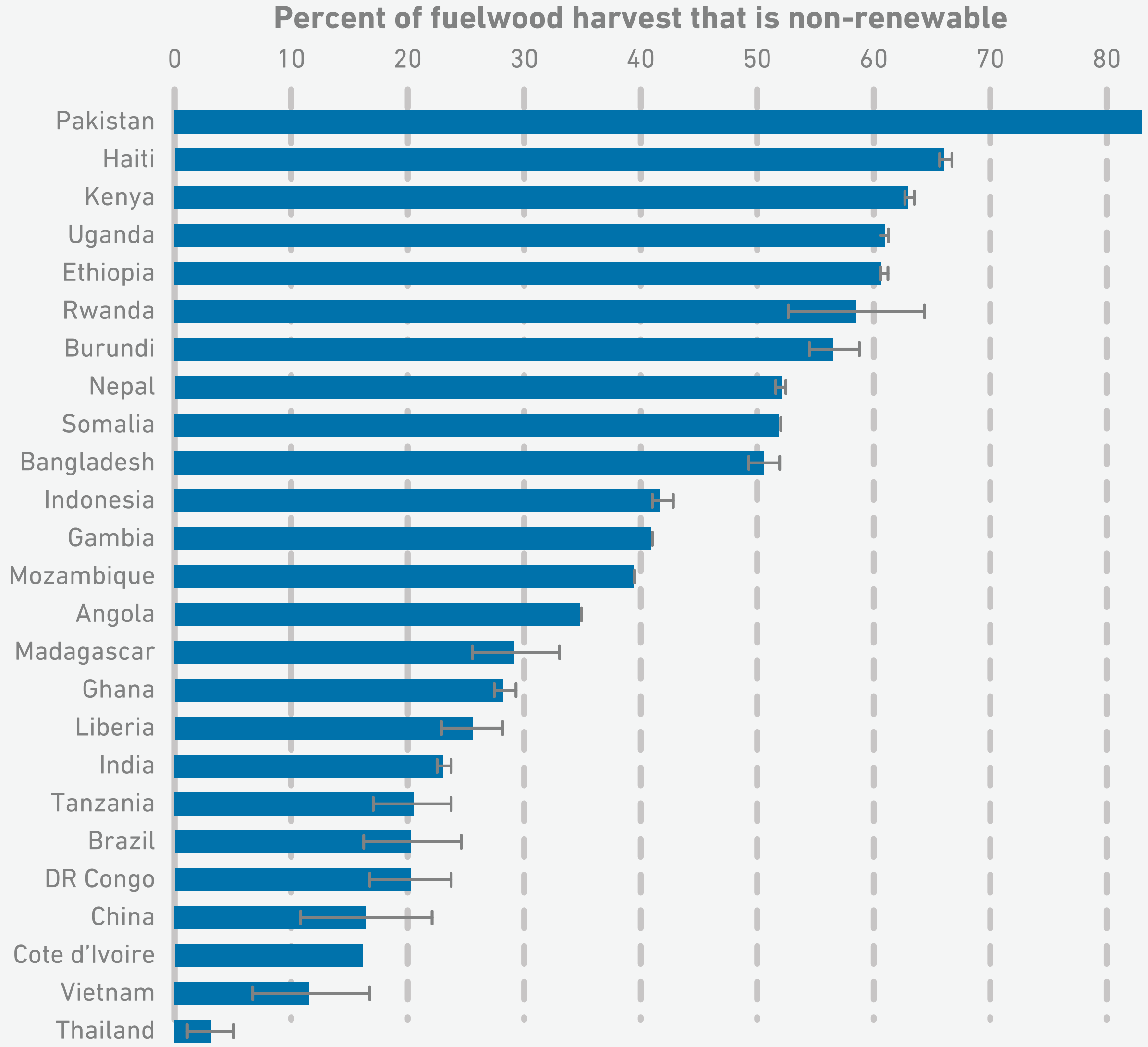


Exhibit 9: There is wide variation between countries in sustainability of fuelwood harvest. In some countries, mainly in East Africa and South Asia, more than half of harvested fuelwood is non-renewable, defined as annual harvest levels that exceed incremental growth. Error bars indicate uncertainty regarding growth rate of plantations and utilization of residues from forest clearance for agriculture. (Source: Bailis, et al., 2015)

Climate change

The climate impacts of cooking fuels are complex, involving atmospheric emissions from both fossil and biological sources (SEI, 2013). All cooking methods tend to emit greenhouse gases (GHG), though their ultimate climate impacts are not always straightforward.

Burning biomass directly emits carbon dioxide (CO_2) as a combustion byproduct, though if the biomass is harvested from sustainably managed forests, on a landscape level there will be no net CO_2 emissions because forest regrowth removes CO_2 from the atmosphere at the same rate it is emitted by burning (Sathre, et al., 2013). Biomass harvested from unsustainable forestry, on the other hand, causes net CO_2 emissions contributing to climate change.

Another important emission from cookstoves is black carbon, commonly known as soot, which is a component of PM2.5 particulate emission and strongly absorbs light and emits heat. About 25 percent of total anthropogenic black carbon emissions come from household cookstoves burning solid fuels (Garland, et al., 2017).

Black carbon is considered a short-lived particle, but it has a very high global warming potential (GWP) and causes significant short-term, regional climate impacts. The impacts of black carbon vary locally and regionally, with stronger potential warming impacts in areas with high albedo surfaces, such as snow and ice.

Accounting for the climate effects of black carbon can significantly improve the mitigation effectiveness of clean cooking initiatives (Freeman & Zerriffi, 2014).

Shifting to clean cooking fuels does not necessarily reduce or eliminate climate impacts, however, as clean fuels also emit GHGs. Natural gas and liquified petroleum gas are both fossil fuels, with CO_2 emissions of roughly half that of coal for the same amount of heat energy.

In addition, leakage of methane from natural gas production and transport facilities can result in additional climate impacts that are about the same magnitude as those from CO_2 emission of gas combustion (Alvarez, et al., 2018).

Electric stoves have no direct climate impact at the point of use, but the source of electricity used by the stove may be very carbon intensive (Masanet, et al., 2013).

Globally, 38 percent of electricity is generated by burning coal and 23 percent from natural gas. In India, 76 percent of electricity is currently generated using coal, thus widespread adoption of electric cooking in India would cause significant climate impact, unless the electricity system were made much less carbon intensive.

Gender equity

Household air pollution disproportionately affects women and children due to their greater amount of time spent cooking and preparing food in households, compared to men (**Exhibit 10**). Globally, it is estimated that women experience almost 5 percent more exposure to risk from solid fuel household air pollution than men, however the effects of this exposure discrepancy vary significantly between regions (Forouzanfar, et al., 2016).

Women and children also bear a disproportionate opportunity cost for collecting wood fuel. The extent of this disproportion varies by region and can reach several hours per day in areas facing fuelwood scarcity (WHO, 2016a). Women are also more likely to miss opportunities to attend school and work, and more likely to be injured or attacked while collecting fuel.

Cooking-related health impacts, by gender

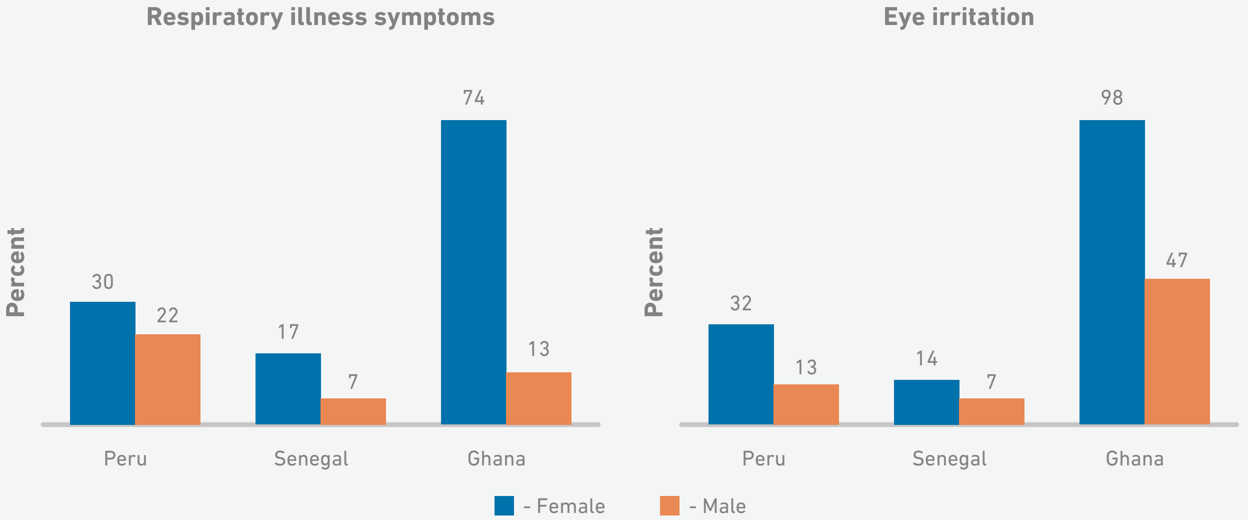


Exhibit 10: Women in developing countries tend to spend more time near cooking fires and are more likely than men to suffer from respiratory illness and eye irritation. (Source: Putti, et al., 2015)

5. Improved biomass cookstoves offer varying levels of improvement over traditional cooking methods

For many decades, design and deployment of improved cookstoves has been an important goal of global development efforts (Westhoff & Germann, 1995). A wide range of biomass cookstove improvements have been proposed and trialed, and some have reached moderate levels of deployment (MacCarty, et al., 2010).

Improved cookstove initiatives have historically been promoted through government programs such as China's National Improved Stove Program, which has been effective in distributing and promoting improved stoves since the early 1980s. India's National Programme on Improved Chulha was founded during the same era as China's program, seeking to replace the traditional chulha stove with improved versions (Hanbar & Karve, 2002).

Efforts in India were not as successful as in China, as improved chulha stoves have not been widely adopted (Khandewal, et al., 2017). More recently, international organizations such as the Clean Cooking Alliance (formerly called the Global Alliance for Clean Cookstoves) have advocated and helped in the distribution of improved cookstoves.

Improved biomass cookstoves refer to a large spectrum of stoves that use traditional biomass (wood, charcoal, crop waste and dung) as fuel, but employ improved combustion and fuel loading methods to increase thermal efficiency and lower indoor air pollutants that cause negative health, environmental, social and economic outcomes (Kshirsagar & Kalamkar, 2014).

Literature on improved biomass stoves often distinguishes between basic, intermediate and advanced stoves in order to differentiate and analyze the levels of technological complexity and benefits achieved by stove improvement. These umbrella categories are benchmarks for assessing the many stove technologies that currently exist and are being developed, but any individual improved biomass cookstove fits into a spectrum of stove technologies as opposed to one broad category.

Basic improved cookstoves aim to increase thermal efficiency and redirect household air pollution without greatly changing the combustion mechanism of traditional cookstoves. The improved Kenya Ceramic Jiko is an example of a portable basic improve stove that uses metal cladding and a ceramic liner to increase the efficiency of charcoal combustion by up to 30 percent (NL Agency, 2010).

Basic improved cookstoves also include built-in-place traditional cookstoves with chimneys added to increase thermal efficiency and move smoke out of the house, such as the smokeless chulhas promoted in India. These basic improved cookstoves are often made artisanally and sold by local vendors, but can also be mass manufactured and distributed through government, NGOs or other programs.

Intermediate improved cookstoves typically use simple means to improve the combustion process and achieve higher thermal efficiency. The rocket stove is an example of an intermediate cookstoves, employing an L-shaped combustion chamber design with air ducts that direct preheated air into the top of the chamber.

Although intermediate stoves have somewhat greater thermal efficiency, their emission is only moderately less when compared to traditional stoves. Some rocket stoves are reported to have increased black carbon emissions compared to traditional stoves (Garland, et al., 2017).

Improved biomass cookstoves are most often deployed in rural areas that have historically relied on traditional stoves and that lack access to other clean cooking solutions.

Such stoves vary widely in price, with higher prices usually translating to more advanced technology, higher efficiency and lower emissions. Manufacturing methods range from local and artisanal to large-scale industrial production.

6. Current improved biomass stoves do not improve health outcomes because of non-linear exposure-response functions of air pollution

Improved cookstoves can bring a number of benefits to users, due to their moderate improvement in thermal efficiency that leads to reduced fuel use. This fuel efficiency means cost savings for households that purchase fuel and time savings for those that gather fuelwood. Nevertheless, these cookstoves fail to significantly reduce exposure to household air pollution and the associated health risks.

A growing number of studies have reported exposure-response relationships for household air pollution exposure (Ezzati & Kammen, 2001; Smith, et al., 2011; Burnett, et al., 2014; Liu, et al., 2014). It is increasingly understood that the shapes of these relationships are non-linear, being steeper at lower exposure levels and tending to flatten off at higher exposures (**Exhibit 11**).

This non-linear relationship appears to be valid for acute lower respiratory infection in children and adults, ischemic heart disease and stroke. By contrast, the relationship for lung cancer is much closer to a linear function, while that for chronic obstructive pulmonary disease (COPD) is in between.

The implication of this non-linear function is that, while current improved biomass cookstoves can bring large reductions in emissions in both absolute and percentage terms, such reductions bring only a modest decrease in health risk (Bruce, et al., 2015; Thakur, et al., 2018).

To effectively eliminate the serious health risk of household air pollution, stove emissions must be reduced much further than is possible with current biomass stove designs. Cooking options with sufficiently low emissions include the established solutions of gas and electric stoves, and potentially a new generation of advanced biomass cookstoves with greatly reduced emissions.

Non-linear exposure-response function for air pollution

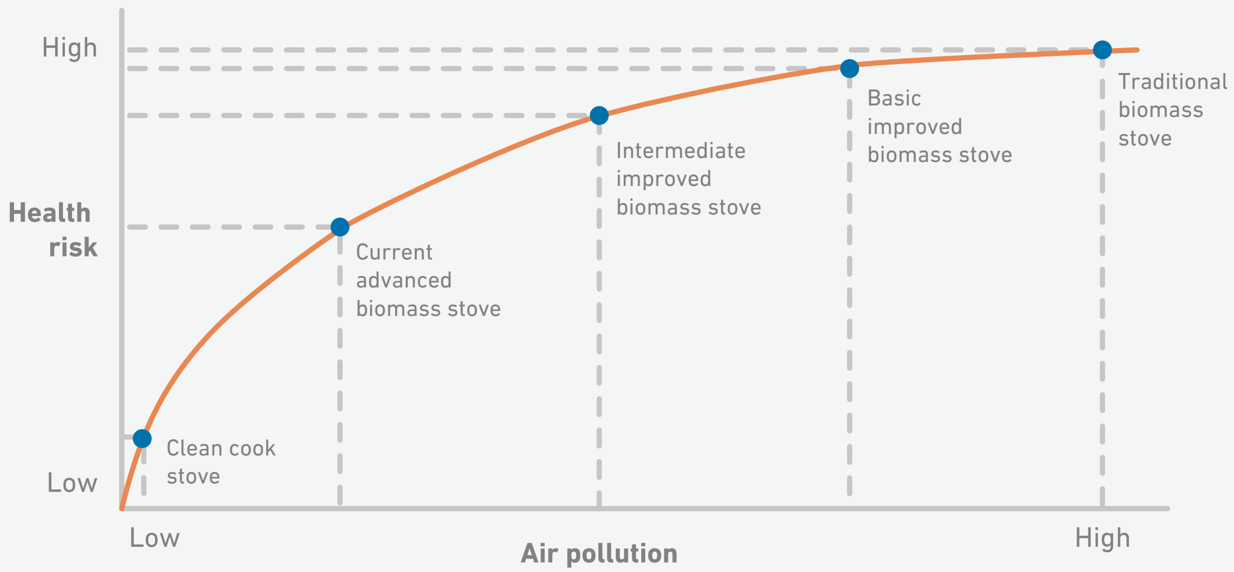


Exhibit 11: The relationship between air pollution and health risk is non-linear, thus the large absolute difference in pollution emission between traditional stoves and improved biomass stoves leads to a relatively small change in health risk. Stove emissions must be greatly reduced in order to achieve significant health benefits. This figure is illustrative, due to uncertainty regarding the exact shape of the curve and variability in the performance of stoves. (Source: ITT analysis based on Ezzati and Kammen, 2001; Smith, et al., 2011; Liu, et al., 2014; Burnett, et al., 2014)

7. Advanced biomass cookstoves have potential to reduce health risks, but are currently too expensive and complex for most users or do not achieve clean cooking metrics

Advanced biomass cookstoves use more complex, multiple stage combustion methods in order to burn fuel efficiently and minimize harmful emissions.

These cookstoves have yet to show that they can produce clean cooking levels of efficiency and emissions in the field, but they offer much promise for rural communities specifically because they do not require access to fossil fuels or electricity infrastructure.

However, current versions of advanced biomass cookstoves offer less cooking flexibility and often require pre-processed fuels.

Most advanced cookstoves have high upfront costs, are manufactured industrially to relatively high quality standards and are not yet widely used (Putti, et al., 2015).

There are several potential pathways towards clean biomass stoves, including air injection and gasification. Injecting air into the gas-phase combustion zone generates turbulence that leads to more complete combustion and reduced particulate emission (Rapp, et al., 2016). Air injection promotes better gaseous mixing of fuel and air, and increases the residence time of soot in the flame thus promoting oxidation of soot.

Exhibit 12 shows an experimental air injection wood stove developed and tested at Lawrence Berkeley National Laboratory. While showing great promise, current stove performance is quite sensitive to the flow rate and velocity of injected air, and the number of harmful ultrafine particles may be of concern (Caubel, et al., 2018).

Experimental advanced biomass stove

Exhibit 12: Experimental advanced biomass stove using air injection. (Source: Berkeley Lab Cookstoves Lab)

Gasification is another process that is used in advanced biomass cookstoves. During gasification, fuel is first heated in a low-oxygen chamber to release gases, primarily hydrogen, carbon dioxide and carbon monoxide. These gases are then mixed with air towards the top of the cookstove and ignited (Kshirsagar & Kalamkar, 2014).

Gasifier cookstoves sometimes use internal fans to assist with airflow and proper combustion. These fans may be powered by batteries, solar panels or thermoelectric generators, which increase the cost and complexity of the stoves.

Under laboratory conditions, gasifier stoves have been able to reach ISO Tier 3 (based on previous ISO standards) emission levels, which shows promise for gasifier stoves as a future clean cooking solution.

Nevertheless, there is a large gap in efficiency and emissions between well- and poor-performing fan gasifier stoves (see **Exhibit 2**). Furthermore, current gasifier stove designs tend to be costly, batch fed, slow to ignite and requiring specific fuel types.

Many advanced biomass stoves require users to process their fuel or use pre-processed fuel pellets and briquettes. Fuel pellets and briquettes are made from compacted biomass, including dung and crop waste.

Compacting the biomass into smaller units creates a more energy dense fuel that outperforms unprocessed biomass in efficiency and emissions when used to fuel gasifier stoves (Vesterberg, 2014).

Fuel processing can take place at various scales, from small-scale localized plants to large-scale centralized facilities, with trade-offs in terms of logistics, capital cost and unit production cost (Helbig & Roth, 2017). Pellets and briquettes can be a renewable fuel if they are made from sustainably-sourced agricultural or forestry residues (Putti, et al., 2015). The need for purchasing expensive processed fuel can lead to non-adoption of advanced cook stoves.

An innovative approach is currently being trialed in Rwanda by the company Inyenyeri. This enterprise provides BioLite gasifier stoves to customers for free, and exchanges unprocessed wood collected by customers for processed pellets (Goodman, 2018).

8. Gas is a clean and flexible energy for cookstoves, but supply chains are challenging in rural areas

Cooking gas burns very cleanly, as it can fluidly intermix with oxygen to enable complete combustion. Furthermore, it is composed of compounds containing hydrogen and carbon, which when completely combusted are converted to carbon dioxide and water vapor, with minimal health impact. Three main pathways are used to produce and distribute cooking gas: liquefied petroleum gas (LPG), natural gas and biogas.

Liquified Petroleum Gas (LPG)

Liquified petroleum gas (LPG) is a fossil fuel mixture of propane (C_3H_8) and butane (C_4H_{10}). It is obtained during the extraction or refinement of crude oil and can be stored in portable cylinders. LPG is considered a clean cooking solution because it burns efficiently and produces much less household air pollution than current solid fuel stoves (**Exhibit 2**).

LPG is also easy to store and cook with, which has led to it being used by a majority of urban households in developing countries (**Exhibit 4**). However, both the initial and operating costs of cooking with LPG is high when compared to solid fuel cooking systems. Further, transport of gas cylinders is challenging in regions with limited infrastructure, and LPG supply chains have yet to reach many rural areas of developing countries (**Exhibit 4**).

Despite these challenges, countries such as Brazil have had success establishing LPG supply chains through the use of government subsidies for low-income households, as more than 90 percent of rural households in Brazil have access to LPG (IEA, 2006). In Indonesia, a state-led initiative to convert from kerosene to LPG cooking fuels has used economic subsidies to enable 50 million households to gain access to LPG for cooking in a five-year period (Thoday, et al., 2018).

Organizations, such as the Global LPG Partnership, have had some success in expanding access to LPG supply chains and converting users to cleaner cooking solutions (GLPGP, 2018). LPG holds promise for rural communities since it does not require the same investment in infrastructure as natural gas or electricity, but delivers similar health benefits.

Natural gas

Natural gas, primarily composed of methane (CH_4), is a fossil fuel extracted from underground deposits. Many countries around the world exploit natural gas deposits, though sub-Saharan Africa is less well endowed with natural gas than other global regions (**Exhibit 13**). It is a versatile fuel that has similar thermal efficiency and end use emissions as LPG.

It is primary used in its gaseous form in industrialized countries, which requires high infrastructure costs and regulation, but can also be compressed and cooled into a liquid form and used in a similar way as LPG (Culver, 2017). In developing regions, natural gas is used almost exclusively in urban areas (**Exhibit 4**), mainly due to a lack of pipeline infrastructure in rural settings.

Although the expansion of the use of fossil fuels such as LPG and natural gas for cooking in developing countries could be effective in reducing household air pollution, its use causes concern with regards to climate change and other environmental impacts. In addition, the global market price of fossil fuels is quite volatile (**Exhibit 14**), thus reliance on such fuels by low-income populations runs the risk of these households being unable to afford cooking fuel when prices go up (EIA, 2018b).

Government programs to subsidize the cost of these fuels also face large uncertainty in funding requirements due to market price volatility. The non-renewable nature of LPG and natural gas also means that they will become progressively more depleted and less available, over a time scale of decades. These issues are discussed in detail in the Resilience to Global Change chapter.

Global production of natural gas

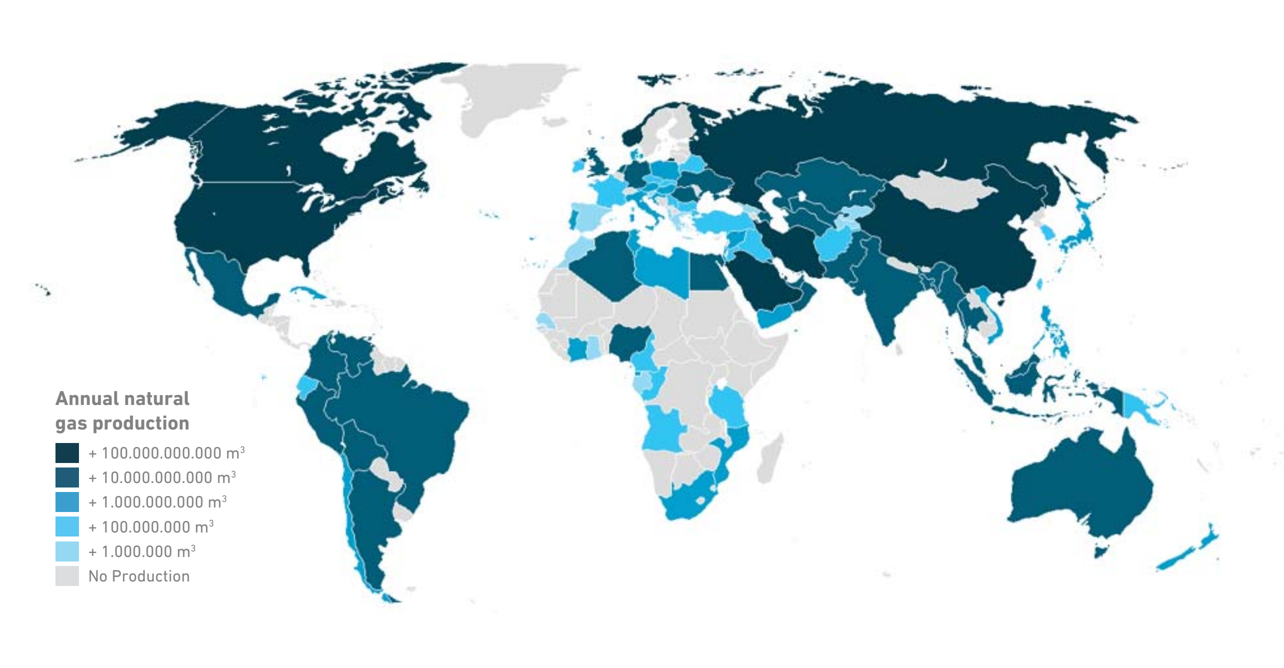


Exhibit 13: Many countries around the world produce substantial amounts of natural gas. (Source: 2013 data from Wikimedia, 2018)

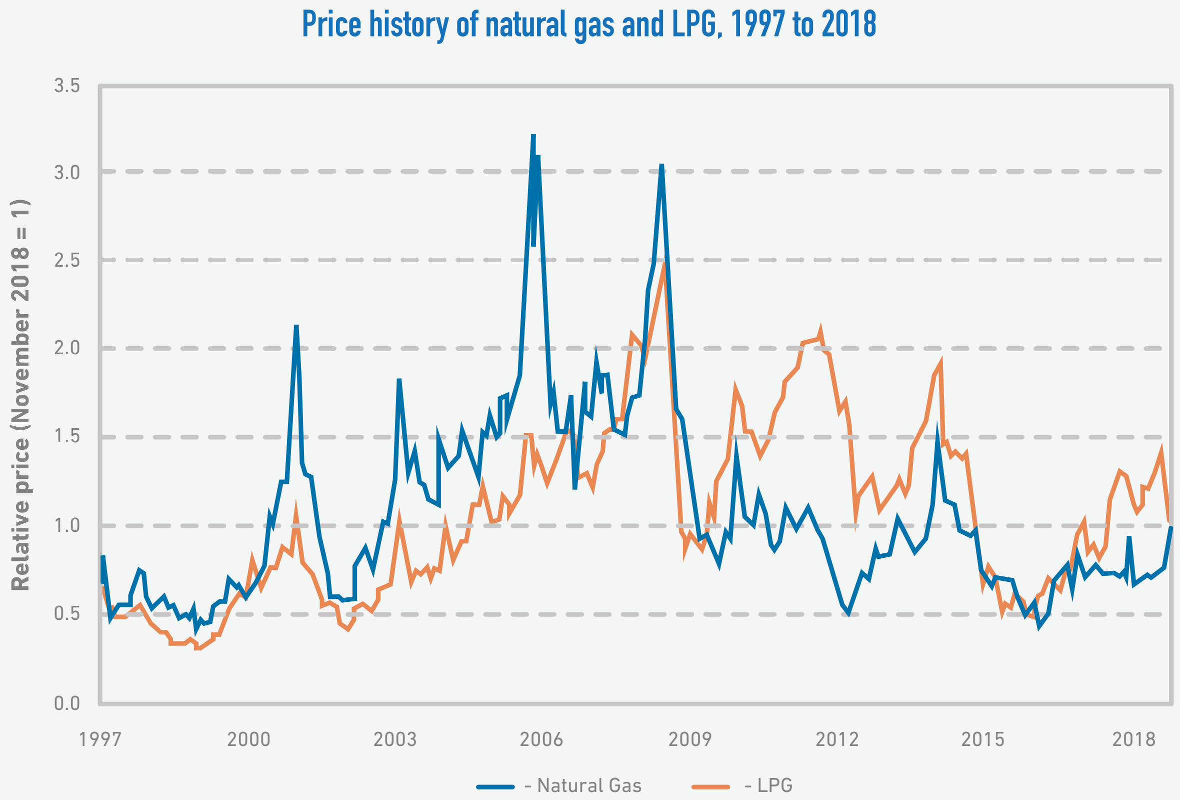


Exhibit 14: The prices of LPG and natural gas are quite volatile and are subject to sharp increases. (Source: EIA, 2018b; monthly average spot prices of natural gas at Henry Hub and propane gas at Mont Belvieu)

Biogas

Biogas is a clean burning fuel that is composed primarily of methane (CH_4) and carbon dioxide (CO_2). It is created by breaking down organic materials, such as animal or human manure and crop or food waste, through the process of anaerobic digestion.

This process takes place in large, stationary biogas digesters and can take anywhere from a few days to a few weeks, depending on the input material and ambient conditions such as temperature (IRENA, 2017).

Biogas can be produced on multiple scales, from small digester systems used to generate cooking gas at the village or individual household level, to large facilities using waste from agriculture, food processing or wastewater treatment.

Household biogas cooking systems are ideal for rural farm owners that can turn their crop and livestock waste into a cooking and energy source at a much lower annual cost than other clean cooking options such as LPG and electricity.

Exhibit 15 shows the three main types of small-scale biogas digesters: the fixed dome, developed in China and now used in many developing countries; the floating drum plant, mainly used in India; and the balloon/bag digester, mainly used in Latin America (IRENA, 2017).

Types of small-scale biogas digesters

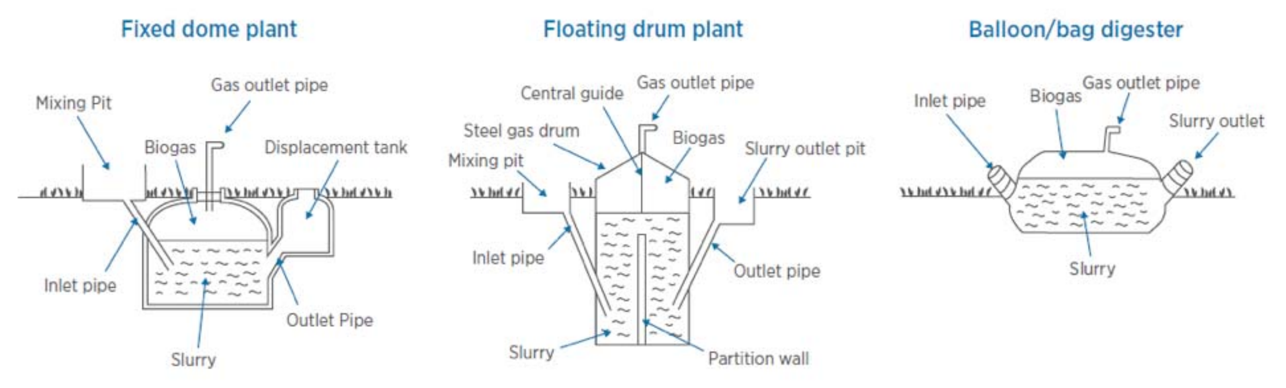


Exhibit 15: There are three main types of small-scale biogas digesters. (Source: IRENA, 2017)

Biogas is currently used as the primary cooking fuel by less than 2 percent of households (Putti, et al., 2015).

China is home to the great majority the world's household biogas users (**Table 2**), as the Chinese government has successfully used economic subsidies to encourage its rural population to produce and use biogas at the household level (Zuzhang, 2013).

Biogas digesters require a large upfront cost, which makes them inaccessible to many rural households without subsidies or other financial incentives. In addition, many biogas digestion systems require skilled installation and maintenance which may be unavailable in some areas (Rajendran, et al., 2012).

Despite these challenges, biogas still holds promise as a clean burning and renewable cooking fuel that competes with the health benefits of fossil fuels without the environmental impacts associated with fossil fuel use.

Prefabricated digesters that are much less expensive than traditional biogas digester and can be installed in a day without the use of skilled labor are being developed (Cheng, et al., 2014).

More accessible and less expensive biogas digesters offer an opportunity to improve health and wellbeing in many rural regions of developing countries.

Household-scale biogas digesters in select countries, 2014

Asia	
China	43,000,000
India	4,750,000
Nepal	330,000
Vietnam	182,000
Bangladesh	37,060
Cambodia	23,220
Africa	
Kenya	14,110
Tanzania	11,100
Ethiopia	10,680
Latin America	
Bolivia	500
Nicaragua	290

Table 2: Most household-scale biogas digesters are installed in Asia, especially in China. (Source: IRENA, 2017)

9. Electricity is a clean and flexible energy for cookstoves, but the high power requirement can be challenging

Using electrical energy for cooking is a clean and convenient method with no end use emissions or smoke, thus posing very low direct health risk. Electricity is an ideal cooking fuel but is currently too expensive with a challenging supply infrastructure. Electric cooking is more prevalent in urban areas, largely due to access to grid infrastructure. Please see the accompanying section on Access to Electricity for an in-depth discussion of the challenges of rural electrification.

Electricity is not widely used for cooking in developing countries, as shown in **Exhibits 3, 4** and **6**. It is the primary cooking fuel for only 5 percent of urban households in developing regions (Putti, et al., 2015). In a few developing countries the rate of electricity use for cooking is much higher.

For example, 80 percent of the total South African population and 12 percent of Chinese population cook with electricity (IEA, 2017). In most low-income countries, electricity use for cooking is far lower than the electricity access rate. This is because cooking requires a large amount of energy (see **Exhibit 1**), which strains most generation and transmission capacity, and is relatively expensive.

Electric cooking is generally not suitable for existing off-grid power systems, which have neither the power nor energy capacity that would be required.

Electricity is much more likely to be used for cooking in industrialized countries. For example, the most common cookstove in the United States is electric (61 percent of household stoves), followed by natural gas ((33 percent) and propane (5 percent) (EIA, 2018a).

Nevertheless, cooking consumes only a small fraction of total household electricity use in the United States, due to very high electricity expenditure for non-cooking purposes, such as refrigerators, TVs, air conditioning, lighting and space and water heating.

While electric cooking produces no indoor emissions that cause household air pollution, it may lead to other environmental problems such as ambient air pollution and climate change. The broader environmental effects of electric cooking depend largely on how the electricity is generated (Masanet, et al., 2013).

In regions where coal is burned for electricity production, the overall electric cooking process is no longer clean. Globally about 40 percent of electricity is made from coal, and in India that rate is 76 percent. Issues of climate change and ambient air pollution are discussed in detail in the Resilience to Global Change chapter.

The most common electric cooking process is resistance, which works on the principle of Joule heating, where an electric current passing through a resistor is converted into heat energy. Inductance is a newer electric cooking method that is gaining acceptance among users.

With this method, an alternating electric current is passed through a coil of copper wire under the cooking pot, which induces an electrical current in the pot, directly heating the pot through resistance heating. For induction cooking to work, the cooking vessel must be made of a ferrous metal, such as cast iron or some kinds of stainless steel.

Although initial reports suggested that induction cooking was more energy efficient than resistance cooking, more rigorous analysis has shown that the efficiency of the two processes are roughly the same, around 70 to 72 percent (US DOE, 2014; Sweeney, et al., 2014). In certain cases, depending on pot size and cooking power, induction stoves may be slightly more efficient.

Induction stoves do have several other advantages. They may be safer to use because the element itself reaches only the temperature of the cooking vessel, and only the utensil generates heat. They are easier to clean because the cooking surface is flat and smooth, and they provide rapid heating with precise control.

Photo by Albert Gonzalez Farran - UNAMID

KEY CHALLENGES

1. Clean cooking methods require more complex infrastructure and supply chains

Cooking methods used in industrialized countries, primarily natural gas and electricity, require a large investment in infrastructure for pipelines and distribution grids. In developing regions, these methods are mostly limited to urban areas (**Exhibit 4**).

Rural areas are often also outside LPG supply chains and require subsidized government programs to reach rural households (Thoday, et al., 2018).
for end use burning or electricity generation, such as natural gas, LPG and electric cooking systems, have both high initial and annual costs, making them financially inaccessible to low-income households. Cooking methods with low upfront and annual costs are those with high pollutant emissions, such as traditional wood stoves.

2. There are social and cultural barriers to changing cooking methods

Cooking practices are often deeply rooted in the traditions and culture of a given community or region, and clean cooking solutions that fail to accommodate existing cooking practices are often not adopted by users, even when these solutions are accessible (Puzzolo, et al., 2016).

This has become especially apparent in programs attempting to distribute improved biomass stoves that require changes in fuel loading methods, do not allow for the cooking of certain dishes or cooking styles, or lack control over certain aspects of cooking such as heat intensity.

Users can also be opposed to the concept of cooking with animal or human waste, as is practiced with biogas cooking systems.

3. Clean cooking methods are more expensive than traditional cooking methods

Current clean cooking solutions have either high upfront costs or high annual fuel costs, and sometimes both, making them inaccessible to low-income households. **Exhibit 16** shows that clean cooking systems using biomass fuels that can be produced, purchased or collected locally, such as biogas digesters and advanced biomass stoves, have high upfront costs but lower annual costs, making initial adoption a large financial burden.

Cooking systems that rely on fossil fuels for end use burning or electricity generation, such as natural gas, LPG and electric cooking systems, have both high initial and annual costs, making them financially inaccessible to low-income households. Cooking methods with low upfront and annual costs are those with high pollutant emissions, such as traditional wood stoves.

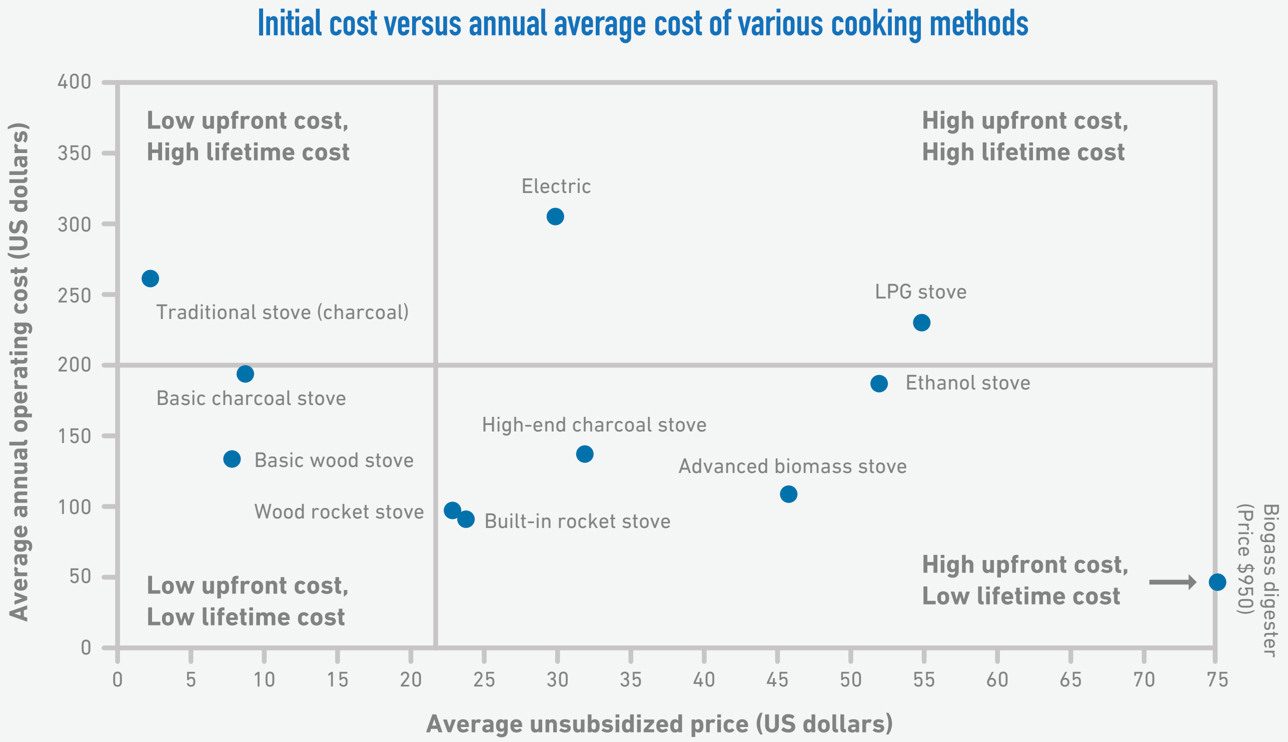


Exhibit 16: Different cooking methods vary greatly in upfront and long-term average costs. Generally, cleaner cooking methods cost more than less clean methods. (Source: Putti, et al., 2015)

4. Fuel stacking often reduces the impact of clean cooking systems

Even after the introduction of a clean cooking system, many households continue to use traditional cooking methods in addition to the new system.

This is true for all clean cooking systems, as developing households rarely rely solely on one fuel or cooking method (Morrison, 2018).

This is known as fuel stacking, and makes a complete transition to clean cooking difficult even when a clean cooking system is implemented successfully.

5. There are several technological obstacles to clean cooking solutions

Performance gap between lab and field tests

Laboratory tests are important for initial theoretical experimentation and development, but field tests reveal how different cooking solutions actually affect users in the world once they are implemented.

Exhibit 17 shows that stove performance tends to be higher during carefully controlled experiments in a lab, and lower during actual field operation by users. Field testing among end users can be more difficult and time intensive than lab tests, but it is essential to understand how cooking methods affect users and their surroundings.

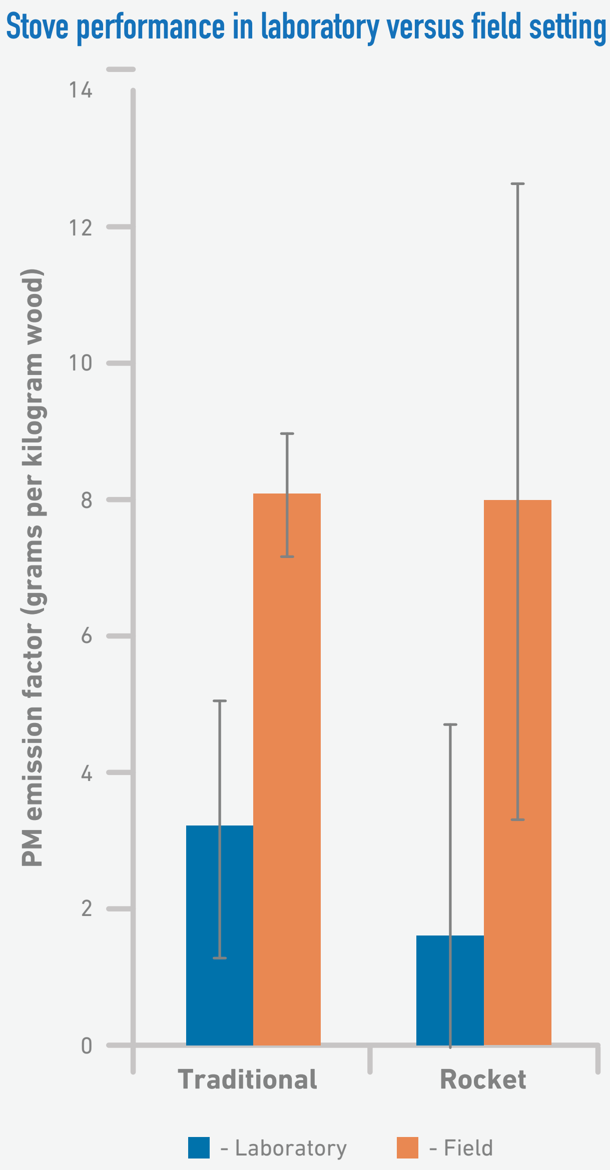


Exhibit 17: Cookstove performance tends to be much lower in field settings with actual users, compared to laboratory settings with trained technicians. (Source: Berkeley Air Monitoring Group, 2012)

Maintenance

Clean cooking methods, such as advanced wood stoves and biogas digesters, often use complex combustion and fuel production technologies that can be difficult to maintain for users who are not familiar with the technology and lack access to skilled labor to help with technological issues.

Many fan gasifier stoves use thermoelectric generators to power internal fans, and finding replacement parts is very difficult in rural and some urban areas. In addition, cooking solutions such as biogas digester systems require regular maintenance, which can be difficult and lead to non-adoption if users do not have access to training or hired skilled labor.

Sparse data

While information concerning clean cooking and household air pollution has been increasing in the last decade, there still exist major gaps in data and knowledge that are crucial to implementing effective clean cooking programs and initiatives.

More in-depth data on fuel stacking practices, advanced biomass stove performance, and the life cycle effects of cooking systems on the health of users and the environment would help to better inform policy makers, organizations and practitioners seeking to identify and implement clean cooking solutions.

SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

Enabling clean cooking is a longstanding challenge, especially for poor households that continue to use solid fuels. Potential solutions must overcome number technical hurdles involving thermodynamics and combustion sciences, but must also be sensitive to the socioeconomic context of the households and the cultural traditions involved in cooking food.

Innovative cooking technologies that excel in laboratory tests will fail in actual deployment and use, if they are not seen by the users (primarily rural women) as desirable implements that improve their quality of life.

Developing successful cooking technologies will require a thorough understanding of the complex activities taking place in rural kitchens, and the extent to which cooking traditions can be adapted to use cleaner methods. We have identified two breakthroughs with high potential to enable clean cooking for all.

Breakthroughs:

1	2	3	4	5	6	7	8	9	10
11	12	13	14	15	16	17	18	19	20
21	22	23	24	25	26	27	28	29	30
31	32	33	34	35	36	37	38	39	40
41	42	43	44	45	46	47	48	49	50

46 Advanced biomass cookstoves that are desirable, affordable, robust and very clean

Biomass such as wood, straw and dung is the primary cooking fuel for about 2.5 billion people, or a third of the world's population. Household air pollution caused by these fuels causes millions of deaths each year, due to illnesses such as lower respiratory infection, lung cancer, ischemic heart disease, stroke and chronic obstructive pulmonary disease. Despite major initiatives to extend access to cleaner cooking fuels like gas and electricity, more households currently use solid fuels for cooking today than at any time in human history, due to growing population size. It is likely that billions of people will continue to cook with biomass for the foreseeable future, due to economic, logistical and cultural barriers to change.

Design and deployment of improved biomass cookstoves has been an important goal of global development efforts for many decades. A wide range of biomass cookstove improvements have been proposed and trialed, with significant reduction in emissions of air pollutants like particulate matter and carbon monoxide. Some of these improved stoves have reached moderate levels of deployment in low-income countries.

However, recent research has shown that the exposure-response relationship for household air pollution is non-linear, thus the large reduction in emissions from current improved stoves brings only a modest decrease in health risk. To effectively eliminate the serious health risk of household air pollution, stove emissions must be reduced much further than is possible with current biomass stove designs.

A new generation of advanced biomass cookstoves is needed, with greatly reduced emissions so they have low health risk that is comparable to other clean cooking solutions like gas and electricity. Advanced biomass cookstoves typically use complex, multiple stage combustion methods in order to burn fuel efficiently and minimize harmful emissions.

Current versions of advanced biomass cookstoves often have high upfront costs, offer less cooking flexibility, need pre-processed fuels and require an electricity supply to power built-in fans, yet still do not reliably achieve emission levels low enough to eliminate health risk in people's kitchens.

Current State

Development Stage: Engineering

Time to market (years): <3 | 4-6 | 7-10 | 10+

Deployment: Challenging

Associated 50BT Chapters

Access to Energy

Gender Equity

SDG Alignment

Impact

Lives Saved (# of People/Year): <1M | 10M+ | 100M+ | 1B+

Health Improved (# of People): <1M | 10M+ | 100M+ | 1B+

Commercial Attractiveness

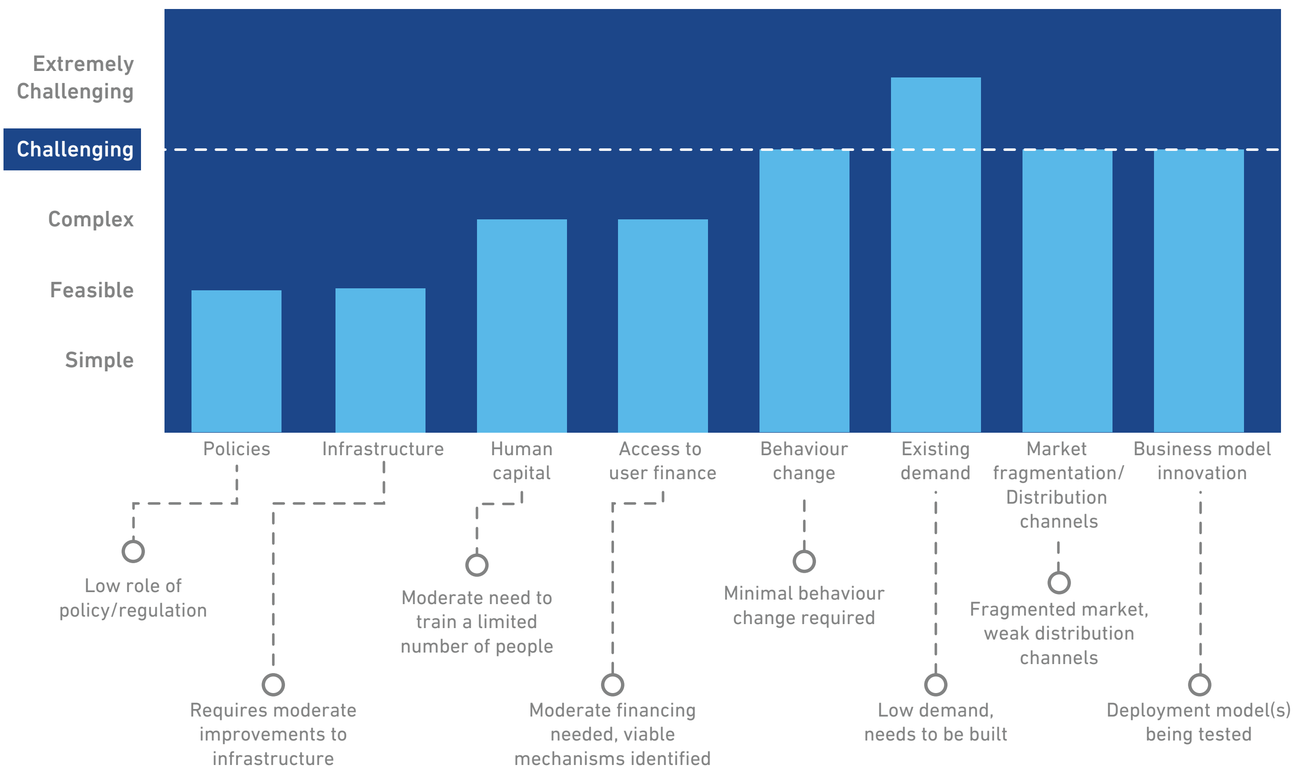
- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

An effective advanced biomass cookstove must be durable, low-cost and low maintenance. It will preferably use unprocessed fuel, or fuels that can be processed locally with available equipment. It will be compatible with traditional foods and cooking styles and not require major behavioral change by the users.

Above all, it must employ extremely efficient combustion processes and emit very low levels of dangerous pollutants. This breakthrough will require significant advances in thermodynamic and combustion sciences, as well as outstanding user-centric design.

Innovative business models will be required, and significant outreach will be needed in some regions to ensure sufficient demand. The projected time to market readiness of a breakthrough advanced biomass cookstove is five to seven years, and the difficulty of deployment is CHALLENGING.

Breakthrough 46: Difficulty of deployment



47 Novel ways of converting household or village waste products into clean cooking fuel or electricity

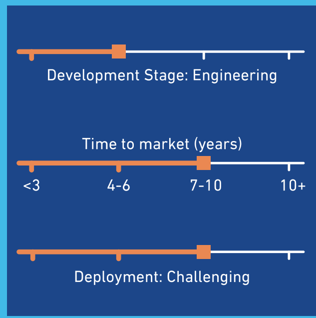
Gas and electricity are recognized as very clean and safe cooking fuels, yet their usage remains very low in rural areas of developing countries. This is mainly due to the high cost and logistical challenges involved in extending the required infrastructure to these areas. Liquified petroleum gas (LPG) is typically transported in cylinders, which requires an adequate road network and sufficient truck fleet that are lacking in many areas. Natural gas is typically transported in pipelines, which are very expensive and therefore limits the use of natural gas in areas distant from gas wells. The price volatility of LPG and natural gas makes it difficult for low-income households to have consistent access to the fuels. Electrification of rural areas is a longstanding challenge, and even in areas that are nominally connected to the power grid, electric cooking is seldom practical due to unreliable supply and the high power requirement of electric cookers.

Decentralized production of biogas by means of anaerobic digestion of organic materials such as manure and crop waste is an established practice, but is used by only a small fraction of households, mainly in China where it is supported by government subsidies. Use of anaerobic biogas digesters requires a large upfront cost, and most biogas systems require skilled installation and maintenance which is unavailable in most developing countries.

While clean cooking fuel is lacking in rural regions, many areas have abundant organic waste materials such as human waste, animal waste, crop residue or household garbage. A breakthrough is needed in the form of an affordable, robust process to convert diverse organic waste products into clean and reliable gas or electricity for cooking. Such a process would not only provide clean cooking fuel, but would safely dispose of waste products and result in cleaner surroundings. In principle, this could be achieved by various conversion routes, such as biochemical, thermochemical or electrical.

- Biochemical processes would use living organisms to produce biogas. This could take the form of improvements to existing anaerobic digestion processes to make them less capital-intensive with easier installation and maintenance. Advances in genetic editing might be used to create microorganisms capable of digesting a wider range of input materials. If human waste were used as input material for fuel production, cultural concerns among some population segments would need to be addressed.

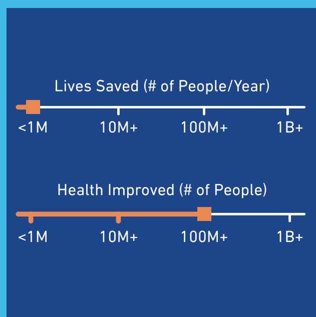
Current State



Associated 50BT Chapters

SDG Alignment

Impact



Commercial Attractiveness

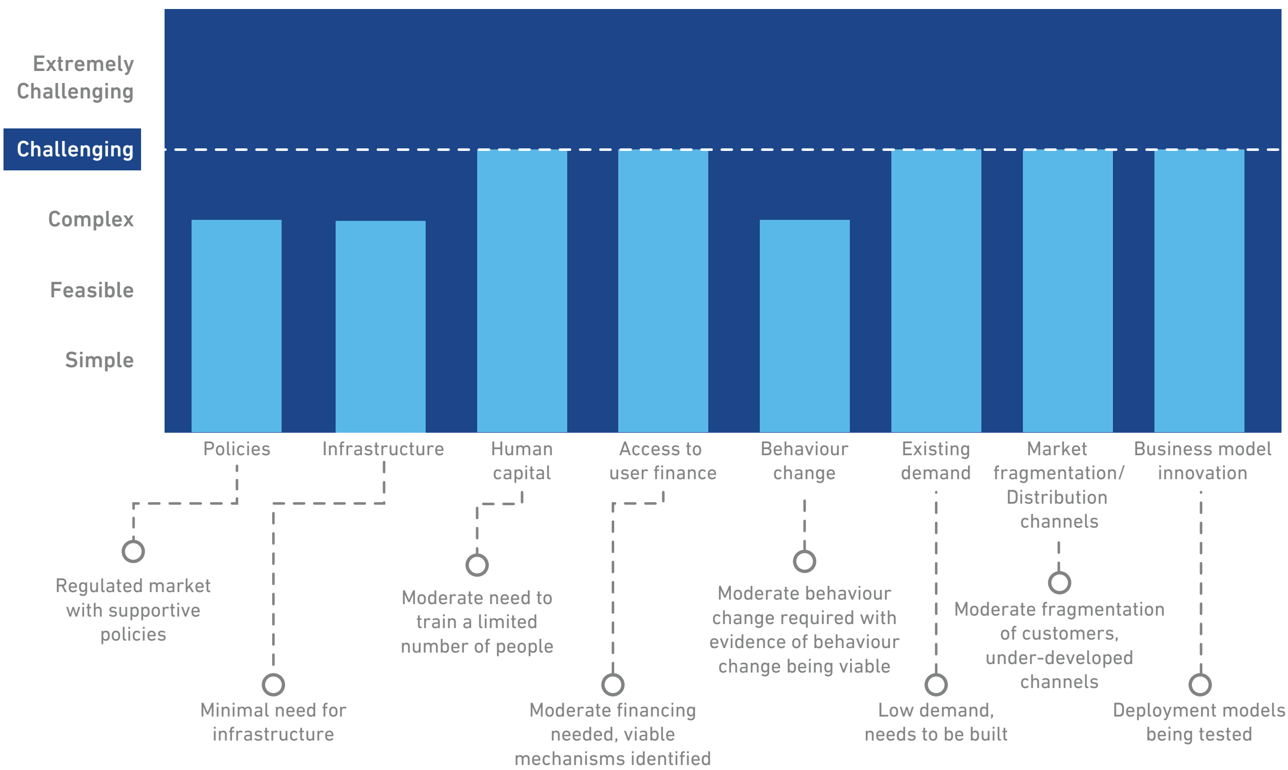
- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

- Thermochemical methods, such as pyrolysis or gasification, use high-temperature processing to produce syngas. These methods are well established at industrial scales, but are less well developed at smaller scales suitable for villages and households. Current small-scale methods are quite polluting, and are relatively complex and require skilled operation and maintenance. In addition to cooking fuel, thermochemical processes typically produce biochar that could be used as a soil amendment.

- Electrical methods would convert the chemical energy of the waste products into electricity, which is a clean and safe form of cooking. Because cooking requires a relatively high electric current, and is typically practiced only at certain times during the day, the most suitable form of village-level electricity production for cooking may be a small-scale "peaker plant" that only operates during limited hours when meals are prepared, and would supplement a solar powered mini-grid that provides continuous power for lighting and other uses. For example, a batch-fired thermochemical gasifier could be combined with an electrical generator to provide a village with sufficient electricity for cooking during several hours in the morning and again in the evening.

There are numerous technology pathways by which this breakthrough could be realized. It will likely require advances in relevant disciplines, such as biological or mechanical engineering. It will also require a thorough understanding of the needs and wishes of the users, and innovative design and implementation to ensure satisfaction. Appropriate business models will be needed to provide economic sustainability. The projected time to market readiness of this breakthrough is seven to 10 years, and the difficulty of deployment is CHALLENGING.

Breakthrough 47: Difficulty of deployment



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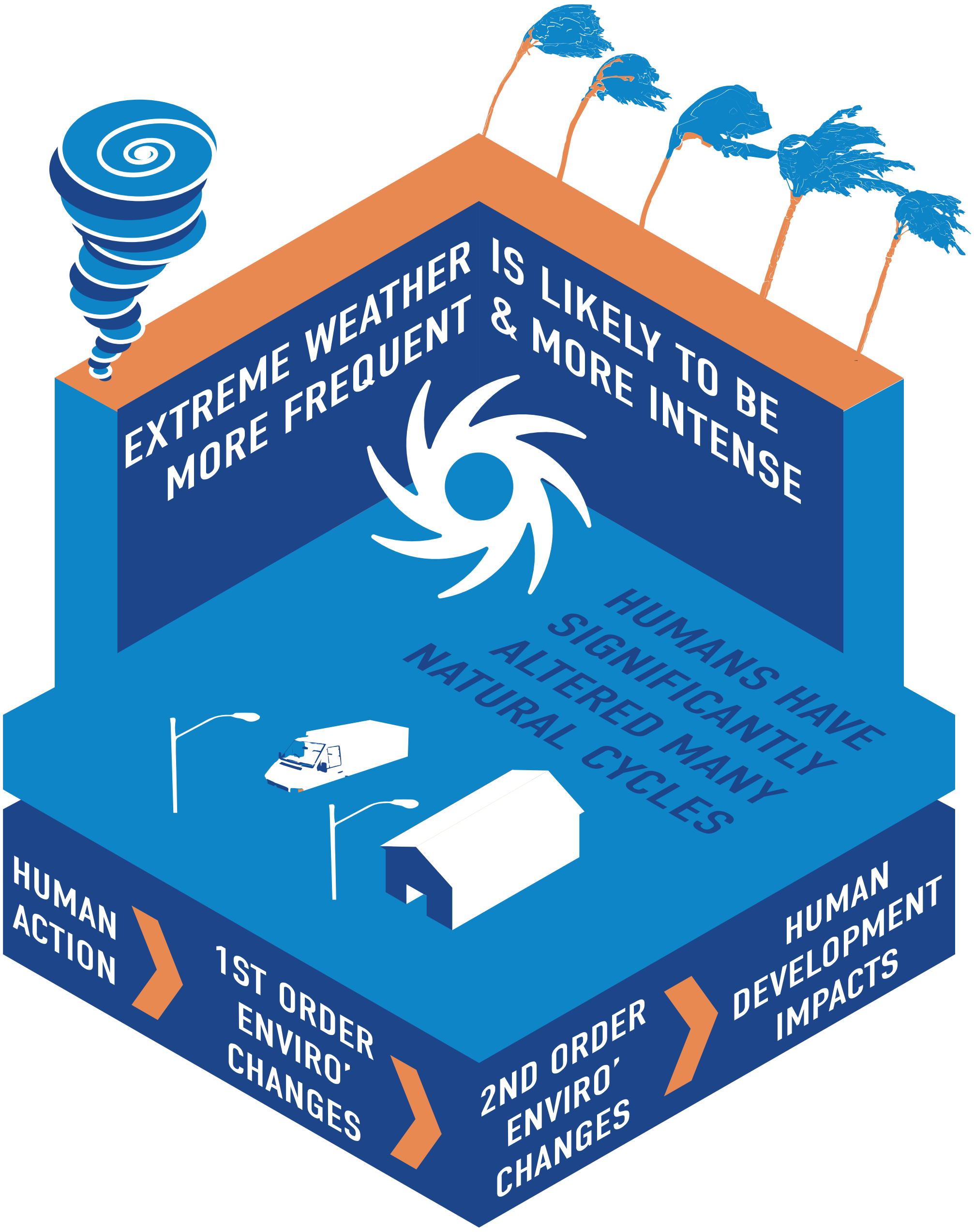
RESILIENCE TO GLOBAL CHANGE



RESILIENCE TO GLOBAL CHANGE

INTRODUCTION

Starting from prehistory, people have been altering our environment in the interest of human welfare.

Manipulating nature has been integral to broad human development. These direct (or first-order) environmental changes have been the basis of fundamental advances, such as the Agricultural and Industrial revolutions. However, as the scale of human enterprise increases relative to natural processes, a growing number of indirect (or second-order) environmental impacts are occurring. Activities that were previously beneficial are now affecting human welfare negatively.

These second-order environmental impacts, with planetary-scale effects, are collectively known as global change. There are a number of pathways through which global change may significantly impact human development, with complex chains of cause and effect. Here we seek to understand the relation between human welfare and global environmental change. Furthermore, we seek technological opportunities to increase the resilience of societies to such change.

We first identify seven broad categories that comprehensively describe the first-order environmental changes caused by human actions. Ranging in nature from biotic changes related to living organisms, to geochemical changes of the physical planet, these direct environmental changes include altered species and population distributions, lower ecosystem complexity (smaller number and variety of species), land cover change, and the alteration of carbon, water, nitrogen and other geochemical cycles.

We further establish the link between these first-order changes and their second-order consequences, including pollution, deforestation, rising sea levels, groundwater depletion and soil erosion among others. These indirect consequences lead to human development challenges in terms of food security, health, displacement and conflict.

Second-order environmental consequences that pose major threats to food security include more frequent and severe droughts and floods, soil loss due to erosion, crop yield reductions due to warmer temperatures, irrigation constraints due to groundwater depletion, and long- term constraints on plant nutrient sources.

Major health threats include water pollution that leads to diarrheal diseases, household air pollution due to indoor burning of solid fuels, outdoor air pollution, environmental toxins, and altered disease vectors and extreme weather events attributed to climate change.

Threats of displacement are expected for coastal populations affected by rising sea level, desertification leading to abandoned farmland due to untenably low agricultural yields, infrastructure failure due to permafrost thawing and agricultural yield limits due to irrigation constraints. Threats of conflict involve control of increasingly limited natural resources, including global markets for fossil fuels and mineral ores, as well as local needs such as water and grazing land.

Our focus is on the impact of first-order environmental changes and second-order consequences on low income human populations, within the year 2050 time horizon, meaning roughly the next human generation. We fully recognize that there are a number of additional major threats that these populations will face beyond 2050, and that environmental change is taking a tremendous toll on non-human forms of life on the planet; those aspects go beyond the scope of this study.

Furthermore, we focus only on those actions that can primarily be taken in developing countries. We recognize that in many cases (such as with regards to climate change), the actions of industrialized countries have caused much of the damage suffered in developing countries. However, we believe that other studies (for example, IPCC reports) are already addressing actions that must be taken by industrialized countries to mitigate such changes.

Identifying solutions to development challenges arising from global change is especially problematic, because the changes are precisely due to prior human efforts towards development. Furthermore, many non-technological hurdles exist that may constrain successful mitigation or adaptation to environmental change. These include the lack of: effective regulatory and enforcement mechanisms, adequate economic means to commit to solutions, and economic incentives among key decision-makers and stakeholders.

Focusing on scientific and technological solutions, many of the breakthroughs identified in other chapters are equally relevant to issues of resilience to environmental change. Examples of such relevant breakthroughs include soil nutrient analysis and sustainable utilization of groundwater resources, as highlighted in our Food Security and Agriculture chapter. Beyond these, we identify 13 technological breakthroughs that could address some of the challenges resulting from environmental change.

- Breakthrough 1. A low-cost system for precision application of agricultural inputs, ideally combining water and fertilizer
- Breakthrough 2. A very low-cost scalable technique for desalinating brackish water
- Breakthrough 3. Network of low-cost distributed monitoring sensors to measure and map air and water quality
- Breakthrough 4. Sustainable, affordable, household-level fecal waste management system
- Breakthrough 5. Medium to large-scale sewage treatment process with recovery of water (and ideally nutrients and energy)
- Breakthrough 16. Alternative meat production system that is affordable, desirable and environmentally sustainable
- Breakthrough 17. New seed varieties that are tolerant to drought, heat, salinity and/or other emerging environmental stresses (ideally using cis-genetic modification)
- Breakthrough 19. Affordable healthy homes that are resilient to extreme weather events
- Breakthrough 43. A standardized, solar mini-grid system that makes it simpler, cheaper and faster to set up and operate mini-grids
- Breakthrough 46. Advanced biomass cookstoves that are desirable, affordable, robust and very clean
- Breakthrough 47. Novel ways of converting household or village waste products into clean cooking fuel or electricity
- Breakthrough 48. A mechanism to remove particulate emission from old trucks and other heavy-duty vehicles
- Breakthrough 49. Small-scale waste incinerators with efficient combustion and clean emissions

By now, there is ample evidence to demonstrate that the effects of global climate change are already being felt. As recent reports by the Intergovernmental Panel on Climate Change (IPCC) and others point out, these effects will continue to worsen, with vulnerable populations in low-income countries bearing the brunt of phenomena like extreme weather events, increased temperatures, rising sea levels, and shifting rainfall patterns. As bad as the impact of climate change on these populations is, it is only part of a larger problem of environmental degradation. In many developing regions, the combination of broad poverty, rapid economic growth in some populations segments and the lack of political will and appropriate regulation has led to significant environmental damage: outdoor air is polluted because of vehicle exhaust, indoor air is polluted due to poor cooking methods and ventilation, water supplies are contaminated by fecal pathogens, urban slums accumulate mountains of trash, and industry often feels unencumbered to pollute the air, water and land with toxins.

CORE FACTS AND ANALYSIS

Although first-order environmental changes bring huge benefits to humans, they also have indirect or second-order consequences that pose risks and challenges to human wellbeing in the longer term. Human-caused first-order environmental changes have increased rapidly during the past 100 years, and many second-order consequences are now becoming conspicuous. Some of these second-order effects may cause significant negative human development impacts related to food security, health, conflict, and human displacement.

1. We propose a new analytical framework to explain the links between environmental change and human development

There are numerous pathways through which environmental changes can seriously impact human development, but direct cause-and-effect has not yet been clearly articulated.

We propose a new analytical framework (**Exhibit 1**), that links human actions to first-order environmental changes, to second-order environmental consequences, and ultimately to human development impacts. These linkages are mapped and further explained later in this chapter in **Exhibit 2, Exhibit 11** and **Exhibit 12**. Together, they seek to explain the complex chain of events linking environmental change and human welfare.

Linkage between human actions, environmental changes and human development

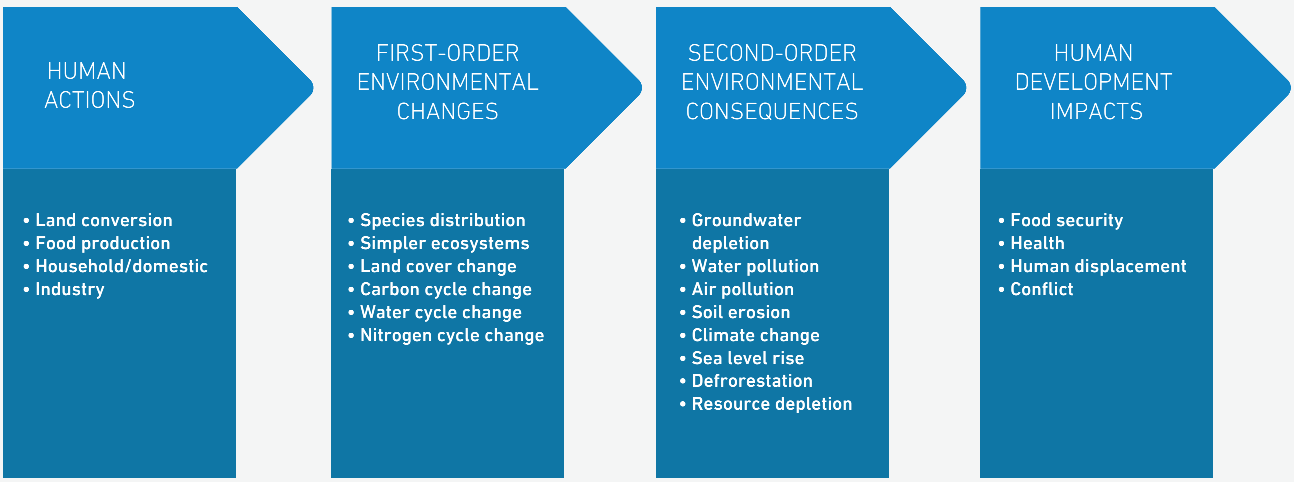


Exhibit 1: While human-caused environmental changes lead to many intended benefits, they can also have indirect consequences that pose long-term challenges. These linkages are mapped and detailed in **Exhibits 2, 11** and **12**.

As the focus of this report is global human development, this analysis is explicitly conducted from an anthropocentric perspective; we ask how environmental changes will affect human wellbeing. We acknowledge that an assessment of environmental change could be made from other perspectives, for example bio-centric or eco-centric, which may yield other conclusions based upon different priorities. Further acknowledging the long-term characteristics of environmental change and sustainability issues, our main interests here are the implications for global development within the next human generation, or until about 2050.

2. Seven first-order environmental changes are caused by human actions

We humans carry out a range of actions in our quest for a better quality of life, stemming from our needs and choices regarding production and consumption in the food, household, and industrial sectors. To enable production of adequate food for a growing human population, we convert untouched and wild land into managed cropland, pastures and orchards. We select, domesticate and care for certain animals while actively excluding other animal species. We favor a relatively small number of plant species such as wheat, rice and maize, and cultivate these species across large areas of cropland. We consider many unwanted plant species weeds and eliminate them by soil tillage or chemical poisons. We operate irrigation systems to provide water and apply fertilizers to the land to provide essential nutrients for the growth of our favored plants.

In order to provide comfortable and healthy household conditions, we convert more wild land to create urban settlements. Within our houses we consume water, food and fuels, and we produce a range of waste products. Households with access to mechanized personal transport, such as automobiles and buses, consume additional fuels to gain mobility.

The food and household sectors are supported by an elaborate industrial system to utilize and process a wide variety of materials from the environment. This involves conversion of additional wild land for industrial purposes, such as mining and timber production. Raw materials are extracted, refined and processed to become consumer goods. Additional resources, such as water and energy, are also used in manufacturing. We generate electricity by various means and distribute it for many uses. We create vast multi-modal cargo transportation networks and shift natural resources globally to suit our needs. Our systems for managing wastes, however, are typically less elaborate and for convenience waste materials are often discarded into our surroundings.

Exhibit 2 lists various examples of these human actions, and describes the first-order environmental changes caused by them. Adapting from Vitousek (1997), we identify seven broad categories (listed below) that comprehensively describe the first-order environmental changes caused by human actions. There are significant interactions between these seven categories.

- Humans now largely determine species and population distributions.
- Humans are making ecosystems simpler and less diverse.
- Humans significantly change land cover when using land.
- Humans have significantly altered the natural carbon cycle.
- Humans have significantly altered the natural water cycle.
- Humans have significantly altered the natural nitrogen cycle.
- Humans have significantly altered other geochemical cycles.

First-order environmental changes resulting from human actions

Human actions (examples)	First-order environmental changes — Biotic changes ←						Geochemical Changes →
	Species Distribution	Lower ecosystem complexity	Land cover change	Carbon cycle alteration	Water cycle alteration	Nitrogen cycle alteration	Other geochemical cycles
Food Production							
Land conversion (Wild land > agricultural land)	Conversion from wild to domesticated species	Relative simplicity of agro-ecosystems	Shift from natural to managed land	Biomass and soil carbon stocks	Change in infiltration and runoff		Increased soil erosion
Soil tillage	Tillage to favor crop species	Plant and soil community disturbance	Soil exposed to wind and rain	Altered soil carbon	Altered water runoff and quality		Increased soil erosion
Animal Husbandry (Intensive/extensive)	Several animal species are favored	Simple system of managed species	Land use for pasture	Biomass of animals and feed	Change in pasture land cover	Nitrogen in animal feed and manure	Nutrients for animals
Irrigation	Crop plant range is expanded		Expands range of agriculture		Watershed management for irrigation		Salinization of irrigated land
Fertilizer production and use				Increased biomass growth	Water quality from runoff, eutrophication	Nitrogen fixation via Haben-Bosch process	Mining and applications of phosphorus
Pesticide/herbicide use	Target species are eliminated	Loss of target species	Plant cover by target species		Water quality from runoff		Creation of synthetic organic chemicals
Killing/consumption of wildlife	Target species are eliminated	Population reduction from overexploitation					
Household/domestic activities							
Land conversion (Wild land > urban land)	Conversion from wild to human habitat	Relative simplicity of urban ecology	Land cover by urban infrastructure	Biomass and soil carbon stocks	Change in permeability, transpiration		Mining of construction materials
Indoor solid fuel burning			Forest harvest for charcoal	Carbon stocks in fuel and forest			Contaminants in fuel
Mechanized public transport	Carriage of introduced species		Land cover by road infrastructure	Carbon in fossil fuels		NDx emissions from vehicles	Lead added to gasoline
Household water consumption	Aquatic species affected by dams	Managed river ecosystems	Water supply infrastructure		Alteration of natural water flows		
Waste sewage disposal	Aquatic species biopathogens			Methane from decomposition	Water quality reduction from pollutants	Nitrogen content of sewage	phosphorus content of sewage
Industrial activities							
Land conversion (Wild land > industrial land)	Conversion from wild to managed forest	Relative simplicity of managed forests	Land cover by managed forests	Biomass and soil carbon stocks	Changes in infiltration and runoff		
Extraction and processing of mineral raw materials			Land cover by mines and quaries	Carbon in fossil fuel, cement			Various elements, e.g. iron, copper
Mechanized cargo transport	Carriage of introduce species		Land cover by road infrastructure	Carbon in fossil fuels		NDx emission from vehicles	Lead added to gasoline
Material processing and fabrication				Carbon in fossil fuels, cemement		NDx emission from vehicles	Industrial materials and byproducts
Electricity generation and distribution				Carbon in fossil fuels	Hydroelectric and cooling water	NDx emissions from power plants	Air emission of e.g. mercury
Industrial water consumption	Aquatic species affected by dams		Water supply infrastructure		Alteration of natural water flows		
Waste disposal	Aquatic species		Land cover by waste sites		Water quality reduction from pollutants	Nitrogen in fertilizer runoff	Toxic wastes, heavy metals POPs

Legend: - Little Effect - Moderate Effect - Strong Effect - Very Strong Effect

Exhibit 2: Mapping of select human actions (food production, household activities, and industrial activities), to first-order environmental changes.

2.1. Humans now largely determine species and population distributions

While humans were once a minor species struggling for existence in a landscape largely full of wild animals and plants, we have now dominated most land ecosystems. By favoring and domesticating certain plant and animal species, humans have developed extensive agricultural ecosystems and caused substantial changes in the number and range of many other organisms. Wheat, rice and maize are wild grasses that were domesticated and reproduced to such an extent that they now comprise the three most abundantly cultivated plants on Earth. Domesticated animals are fed and protected by humans, while other animals that threaten them are killed or expelled.

Our analysis demonstrates the current dominance of humans and domesticated animals over land by comparing the total mass of different animal species, in terms of carbon content in their collective biomass in living bodies (**Exhibit 3**).

Living humans are estimated to contain about 60 million metric tons (Mt) of carbon; domesticated animals maintained by humans have about 100 million metric tons of carbon (Smil, 2003; UN, 2017; FAO, 2018; Dirzo, et al., 2014; Bar-On, et al., 2018). These quantities have more than doubled since 1950. In contrast, the biomass of all wild land mammals and birds contains only about 5 million metric tons of carbon, and is steadily decreasing. This is a large reduction from the estimated 40 million metric tons of carbon in wild mammals that lived prior to the rise of human civilization (Bar-On, et al., 2018). Humans now largely control which animals live in most land areas of the world.

However, human dominance does not extend to the smaller creatures, including the 200 million metric tons of carbon in terrestrial arthropods (like insects), 12,000 million metric tons in fungi, and 70,000 million metric tons in bacteria (Bar-On, et al., 2018). Similarly, humans do not have complete dominance over the oceans, which contain about 4 million metric tons of carbon in marine mammals, 700 million metric tons in fish and 1000 million metric tons in marine arthropods.

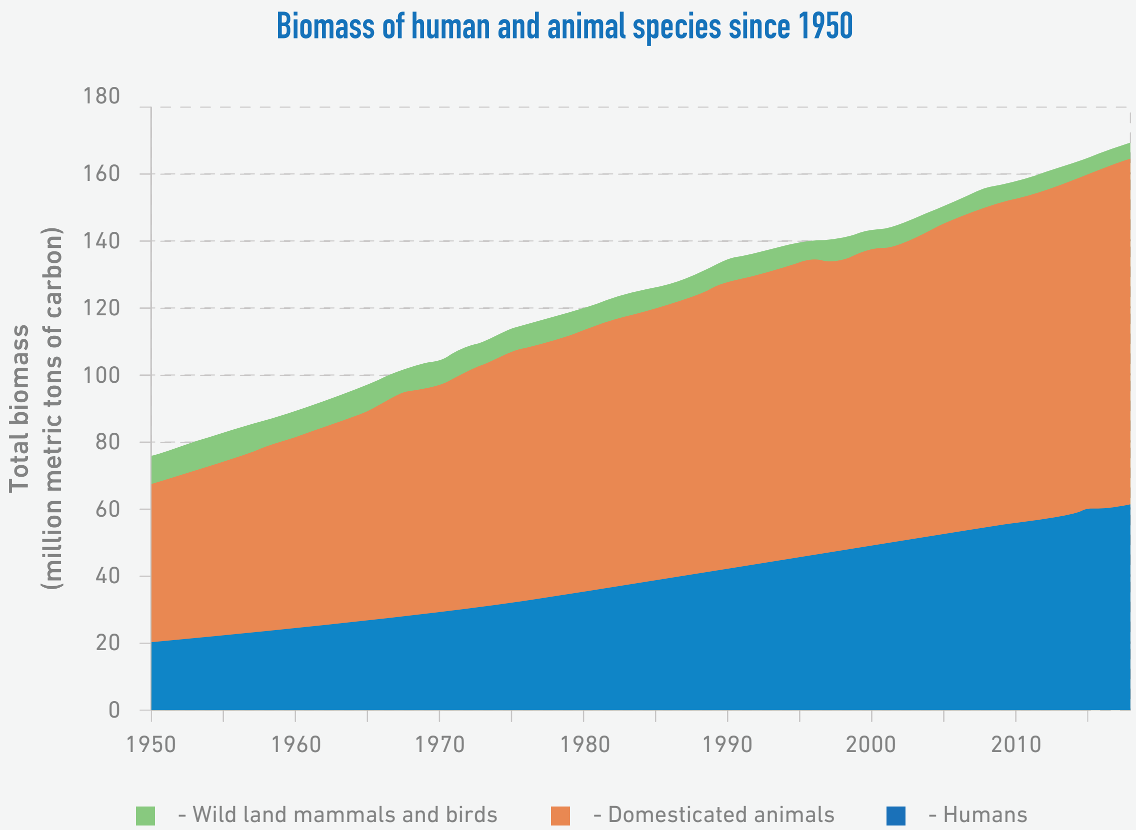


Exhibit 3: Humans and domesticated animals dominate over all other land animals. This figure shows the estimated amount of carbon contained in the living bodies of all humans, domesticated animals and wild land mammals and birds. (Source: ITT analysis based on Smil, 2003; Dirzo, et al., 2014, UN, 2017; FAO, 2018; Bar-On, et al., 2018)

2.2. Humans are making ecosystems simpler and less diverse

The population shift from wild to domesticated animals and plants necessarily involves the simplification of the structure and functioning of ecosystems. Humans are causing ecosystems to lose complexity at several levels: species diversity (the number and variety of species), genetic diversity (the genetic possibilities a species contains), and ecosystem diversity (the variation between global ecosystem characteristics) (MEA, 2005).

The distribution of species on Earth is becoming more homogenous, meaning that the differences are, on average, diminishing between the group of species at one location on the planet and groups at other locations. Various types of species evolved in ecosystems in different regions, through the combination of natural barriers to migration and local adaptations. These regional differences in the biota of the Earth are now diminishing. Thus, there's loss in genetic diversity, which serves as a way for populations to adapt to changing environments.

Species tend to come and go, evolutionarily speaking, but human actions are now causing species extinction at a rate 1000 times greater than the natural background rate of extinction estimated at roughly 130 extinctions per million species-years (Pimm, et al., 2014). This ongoing simplification is illustrated in **Exhibit 4**, based on the Living Planet Index that is calculated periodically by WWF International (WWF, 2014).

This index estimates changes in the state of the planet's biodiversity, using trends in population size for vertebrate species from different biomes and regions to estimate average changes in abundance over time (Collen, et al., 2008).

The latest index shows that across the globe, wild populations of vertebrate animals were on average 60 percent smaller in 2014 than they were in 1970 (WWF, 2018). The greatest reductions occurred in tropical regions, in particular South and Central America, where populations declined by 89 percent since 1970.

Tropical Asia also has strong declines. Temperate regions show smaller reductions, largely because those lands were cleared for agricultural use long before 1970, and now include abandoned farmlands that are reverting to natural growth. Freshwater species numbers have also declined dramatically, with the Freshwater Index showing an 83% decline since 1970.

Simple proxy indicators such as species populations are imprecise measures of overall impact to complex ecosystems. Nevertheless, the global trends toward simpler ecosystems with fewer species number and variety are robust and increasingly well documented. For example, Hallmann, et al. (2017) report a 76 percent decline in flying insect biomass in German nature protection areas over the last 27 years, and Lister & Garcia (2018) report that populations of insects, lizards, frogs and birds have declined by more than half during the past four decades in rainforests of Puerto Rico.

A global review of insect biodiversity found that some taxa (such as butterflies, bees, and beetles) are decreasing strongly and face eventual extinction, while a small number of adaptable, generalist species (such as *Plusia putnami, Laemostenus terricola* and *Hippodamia variegatais*) are increasing and occupying the vacant niches left by the declining insects (Sánchez-Bayo, et al., 2019). Wild fish populations are also declining strongly, which is detailed in the Fisheries and Aquaculture section of the Food Security and Agriculture chapter.

Change in animal biodiversity since 1970

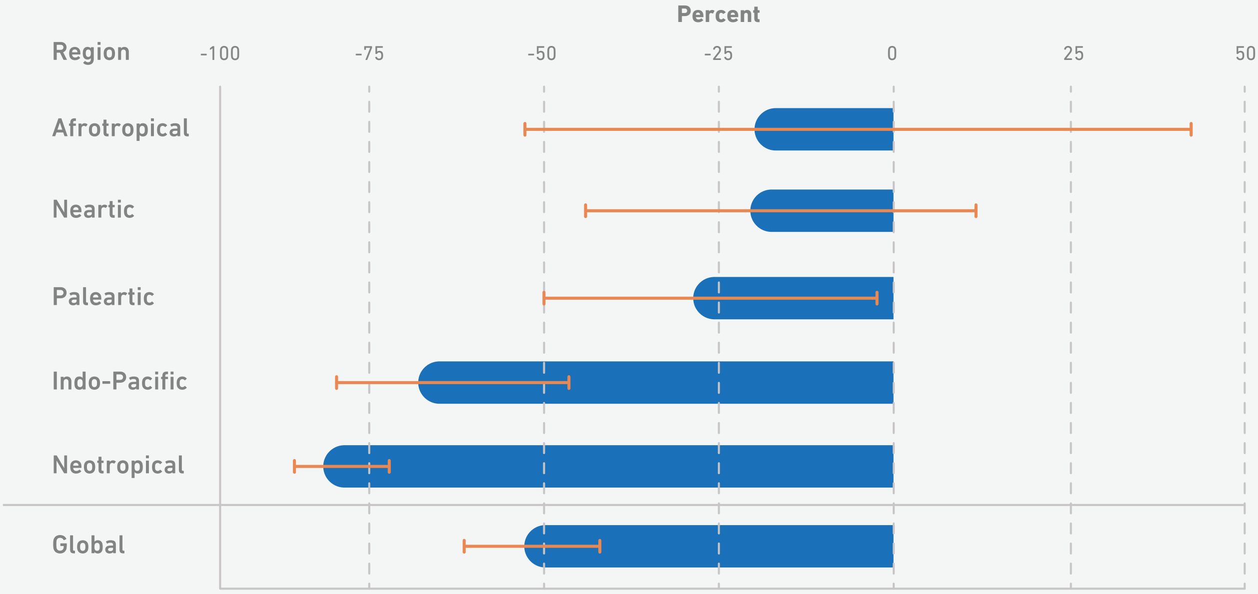


Exhibit 4: Regional and global biodiversity has generally decreased in recent decades, as estimated by WWF's Living Planet Index, based on wild populations of vertebrate animals between 1970 and 2010. Error bars represent 95 percent confidence limits. The five regions are biogeographic realms, where terrestrial species have evolved in relative isolation over long periods of time. Afrotropical includes sub-Saharan Africa. Nearctic includes North America. Palearctic includes Europe, North Africa, the Middle East, and most of Asia. Indo-Pacific includes South Asia and Australasia. Neotropical includes South and Central America. (Source: WWF, 2014)

2.3. By using land, humans significantly change the land cover

Human use of land typically alters the interface between the atmosphere and the geosphere, affecting interactions between land, plants, air and water. For example, land cover largely determines the partitioning of precipitation into evapotranspiration, runoff, and groundwater flow. Humans have, over a span of millennia, converted land once covered by wild forests, grassland and wetland into cropland and pastures.

The global number of trees is estimated to have fallen by about 46 percent since the onset of human civilization about 12,000 years ago, due to deforestation and forest degradation (Crowther, et al., 2015). Global wetland area has declined by 35 percent since 1970, and the quality of remaining wetlands is deteriorating due to drainage, pollution, invasive species, disrupted flow regimes and climate change (Ramsar Convention on Wetlands, 2018). Natural grassland area has also decreased, largely replaced by managed agricultural and pasture land.

Exhibit 5 shows that approximately 10 million square kilometers of forest land has been converted and used for other purposes during the last three centuries (Ramankutty & Foley, 1999; Pongratz, et al., 2008; FAO, 2010; World Bank, 2013). Cropland area (the extent of which may vary, depending on the definition used), increased by about 15 million square kilometers during the same period. The area of natural grassland also has decreased, and pasture land area has increased, during the period (not shown in the exhibit).

The rates of forest land decrease and cropland increase have remained fairly steady over the last 300 years, though have accelerated somewhat since about 1850. During the last three centuries, global forest area has decreased at an average rate of about 3.2 million hectares per year. The rate of deforestation from 2010 to 2015 is quite close to this centuries-old trend: forest area decreased by about 3.3 million hectares per year (FAO, 2015).

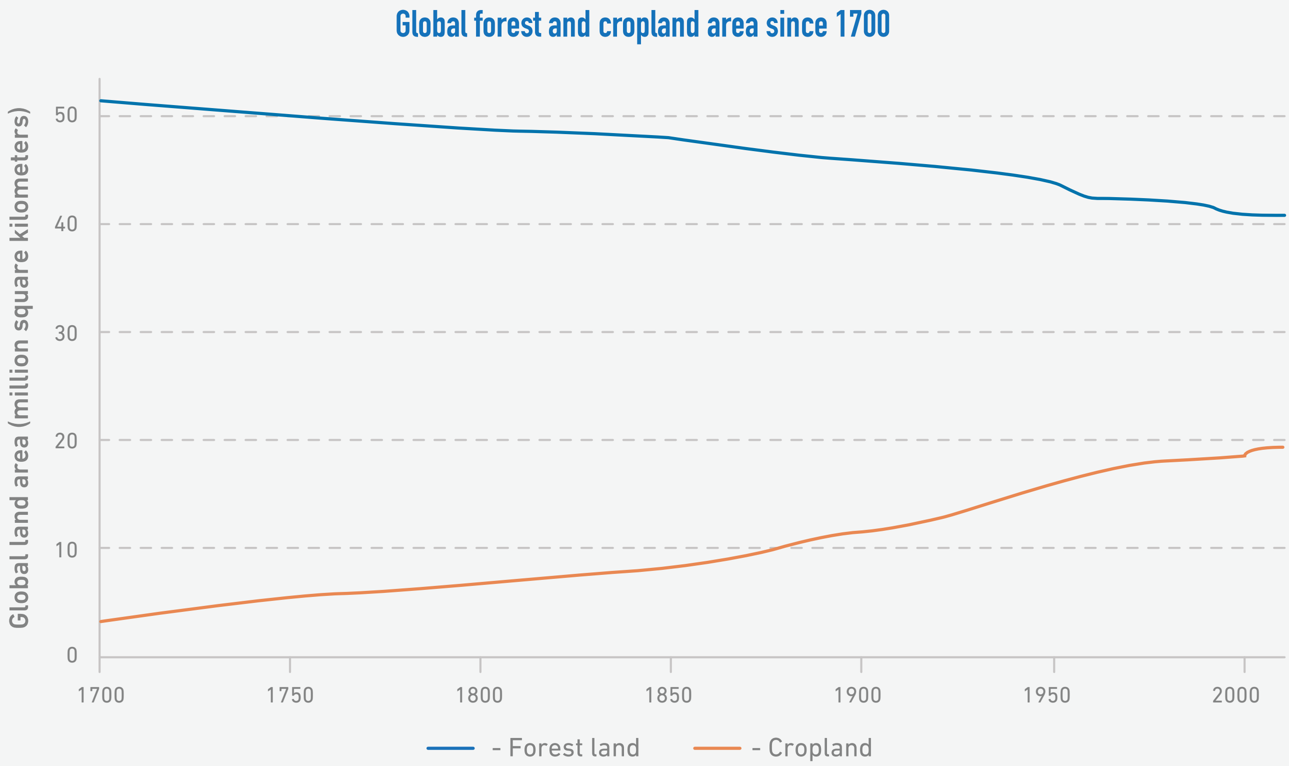


Exhibit 5: Global forest cover has gradually and steadily decreased over the past three centuries, while agricultural cropland has steadily increased. (Source: ITT analysis based on Ramankutty & Foley, 1999; Pongratz, et al., 2008; FAO, 2010; World Bank, 2013)

2.4. Humans have significantly altered the natural carbon cycle

Carbon is continually cycled between the atmosphere, land and ocean. This chemical element is found in the atmosphere as carbon dioxide gas, in the biosphere as organic carbon compounds, in the oceans as dissolved carbon dioxide, and in the lithosphere, or the hard, outer part of the Earth, as carbonate and hydrocarbon minerals.

Humans have significantly changed natural carbon cycling by altering living biomass due to land use change and by shifting carbon from geologic storage in the form of fossil fuels into the atmosphere in the form of carbon dioxide. Even before the introduction of agriculture, humans have long influenced land cover.

For example, fire has long been a relatively easy and effective way for small-scale societies to reshape the vegetation communities in their regions, to increase the relative abundance of preferred plant and animal food resources (Smith, 2011).

During the last century, however, the use of fossil fuels in the form of coal, oil and gas has become the primary source of human-caused carbon emissions (**Exhibit 6**) (Le Quéré, et al., 2018). The process extracts and utilizes the chemical energy stored in fossil hydrocarbon fuels. In doing so, carbon in the fuel changes into a more stable form, carbon dioxide.

Currently, about 9.4 billion metric tons of carbon—over 200 times more than the amount of carbon contained in all living humans (**Exhibit 3**)—is emitted each year from fossil fuel use (Le Quéré, et al., 2018). Another 0.5 billion tons of carbon is emitted each year from cement production, which heats calcium carbonate in manufacturing kilns and creates carbon dioxide as a waste product. Roughly 1.3 billion ton of carbon is currently emitted per year, due to land use change.

There are vast differences in the country-level emissions that comprise these global totals: Developing countries have relatively low emission levels that are typically dominated by land use, while industrialized countries have much higher emission levels that are primarily due to fossil fuel use (IPCC WG3, 2014).

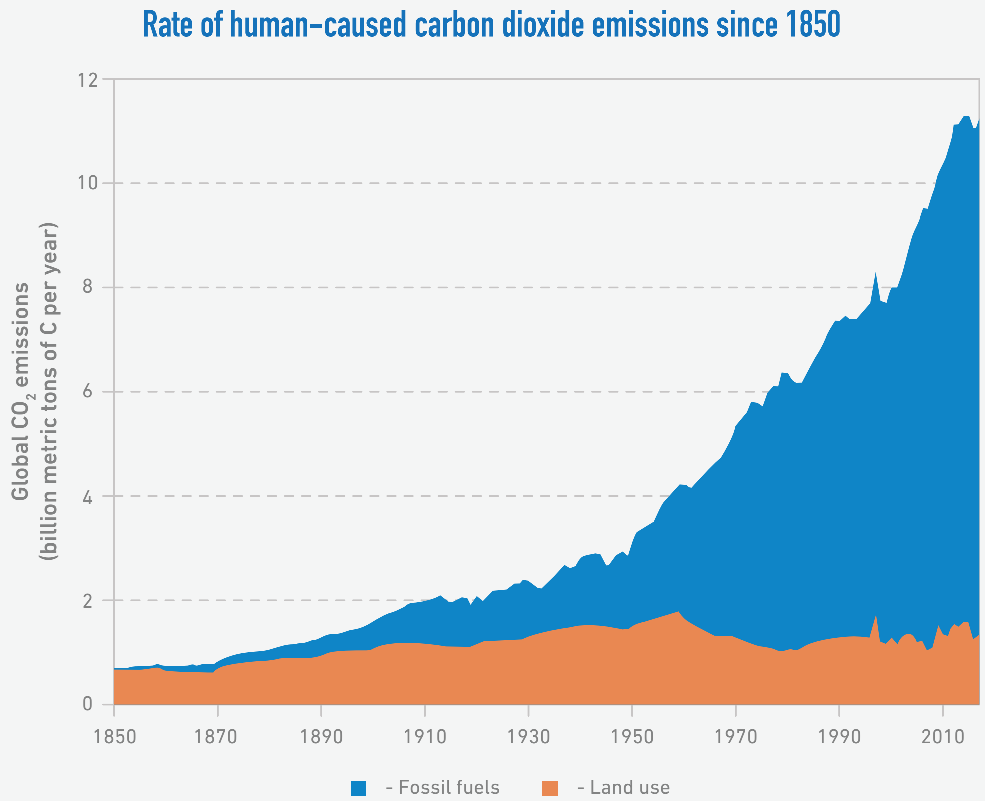


Exhibit 6: Land use change, such as deforestation, had long been the dominant human-caused source of carbon dioxide (CO_2) emissions. During the last 100 years, emissions from industry and fossil fuel burning have increased considerably and are now the largest source of emissions. Of the industry and fossil fuel emissions in 2017, coal was responsible for 40 percent, oil for 35 percent, gas for 21 percent and cement manufacture for 5 percent. (Source: Le Quéré, et al., 2018)

Between 1750 and 2011, the combustion of fossil fuels and the production of cement have released a cumulative total of about 375 billion metric tons of carbon—over 8,000 times more than the amount of carbon in all living humans. Land use change since 1750, mainly deforestation, has released an additional 180 billion metric tons of carbon. Clearly, humans have a disproportionately significant effect on the global carbon cycle. The substantial and sustained emissions of carbon dioxide have steadily increased the concentration of that gas in the atmosphere.

For at least two million years prior to the industrial era (before 1750), the concentration of carbon dioxide in the atmosphere fluctuated between roughly 180 parts per million (ppm) and 290 parts per million (IPCC, 2013). It has since increased from about 280 parts per million in 1750 to 411 parts per million in 2019 (NOAA, 2019). The concentration of carbon dioxide in the atmosphere has continued to rise at an increasing rate—about 1 part per million per year in the 1960s, 1.5 parts per million per year in the 1980s, 2.0 parts per million per year in the 2000s, and about 2.5 parts per million per year in recent years (**Exhibit 7**).

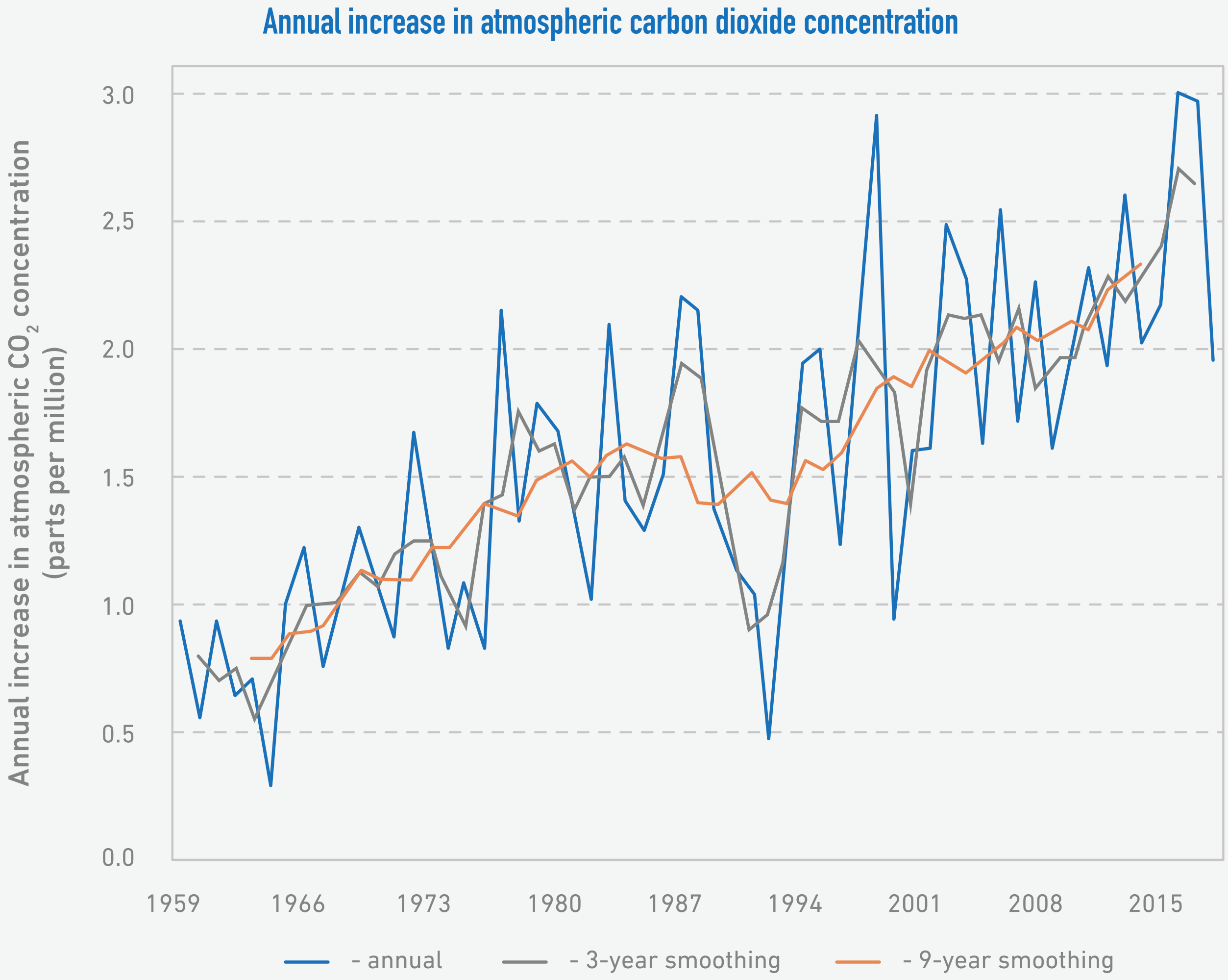


Exhibit 7: The concentration of carbon dioxide (CO_2) in the atmosphere is rising, at an increasing rate. (Source: NOAA, 2019)

2.5. Humans have significantly altered the natural water cycle

Water falls as rain or snow, flows downhill within soil and rivers, is absorbed into plants and eventually returns to the atmosphere as water vapor, from which it falls again. Humans have changed this cycle in intended and unintended ways (Meybeck, 2003).

Management of the water cycle has improved human wellbeing by controlling floods, generating hydroelectricity, providing transportation and irrigation. Furthermore, humans have changed the patterns of surface water flow, such as by impounding river water behind dams and by reducing rainwater infiltration through paved surfaces.

Exhibit 8 shows that artificial reservoirs now have the capacity to hold about as much water as contained in Lake Michigan, one of the great lakes of North America (Vörösmarty & Sahagian, 2000; van der Leeden, et al., 1990).

In densely populated areas of the world, actions such as river engineering, water withdrawals and waste dumping have significantly altered the water and material transfers through river systems, such that these actions now likely exceed the influence of natural geomorphological drivers of erosion and sedimentation (MEA, 2005).

Surface runoff and river discharge generally increase when natural vegetation, especially forests, is cleared. Such actions to manage and control water flows have involved environmental trade-offs, including fragmentation and loss of habitat for other organisms, biodiversity loss and changes in sediment transport.

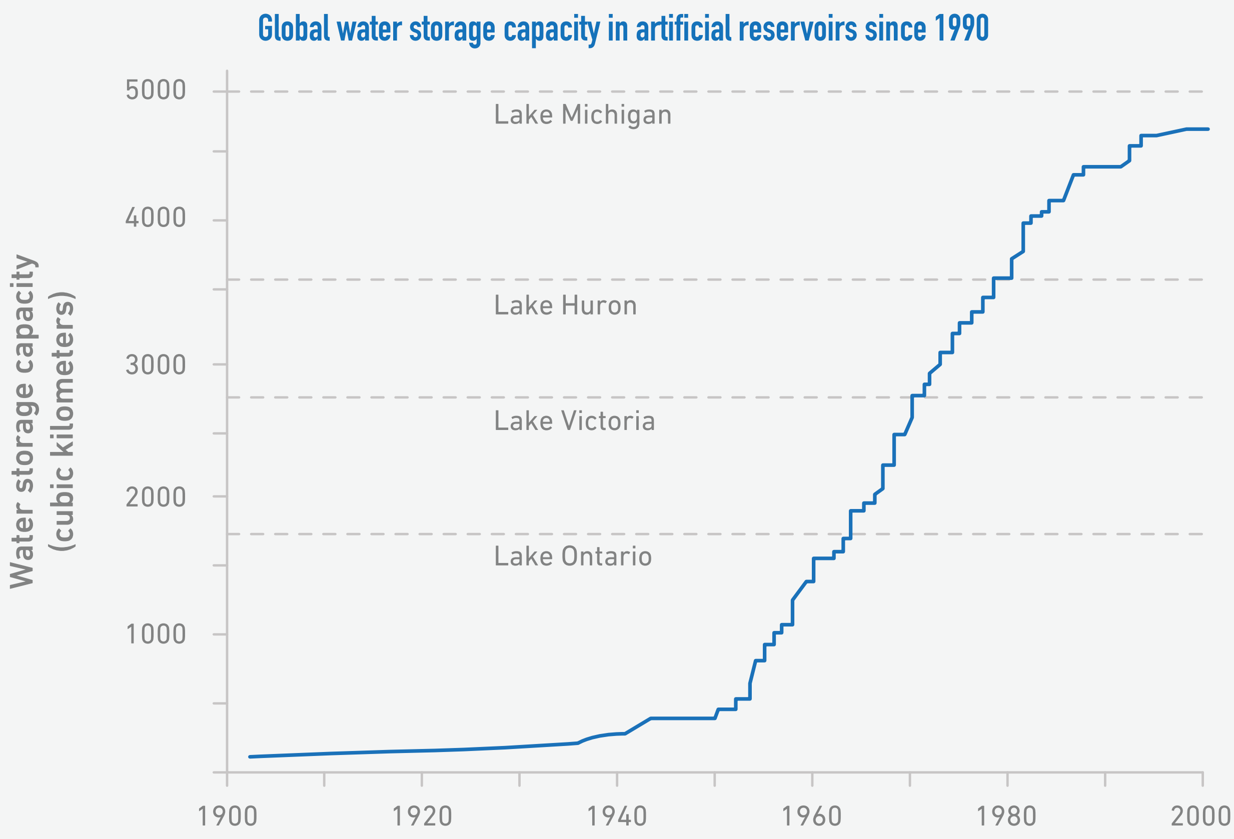


Exhibit 8: Human alterations to the water cycle, including intercepting and storing water flows, have increased substantially during the last century. Construction of dams and reservoirs increased significantly after 1950. By 1960 the total water storage capacity within artificial reservoirs globally was equivalent to that of Lake Ontario; by 1980 it was equal to Lake Huron. Currently, human-created reservoirs have the capacity to hold about as much water as contained in Lake Michigan. (Source: Vörösmarty & Sahagian, 2000)

In addition to changing the amount and timing of water flows, humans have also altered the quality of water by using water bodies like rivers, lakes and oceans as a dumping ground for biological wastes like sewage and inorganic pollutants.

Pollution is typically an unintended consequence of other activities; disposing of waste products into a nearby water body is often the most convenient, and inexpensive, form of disposal. Although 'the solution to pollution is dilution' approach was relatively effective when the amount of waste was small relative to the capacity of the environment to assimilate it, this approach is far less effective at larger scales.

2.6. Humans have significantly altered the natural nitrogen cycle

Nitrogen comprises about 78 percent of Earth's atmosphere. However, it typically exists in the very stable N_2 form, with two nitrogen atoms bound tightly together unwilling to form partnerships. Essential to life on Earth, nitrogen is needed to make amino acids, nucleotides and other basic building blocks of plants, animals and other life forms.

A limited amount of nitrogen, known as reactive nitrogen, is 'fixed' from the atmosphere and then made available to living organisms in a more reactive form. There are several natural routes of nitrogen fixation, including by particular bacteria living in symbiosis with specific types of plants. Humans have long managed croplands to incorporate these types of plants within crops rotation systems in order to fix a modest amount of nitrogen within agroecosystems.

During the last 50 years, the amount of nitrogen that is fixed through human actions has increased steadily and now occurs at a scale similar to that of all natural land ecosystems (Robertson & Vitousek, 2009) (**Exhibit 9**).

Most of this increase is due to fertilizer production using the Haber-Bosch process (described in the Food Security and Agriculture chapter). The temporary reduction in nitrogen fertilizer production during the early 1990s was due to the collapse of the Union of Soviet Socialist Republics (USSR). Other human actions that fix atmospheric nitrogen include fuel combustion and managed biological fixation.

This alteration of the nitrogen cycle has allowed us to grow significantly more food for consumption than otherwise would be possible. However, the increased overall availability of nitrogen fertilizer, coupled with the difficulty of precisely targeting application to ensure maximum absorption by plants, has led to nitrogen runoff well beyond the farmlands the fertilizer is applied to.

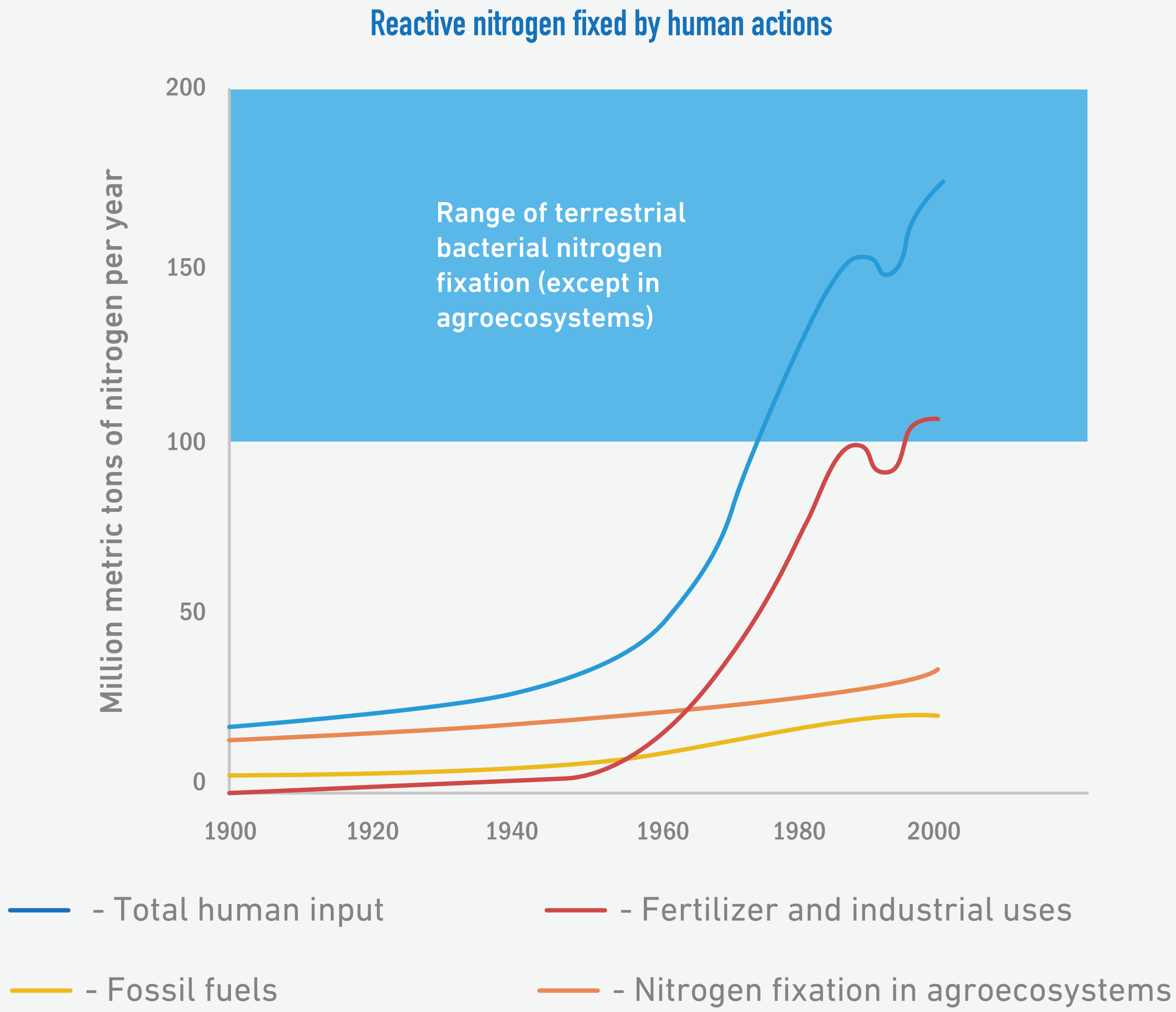


Exhibit 9: Human production of reactive nitrogen has increased substantially during the last 50 years, and now occurs at the same rate as it does in all natural land ecosystems put together. Most of this increase is due to fertilizer production using the Haber-Bosch process using natural gas as feedstock. (Source: adapted from MEA, 2005)

2.7. Humans have significantly altered other geochemical cycles

In terms of shaping the surface of the Earth, humans now cause about 10 times more erosion and sedimentation than that caused by glaciers, rivers and other natural processes combined (Wilkinson, 2005). From intentional transport of construction materials and mineral ores to unintentional facilitation of natural erosion processes through soil tillage, humans have become the dominant geologic force on the planet.

An important geochemical example is the element phosphorus, which is an essential nutrient for plant growth. Phosphorus fertilizers are important because of the slow natural cycling of phosphorus, the low solubility of natural phosphorus-containing compounds and the essential nature of phosphorus to living organisms.

Traditional sources of agricultural phosphorus are animal manure and guano (bird droppings). **Exhibit 10** shows that phosphate rock mining expanded considerably after 1950 and is now the dominant source of phosphorus fertilizer, an essential input to intensive agriculture (Cordell, et al., 2009). Countries currently mining the most phosphate rock are China, the United States and Morocco (USGS, 2018).

Phosphate is mined from deposits that took millions of years to form and that are gradually being depleted. There is considerable uncertainty about the total global quantities of phosphate reserves remaining (Edixhoven, et al., 2014).

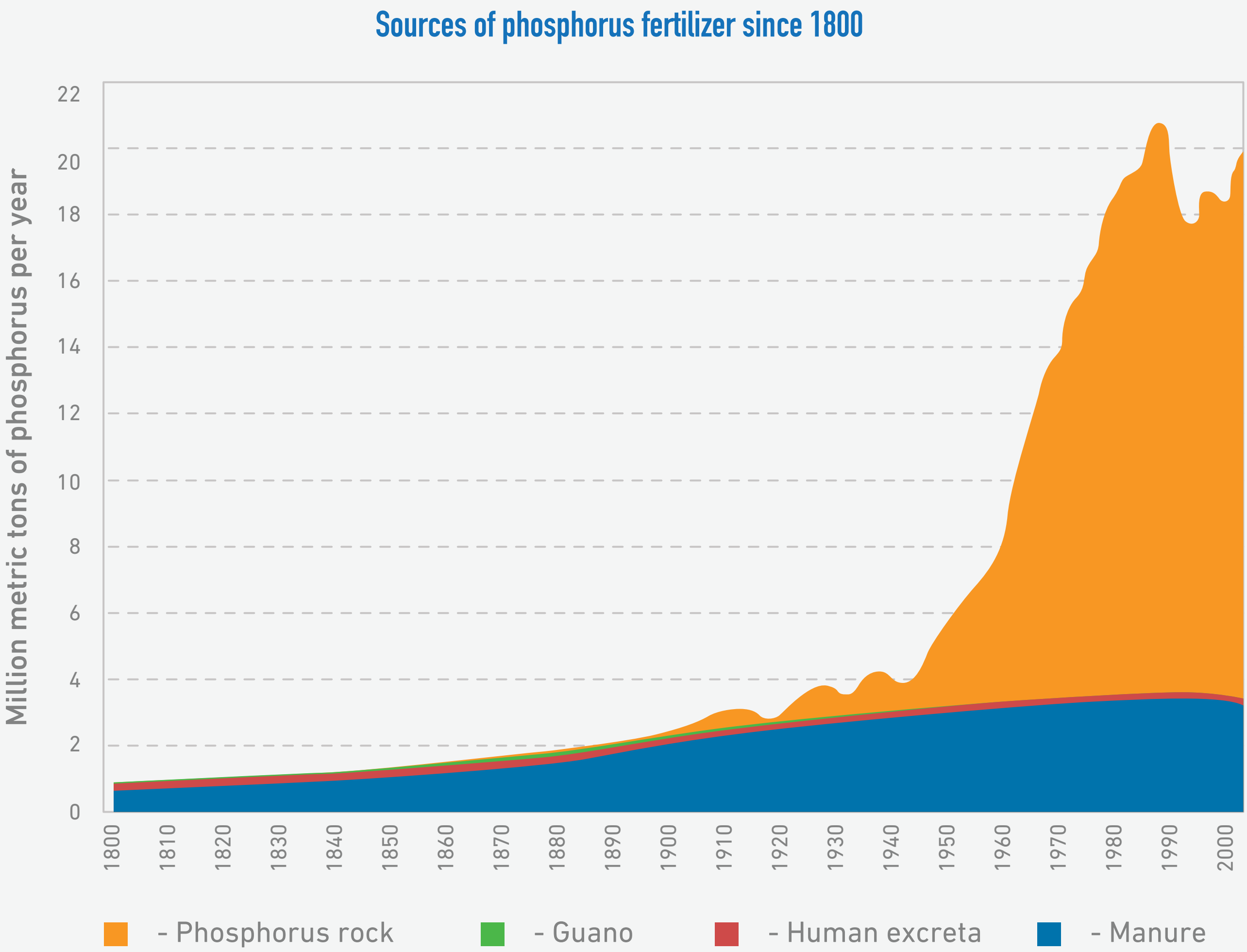


Exhibit 10: Mining of phosphate rock expanded considerably after 1950 and is now the dominant source of phosphorus fertilizer used in agriculture. (Source: adapted from Cordell, et al., 2009)

3. First-order environmental changes cause a variety of second-order environmental consequences

The first-order environmental changes described so far have mainly brought positive benefits for human populations, including provision of basic needs like food and shelter. Indeed, these changes were made primarily to improve the quality of our lives. However, as the scale of human enterprise increases relative to the scale of natural (those not managed by people) processes, a number of indirect or second-order consequences can be identified. Activities that were previously overwhelmingly beneficial now bring both positive and negative effects on human welfare.

Exhibit 11 shows how first-order environmental changes lead to second-order environmental consequences for human populations. These unintended consequences result from first-order changes brought about by human activities as described in **Exhibit 2**. As illustrated in **Exhibit 1** earlier and now in a sectional view reproduced below, second-order environmental consequences have significant human development impacts.

Second-order Environmental Consequences

- Goundwater depletion
- Water pollution
- Soil erosion
- Household air pollution
- Environmental toxicity
- Global average temperature rise
- Change in average percipitation
- Extreme weather events
- Sea level rise
- Ocean acidification
- Deforestation
- Reduced wild food
- Non-renewable resource depletion

- Food security
- Health
- Human Displacement
- Conflict

Human Development Impacts

Some of these second-order environmental consequences manifest locally, close to the human actions that provoked them while others are seen globally. For example, household air pollution occurs immediately within dwellings where solid fuels are burned for cooking.

Climate change, on the other end of the spectrum, is a global phenomenon regardless of where greenhouse gases are emitted.

Second-order environmental consequences of first-order environmental changes

First-order environmental changes							Second-order environmental consequences (examples)
Biotic changes ←						→ Geochemical changes	
Species distribution	Lower ecosystem complexity	Land cover change	Carbon cycle alteration	Water cycle alteration	Nitrogen cycle alteration	Other geochemical cycles	
		Reduced infiltration of precipitation		Over-extraction of ground water resources			Groundwater depletion
		Sediment flow due to soil erosion	Organic matter in sewer	Waste dumping into water bodies	Sewage and fertilizer runoff	Other pollutants	Water pollution
Loss of soil cover plants	Simpler plant communities	Soil exposed to wind and rain		Altered water flows and landform			Soil erosion
			Combustion of solid fuels			Contaminants in fuels	Household air pollution
		Burning of land cover	Combustion of fossil fuels		NOx from vehicles and industry	Contaminants in fuels	Outdoor air pollution
			Synthetic organic chemicals			Heavy metals, POPs, etc	Environmental toxicity
Emission of CH_4 from livestock		Net emission of CO_2	Emission of CO_2 and CH_4		Emission of N_2O	Emission of other GHGs	Global avg. temperature rise
Emission of CH_4 from livestock		Net emission of CO_2	Emission of CO_2 and CH_4		Emission of N_2O	Emission of other GHGs	Change avg. precipitation
Emission of CH_4 from livestock		Net emission of CO_2	Emission of CO_2 and CH_4		Emission of N_2O	Emission of other GHGs	Extreme weather events
Emission of CH_4 from livestock		Net emission of CO_2	Emission of CO_2 and CH_4		Emission of N_2O	Emission of other GHGs	Sea level rise
		Net emission of CO_2	Emission of CO_2				Ocean acidification
Growth of crops instead of trees	Simpler managed ecosystems	Growth of crops instead of trees					Deforestation
			Extraction and burning of fossil fuels	Exploitation of fossil water aquifers	Inputs to Haber-Bosch process	Exploitation of phosphorus and other minerals	Non-renewable resource depletion

Legend: - Little Effect - Moderate Effect - Strong Effect - Very Strong Effect

Exhibit 11: Mapping of first-order environmental changes to second-order environmental consequences. (GHGs are greenhouse gases, CO_2 is carbon dioxide, CH_4 is methane, N_2O is nitrous oxide and POPs are persistent organic pollutants)

4. Second-order environmental consequences lead to significant impacts for low-income human populations

Exhibit 12 indicates how second-order environmental consequences lead to challenges for human development, including issues of food security, health, human displacement and conflict. Major threats to food security include more frequent and severe droughts and floods, soil loss due to erosion, crop yield reductions due to warmer temperatures or, untimely precipitation, irrigation constraints due to groundwater depletion (especially in South Asia) and long-term limitations on nutrient supplies.

Major threats to human health include diarrheal diseases due to water pollution, chronic respiratory and lung diseases caused by household air pollution due to indoor burning of solid fuels, altered disease vectors and extreme weather events attributed to climate change and outdoor air pollution and environmental toxins. Experts expect threats of human displacement for coastal populations affected by sea level rise, abandoned farmland due to untenably low agricultural yields caused by desertification and agricultural yield limits due to irrigation constraints because of groundwater depletion (especially in South Asia), among others. Threats related to conflict include questions of control of increasingly limited natural resources, including global markets for fossil fuels and metal ores for instance, as well as local needs for water and grazing land.

The impact of second-order environment consequences on human development by 2050

Second-order environmental consequences (examples)	Impacts on human development by 2050			
	Food Security	Health	Human displacement	Conflict
Groundwater depletion	Limited supply of irrigation water (SA)		Constraints of irrigated farming (SA)	Conflict over water security
Water pollution		Diarrheal diseases and other health issues		
Soil erosion	Loss of fertile soil and crop yields		Desertification, abandoned farmland	Conflict for farm/pasture land
Household air pollution		Burning of solid fuels indoors		
Outdoor air pollution		Exhaust emissions from vehicles and industry		
Environmental toxicity	Contamination of food products	Chronic and acute effects of toxins		
Global avg. temperature rise	Reduced crop yields, expanded pest ranges	Expansion of disease vectors		
Change avg. precipitation	Long-term reduction in water supply (SSA)		Constraints on rain-fed farming (SSA)	Conflict over water supplies
Extreme weather events	Food production impacts by droughts and floods	Health impacts from storms and floods		Conflict over local food supplies
Sea level rise	Land inundation and groundwater salinization		Displacement of costal populations	Conflict due to displacement
Ocean acidification	Change in supply of ocean foods			
Deforestation			Displacement of forest populations	
Non-renewable resource depletion	Energy for Haber-Bosch process, phosphorus			Conflict over increasingly scare resources

Legend: - Little Effect - Moderate Effect - Strong Effect - Very Strong Effect

Exhibit 12: Mapping of second-order environmental consequences to likely impacts on human development by 2050 (SA is South Asia and SSA is sub-Saharan Africa).

4.1. Groundwater depletion will constrain irrigated agricultural production, especially in South Asia

As detailed in the chapter on Food Security and Agriculture, irrigation plays a key role in global food security. While only an estimated 18 percent of global cropland is irrigated, that land accounts for 40 percent of global food production (Schultz, 2001). There are two types of groundwater sources used for irrigation. The first is renewable groundwater sources, in which the groundwater is periodically replenished when sufficient precipitation infiltrates the soils or when floodplains become inundated.

The second type is non-renewable or fossil groundwater sources, which are typically locked in deep aquifers that have little or no long-term source of replenishment. When this water is extracted, it is effectively 'mined' and the aquifer will eventually be depleted.

In 2000, about 18 percent of global gross irrigation water demand came from non-renewable groundwater extraction (Wada, et al., 2012). **Exhibit 13** shows the sources of water used globally for irrigation in 1960 and 2000, during which time the share of non-renewable groundwater increased from 12 percent to 18 percent.

The share of non-local water resource, transported to the regions via canals and pipelines, for example, increased from 15 percent to 19 percent of global gross irrigation water. In absolute terms, gross irrigation water use increased two-fold (from 630 to 1340 cubic kilometers per year) and non-renewable groundwater use increased three-fold (from 75 to 230 cubic kilometers per year) between 1960 and 2000.

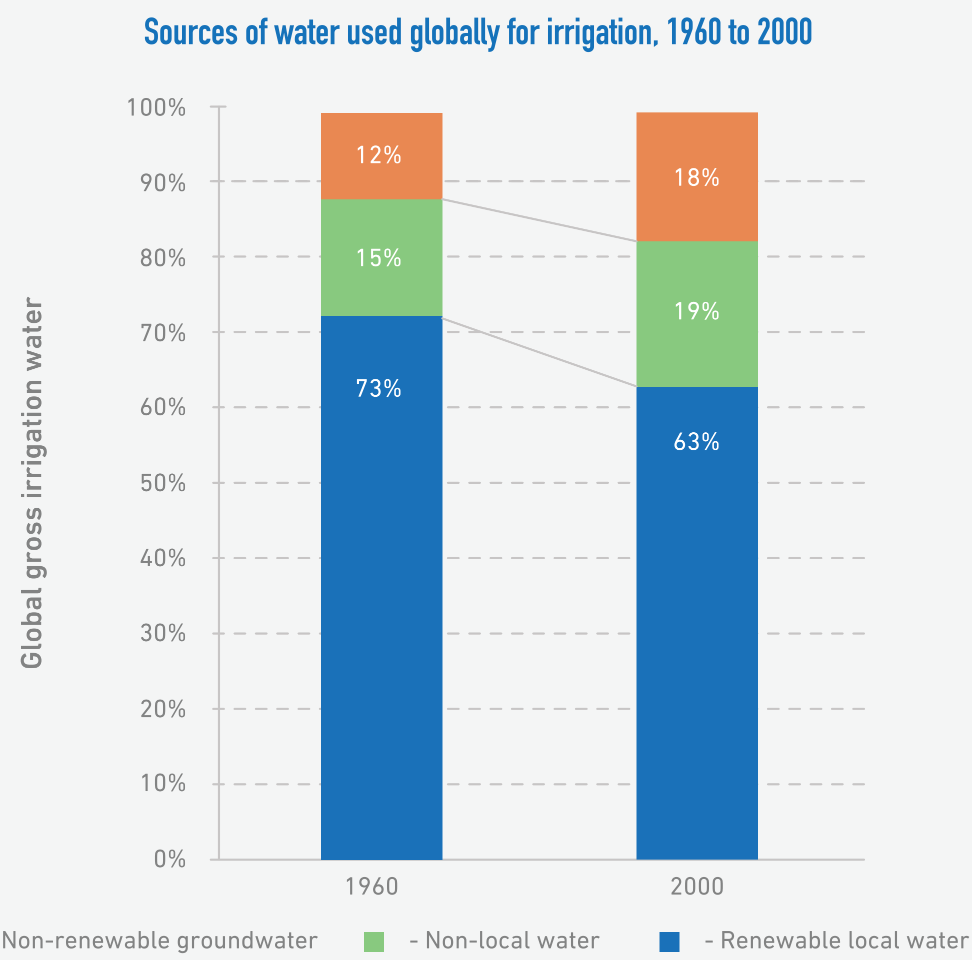


Exhibit 13: Non-renewable groundwater and non-local water comprise an increasing share of global gross irrigation water. (Source: Wada, et al., 2012)

Relatively few countries, including India, Pakistan and USA, are responsible for most of the non-renewable groundwater use (Gleason, et al., 2012). **Exhibit 14** shows that in 2000, India used more non-renewable groundwater for irrigation than any other country. About 19 percent of India's irrigation water came from non-renewable sources.

Other countries used smaller amounts of non-renewable water, but it comprised larger proportion of their total irrigation water use. In both Pakistan and the United States, the share of non-renewable groundwater was 24 percent; in Iran it was 40 percent. In Libya and Saudi Arabia, more than 70 percent of irrigation water was sourced from non-renewable groundwater (Wada, et al., 2012).

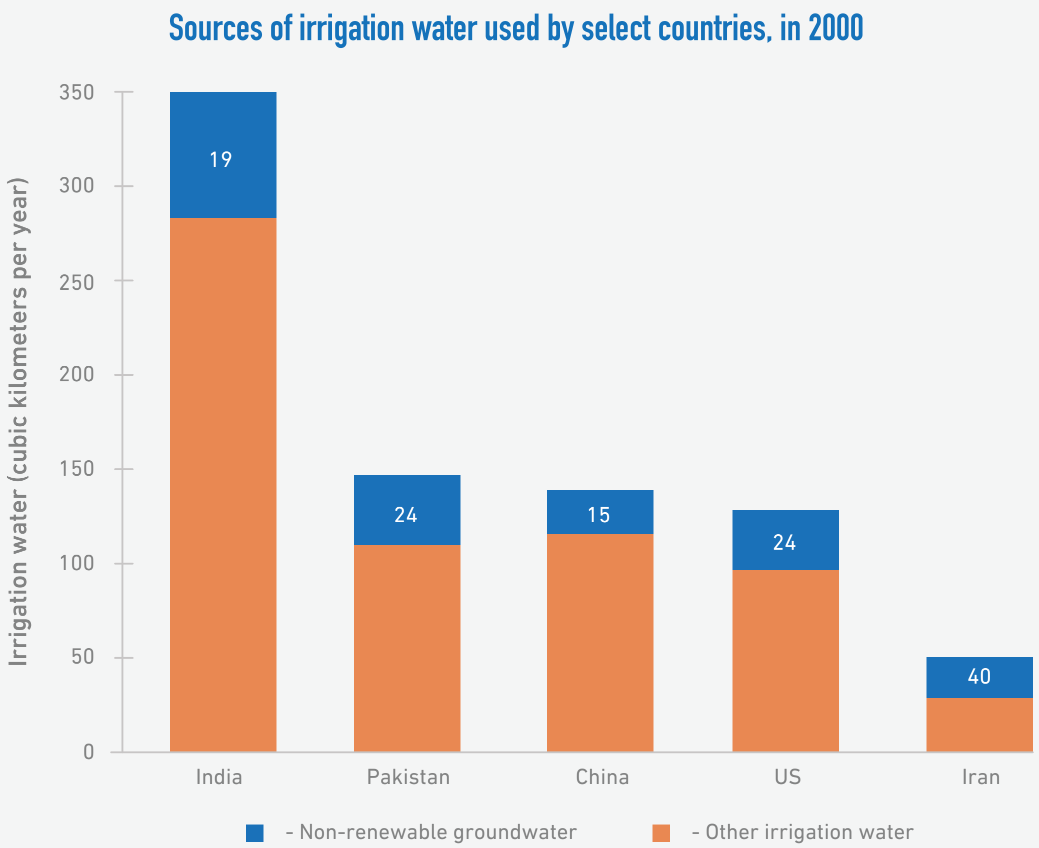


Exhibit 14: Non-renewable groundwater is a significant part of gross irrigation water use in several major countries. India uses more non-renewable groundwater for irrigation than any other country (68 cubic kilometer per year in 2000). Iran uses less in absolute terms (20 cubic kilometer per year) but more as a percent of total irrigation water: 40 percent of Iran's irrigation water is sourced from non-renewable groundwater. "Other irrigation water" includes non-local water and renewable local water. (Source: Wada, et al., 2012)

Groundwater depletion affects global development primarily due to its impact on food security. It limits the amount of water available for agriculture and other human uses and makes the available water more difficult to obtain. As groundwater supply becomes more limited, wells may go dry intermittently or constantly. Wells may need to be extended deeper to reach water and more energy is needed to pump water from greater depths. Furthermore, water quality of depleting freshwater aquifers could deteriorate due to intrusion of brackish water from surrounding aquifers. Land surfaces may subside, or gradually lower in elevation, as aquifers below become depleted.

As a development challenge, South Asia is particularly affected, where strategies for future food security must account for constrained groundwater extraction. Sub-Saharan Africa appears to have relatively abundant renewable groundwater resources (MacDonald, et al., 2012). Unsustainability of groundwater use for irrigation is a concern not only for countries that are using groundwater intensively, but also for the world at large since international trade directly links food production in one country to consumption in another.

4.2. Water contamination by organic and inorganic pollutants adversely affects health

The two types of pollutants that degrade water quality are biological like human sewage and inorganic like fertilizer runoff. Biological water pollution by human sewage is considered in detail in the section on diarrheal diseases in the Global Health chapter. Another important source of water pollution is nitrogen and phosphorus fertilizer runoff from agricultural land.

Just as fertilizing agricultural fields can stimulate crop growth, increasing nutrient levels in rivers, lakes and estuaries can cause eutrophication or excessive growth of algae and other aquatic plants. Huge blooms of cyanobacteria—also known as blue-green algae— and other organisms can come to dominate aquatic ecosystems, seriously degrading water quality (Smith, 2003).

Negative effects include hypoxia, or depletion of oxygen in the water, which causes the death of fish and other aquatic animals. Having approximately doubled each decade since the 1960s, now more than 400 marine "dead zones" resulting from nutrient runoff exist worldwide (Diaz & Rosenberg, 2008).

Many cyanobacteria also produce toxic compounds hazardous to humans and domesticated animals. Mass blooms of toxic cyanobacteria occur regularly in waters subject to nutrient runoff, with the timing and duration of the bloom season varying by location. For example, the water supply for the city of Toledo, Ohio in the United States was in 2014 disrupted for several days due to an algae bloom caused largely by phosphorus fertilizer runoff.

In recent decades, the amount of reactive nitrogen in rivers has increased dramatically (Green, et al., 2004; MEA, 2005), with river basins in North America, continental Europe and South and East Asia showing the greatest change (**Exhibit 15**). Africa suffers little from nutrient pollution, mainly because fertilizer use in Africa is still very low.

Increase in reactive nitrogen flows in river systems since 1750

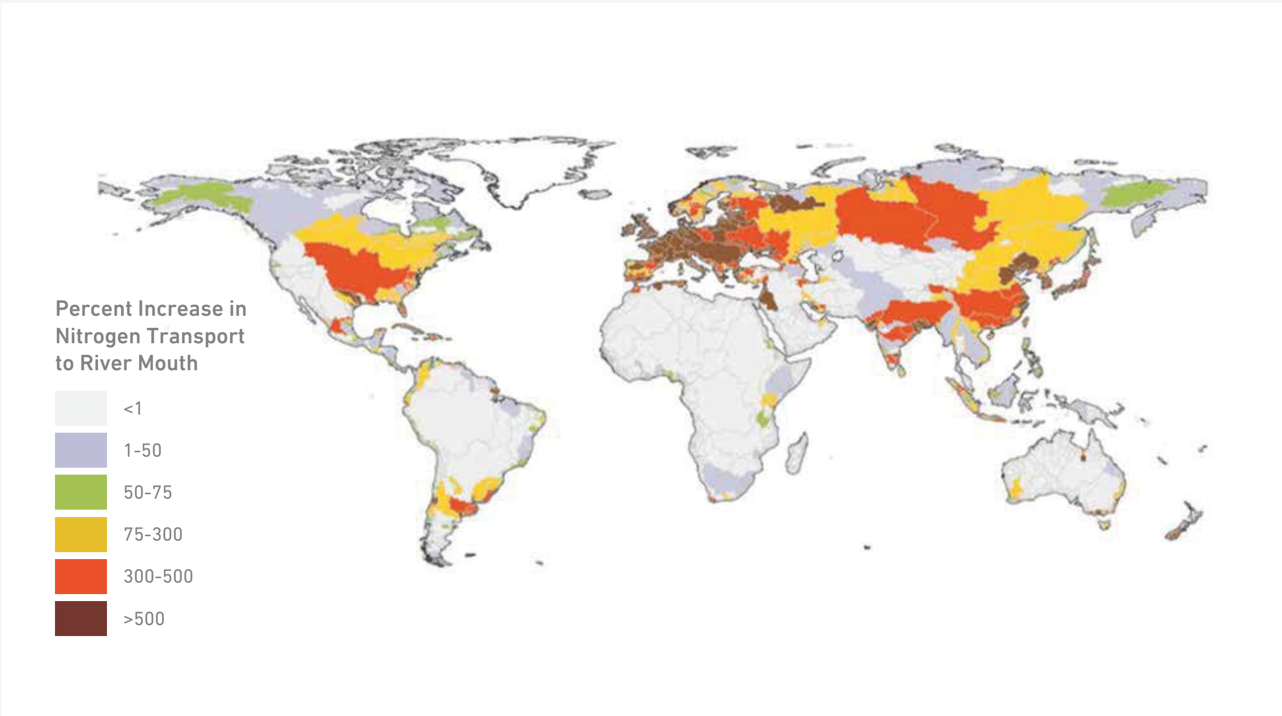


Exhibit 15: Reactive nitrogen flows in many river systems have increased dramatically in recent decades—primarily due to fertilizer runoff from agricultural lands—especially evident in Europe, Asia and North America. This has led to 'dead zones' in waterways. (Source: MEA, 2005)

Other sources of inorganic water pollution include silt and sediment from soil erosion, waste discharge from small- or large-scale industrial activities, heavy metals like mercury or lead and synthetic and persistent engineered chemicals, such as plastics and agricultural pesticides (Meybeck, 2003).

4.3. Loss of fertile agricultural soil due to erosion has significant impacts on farm yields and food security

Soil erosion is the removal of soil from the land surface, typically carried away by rain or wind. Some level of soil erosion is natural and over geologic time spans has shaped the river valleys and deltas of our landscape. Soil erosion under native vegetation occurs at roughly the same rate at which new soil is produced through natural geomorphological processes.

However, agricultural practices, such as tillage and heavy grazing, remove vegetative cover and expose the soil surface to rain and wind. Soil erosion in agricultural fields occurs at rates 10 to 100 times greater than erosion from natural land surfaces (Pimentel, 2006; Montgomery, 2007).

Such soil displacement and degradation are widespread: About 80 percent of global agricultural land suffers moderate to severe erosion (Pimentel & Burgess, 2013). Erosion is much greater on sloping land, where soil particles are carried away downhill by flowing water. Wind can also carry soil particles for long distances. Soil erosion by water is the most serious cause of soil degradation globally and heavy rainfall and extreme weather events aggravated by climate change increase soil erosion (Panagos, et al., 2017).

Exhibit 16 shows a global map of estimated soil erosion (Borrelli, et al., 2017). A global total of 36 billion tons of soil is estimated to erode each year. The continent with the highest average erosion rate is Africa, with 3.9 tons of soil eroded per hectare per year.

South America has the next highest erosion rate at 3.8 tons per hectare per year, followed by Asia at 3.5 tons per hectare per year. Global hot spots with soil erosion exceeding 20 tons per hectare per year include China (6.3 percent of the country), Brazil (4.6 percent of the country), equatorial region of Africa (3.2 percent of the region), India (7.5 percent of the country) and the United States (1.9 percent of the country).

Soil erosion varies widely by region

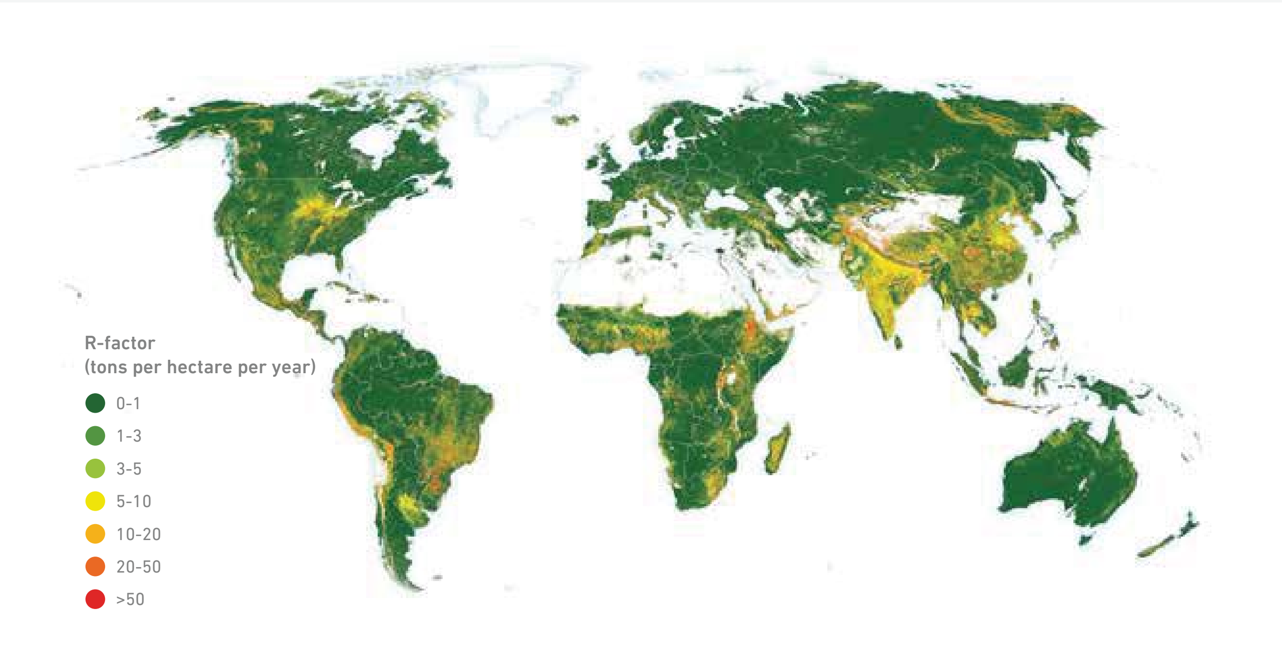


Exhibit 16: Soil erosion varies widely by region, depending on rainfall amount and timing, soil properties, land use, vegetation cover and other factors. Total global erosion is estimated at 36 billion tons of soil per year. (Source: Borrelli et al., 2017; JRC, 2017)

Soil erosion affects global development by reducing food security. Loss of fertile, nutrient-rich cropland soil reduces the productive capacity of the land and causes lower harvest yields (Amundson, et al., 2015). This is a major problem for poor rural populations living on marginal land with low soil quality and steep topography. As productivity of agricultural fields is reduced, farmers are compelled to apply fertilizers to maintain yields (Lal, 2009). Eventually, when enough productive soil is lost, the land is not worth using and is abandoned.

According to FAO (2012), about 3 million hectares of cropland worldwide are abandoned annually because of productivity declines due to severe land degradation. IPBES (2018) estimated that land degradation through human activities is costing more than 10 per cent of the annual global gross product in loss of biodiversity and ecosystem services.

A related issue is desertification, or the gradual degradation of drylands to become infertile. While traditionally ascribed to overgrazing, it is now known that many factors—including soil erosion, climate change, soil nutrient management and water cycle changes—affect desertification (D'Odorico, et al., 2013). Underlying driving forces consist of demographic, economic, technological, institutional, socio-cultural and meteorological factors.

Land degradation and desertification is caused by interactions between natural processes, such as weather variability including droughts and floods and human actions of unsustainable land use practices on fragile resources. External forces are also key drivers, including inadequate governance mechanisms, ineffective land tenure and global economic forces. Locally, this leads to decreased land productivity, overexploitation and a worsening spiral of land degradation, poverty and food insecurity.

4.4. Outdoor air pollution is a significant health risk in many urban and rural areas

Outdoor, or ambient, air pollution in both cities and rural areas caused an estimated 4.5 million premature deaths globally in 2015 (Landrigan, et al., 2018). In India alone, an estimated 0.67 million deaths were caused by ambient air pollution in 2017, with the highest rates occurring in the north Indian states of Uttar Pradesh, Haryana, Delhi, Punjab, and Rajasthan (Balakrishnan, et al., 2018).

The majority of premature deaths related to outdoor air pollution are due to strokes and ischemic heart disease. Chronic obstructive pulmonary disease, acute lower respiratory infections and lung cancer cause additional deaths. The bulk of deaths and disabilities associated with air pollution occurred in low- and middle- income countries, particularly in Asia and Africa.

Household air pollution, largely caused by burning solid cooking fuels indoors, is also serious health threat and is detailed in the Clean Cooking section of the Access to Energy chapter.

These air pollution related deaths are largely due to exposure to small particulate matter with diameter of 10 micrometers or less (PM10 and PM2.5). WHO recommends annual mean concentrations of PM2.5 less than 10 micrograms per cubic meter, and PM10 less than 20 micrograms per cubic meter.

As shown in **Exhibit 17**, concentrations of ambient air pollutants are higher than these values in most low- and middle- income countries. Chronic exposure to PM contributes to the risk of developing cardiovascular and respiratory diseases, as well as lung cancer.

Other serious risks to health from outdoor air pollution are due to excessive exposure to ozone (O_3), nitrogen dioxide (NO_2) and sulfur dioxide (SO_2).

Ozone plays a major role in asthma morbidity and mortality, while nitrogen dioxide and sulfur dioxide contribute to asthma, bronchial symptoms and reduced lung function.

Outdoor air pollution is primarily due to fuel combustion, mainly from mobile sources, such as vehicles, and also from stationary sources, such as power plants. Most air pollution in cities of developing countries is attributed to vehicle emissions (UNEP, 2014).

In rural areas, outdoor air pollution is a result of burning agricultural waste, forest fires and activities like charcoal production. Air pollution is not exclusively caused by human activity and can be greatly influenced by dust storms, particularly in areas close to deserts.

Average annual particulate matter ambient air pollution

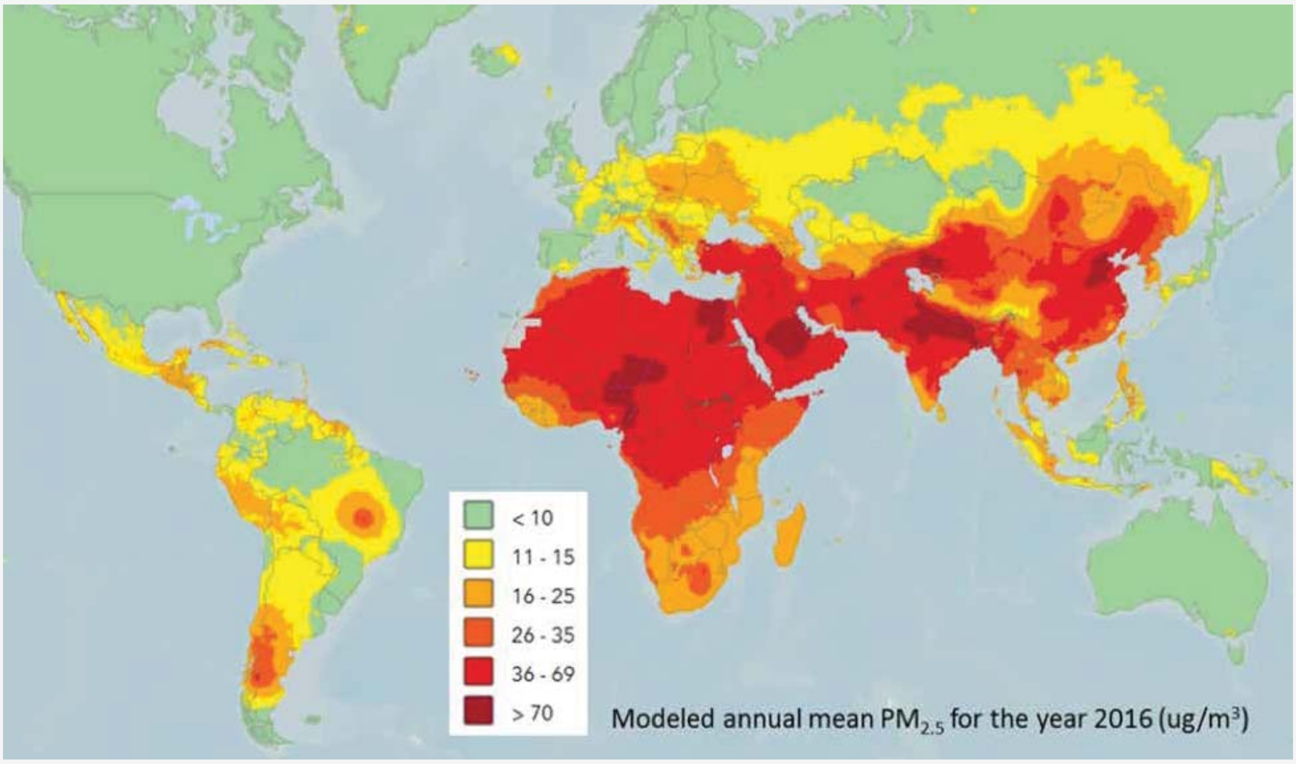


Exhibit 17: Health conditions due to outdoor (ambient) air pollution are primarily caused by exposure to particulate matter (PM). Estimated mean annual concentrations of PM2.5 (smaller than 2.5 micrometers in diameter) are shown here. PM levels are highest in Asia and Africa. Most areas in North America, Australia and Europe have PM levels below 10 micrograms per cubic meter, the annual mean concentration limit recommended by WHO. (Source: WHO, 2018).

4.5. Exposure to a broad range of environmental toxins causes chronic health conditions

People are exposed to environmental toxins—a diverse range of chemicals with potentially serious health effects—through air, water, food, or other means. Important examples of environmental toxins include heavy metals and persistent organic pollutants (POPs). Environmental toxins play a role in global development primarily due to their observed or projected chronic health impacts. Acute health impacts can also occur.

Toxic materials from industry, mining and agriculture, including substances such as heavy metals and pesticides, affect populations in many countries throughout the world (GAHP, 2013). Although environmental toxins may be less prevalent overall in developing countries because of lower industrial activity compared to industrialized countries, the less stringent industrial regulations typically found in developing countries is a serious concern.

Sources of toxic pollution include small- to large-scale mining and processing (such as battery recycling) activities, agricultural run-off containing fertilizer and pesticide residues and toxic wastes that have been illegally disposed of. Locations in developing countries that process post-use electronic devices, known as e-waste, have become 'hot-spots' of toxic exposure. The Agbogbloshie area in Accra, Ghana is a prime example (Blacksmith Institute, 2013).

Industrial accidents, such as the tragic 1984 gas leak at a pesticide factory in Bhopal, India, are another source of exposure that could have lingering, adverse health effects.

While deaths due to traditional pollutants are gradually decreasing, pollution mortality due to modern industrial development are on a gradual rise (**Exhibit 18**). Traditional pollutants are linked to poverty and include household air pollution, unsafe water sources and inadequate sanitation, typically associated with lifestyles in low- and middle-income countries.

Modern pollutants are linked to industrial development and include pollution from industrial emissions, vehicular exhausts and chemical releases. These include ambient fine particulate matter (PM2.5), tropospheric ozone pollution, toxic occupational exposures and soil pollution caused by lead. Such pollutants are quite challenging to eliminate, as they are unintended by-products of conventional development efforts.

For example, modern pollutants can be emissions from industrial production processes, exhaust from motorized vehicles and exposure to chemical products such as pesticides.

Reducing these pollution sources will require a multi-faceted approach. This can include the introduction of technologies that are cleaner throughout their full life-cycle, considering raw material sourcing, manufacturing and end-of-life disposal. We also need forward-thinking policies like the Precautionary Principle, which avoids the use of novel products unless the balance of evidence suggests they are safe. Further, consumption patterns should be based on an awareness of the benefits and risks of decisions and actions.

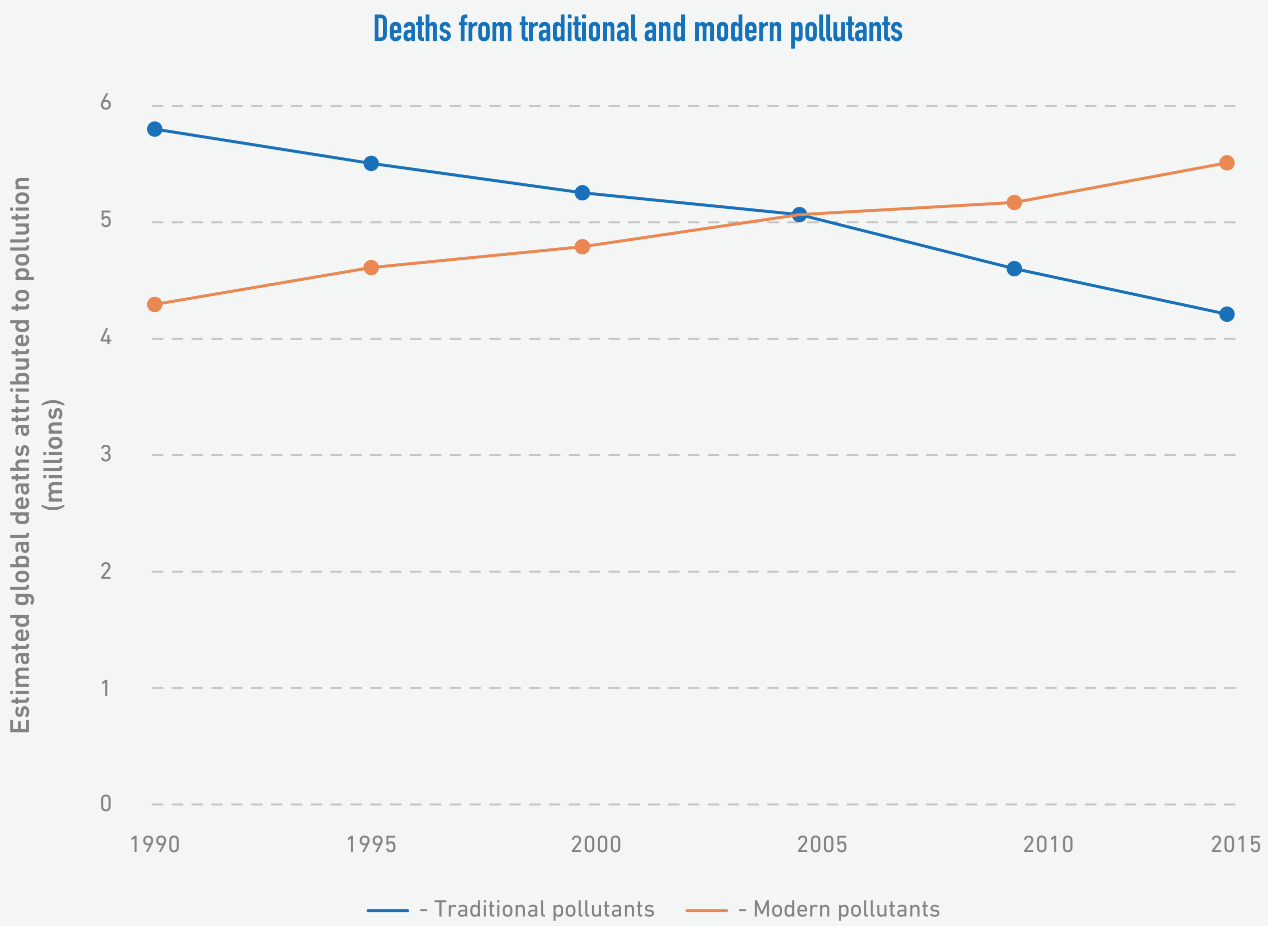


Exhibit 18: Modernization comes at a cost. Global deaths are declining from traditional pollutants such as household air pollution, unsafe drinking water and inadequate sanitation. Meanwhile, modern pollutants, such as industrial emissions, vehicular exhausts and chemical releases are leading to increased deaths. (Source: Landrigan, et al., 2018)

An important type of environmental toxin is persistent organic pollutants (POPs), organic compounds that do not degrade readily and remain in the environment for a long period of time. They tend to bioaccumulate, or build up within the bodies of organisms.

Many POPs are pesticides, such as DDT, that are either currently in use or formerly used but are still present in the environment. This chemical group also includes dioxins, furans and polychlorinated biphenyls. Dioxins are formed during incomplete combustion and when materials containing chlorine like some plastics are burned.

Another important type of environmental toxin is heavy metals, which are basic metal elements such as lead, mercury, cadmium and chromium. As elemental materials they cannot be degraded or destroyed and also bioaccumulate over time.

Exposure to lead affects multiple body systems. Young children are particularly vulnerable to the toxic effects of lead and can suffer profound and permanent brain and nervous system damage. An emerging threat from some environmental toxins is their potential impact to the endocrine system.

Some chemicals, including POPs and heavy metals, act as endocrine disruptors, interfering with the body's natural hormones. This leads to reproductive and other health problems in humans and animals, including infertility and early puberty (Frye, et al., 2011).

There is a growing number of analyses of risks faced by humans due to environmental toxins in developing regions (Prüss-Ustün, et al., 2011, WHO, 2016a, 2016b; UNICEF, 2018, Heft-Neal, et al., 2018). However, as the problems are more clearly understood, impact estimates will likely increase. WHO (2013) estimated that childhood lead exposure accounted for 143,000 deaths per year worldwide, with the highest burden in developing regions. More recently, Landrigan, et al. (2018) estimated that lead was responsible for 500,000 premature deaths in 2015, and for 9.3 million disability-adjusted life years (DALY) lost that year. DALY is a measure of overall disease burden, expressed as the number of years lost due to ill-health, disability or early death.

Studies carried out at 373 toxic waste sites in India, Indonesia and the Philippines found that 8.6 million people were at risk of exposure, resulting in about 0.83 million DALYs (Chatham-Stephens, et al., 2013). Exposure to lead and hexavalent chromium accounted for 99 percent of the total DALYs from exposure to environmental toxins.

A study on human exposure to POPs in India found levels of the pesticides DDT and HCH that exceeded limits established by international regulatory agencies (Sharma, et al., 2014). Results from human biomonitoring showed levels of these pesticides in human milk and blood exceeding safety limits. This is due to the elevated use of pesticidal POPs in agriculture until recent years and the ongoing application of DDT for malaria control.

In addition to direct impacts on human health, environmental toxins may also significantly impact global development through their deleterious effects on other species. For example, honey bees provide an invaluable environmental service by pollinating many crop plants.

For over a decade, bee populations have suffered from the symptomatic disease of colony collapse disorder (CCD), apparently due to exposure to neonicotinoids (Lu, et al., 2014). Neonicotinoids are a class of neuro-active, nicotine-based systemic insecticide that was brought into commercial use in the mid-1990s. Neonicotinoids have a high persistence in soil and water, resulting in sustained and chronic exposure of non-target organisms, such as honeybees and other invertebrates.

Because they are relatively water-soluble, they run off into aquatic habitats easily and are still toxic even at very low doses. Continued use of neonicotinoids is expected to result in substantial impacts on biodiversity and ecosystem functioning, including the distribution, abundance, and effectiveness of pollinators (van der Sluijs, et al., 2014). This could significantly impact food security due to reduced crop production. Due to concerns about their adverse environmental impacts, three neonicotinoid insecticides (imidacloprid, clothianidin and thiamethoxam) were banned in 2018 from outdoor use in the European Union (EC, 2018).

4.6. Global average temperatures will continue rising in the future, affecting agricultural yields and human health

Climate change is a long-term alteration of global weather patterns due to increased heat energy accumulated in the Earth system largely as a result of greenhouse gases emitted into the atmosphere. Some level of future climate change is unavoidable due to previous emissions, which remain in the atmosphere for long time spans. The extent of future climate change impacts depends on levels of current mitigation and future adaptation efforts. Current greenhouse gas emissions trajectories correspond closely to high emission scenarios (RCP8.5) modeled by climate scientists. If such trends continue, a global mean temperature increase of about 4°C is expected by 2100 (IPCC WG2, 2014) (**Exhibit 19**).

Beyond extrapolation of current trends, there are various self-reinforcing feedback effects that could be triggered by a changing climate, eventually leading to uninhabitable "hothouse Earth" conditions regardless of mitigation efforts (Steffan, et al., 2018).

These feedback effects include the thawing of permafrost, dieback of tropical and boreal forests, decomposition of ocean methane hydrates, loss of polar ice sheets and alteration of ocean circulation patterns. Scientific and political voices in the climate change arena have tended to understate such existential risks (Spratt & Dunlop, 2018).

Nevertheless, global cooperation towards greatly reduced greenhouse gas emissions could curb temperature rise and any corresponding feedback effects. Such cooperation has not been forthcoming to date (UNEP, 2018; WRI, 2019). Indeed, the atmospheric concentration of carbon dioxide continues to go up at an increasing rate (see **Exhibit 7**) and therefore accelerating in the wrong direction.

Historical and projected global average surface temperature, 1900 to 2100

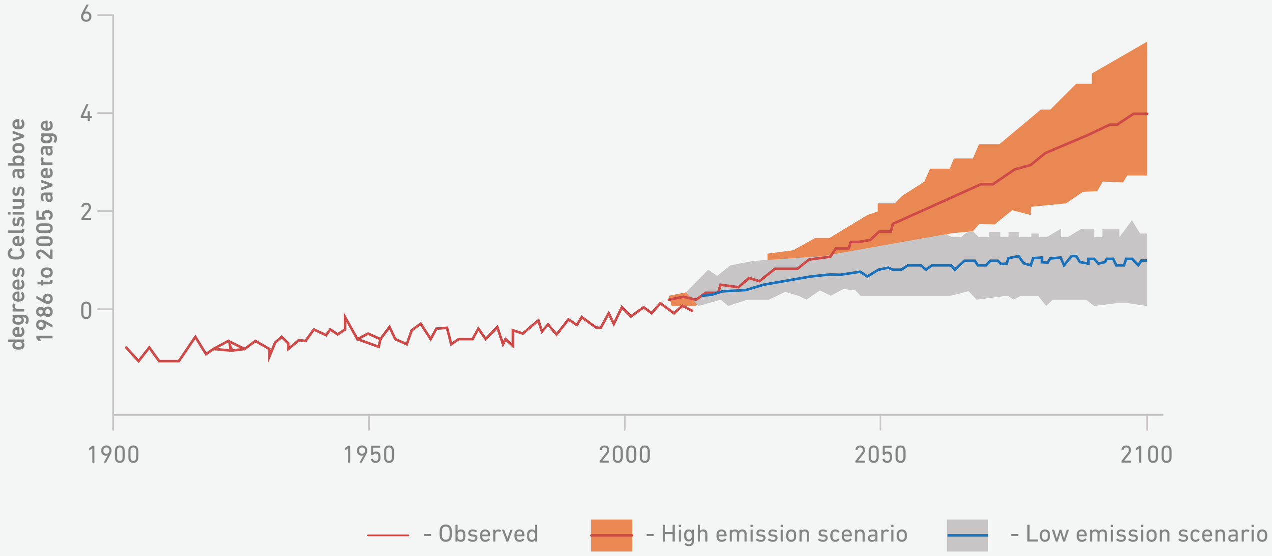


Exhibit 19: Global average surface temperature is projected to increase during this century. The temperature increase will be greater if levels of greenhouse gas emissions continue, as predicted in the RCP8.5 emission scenario. A much smaller temperature increase is projected to occur if emissions are limited to the lower RCP2.6 scenario. Temperature changes are shown relative to the average temperature from 1986 to 2005. (Source: IPCC WG2, 2014)

Rising temperatures are expected to affect global development due to potentially significant effects on food security, water supply and health. **Exhibit 20** summarizes numerous published estimates of the impact of rising temperatures on crop yields, based on a range of analysis methods including global grid-based and local point-based models, statistical regressions and field-warming experiments.

For each degree Celsius increase in global mean temperature, global average yield reductions of 6.0 percent for wheat, 3.2 percent for rice, 7.4 percent for maize, and 3.1 percent for soybean, are expected (Zhao, et al., 2018). These estimates do not include the potential effects of CO_2 fertilization, effective adaptation, and genetic improvement.

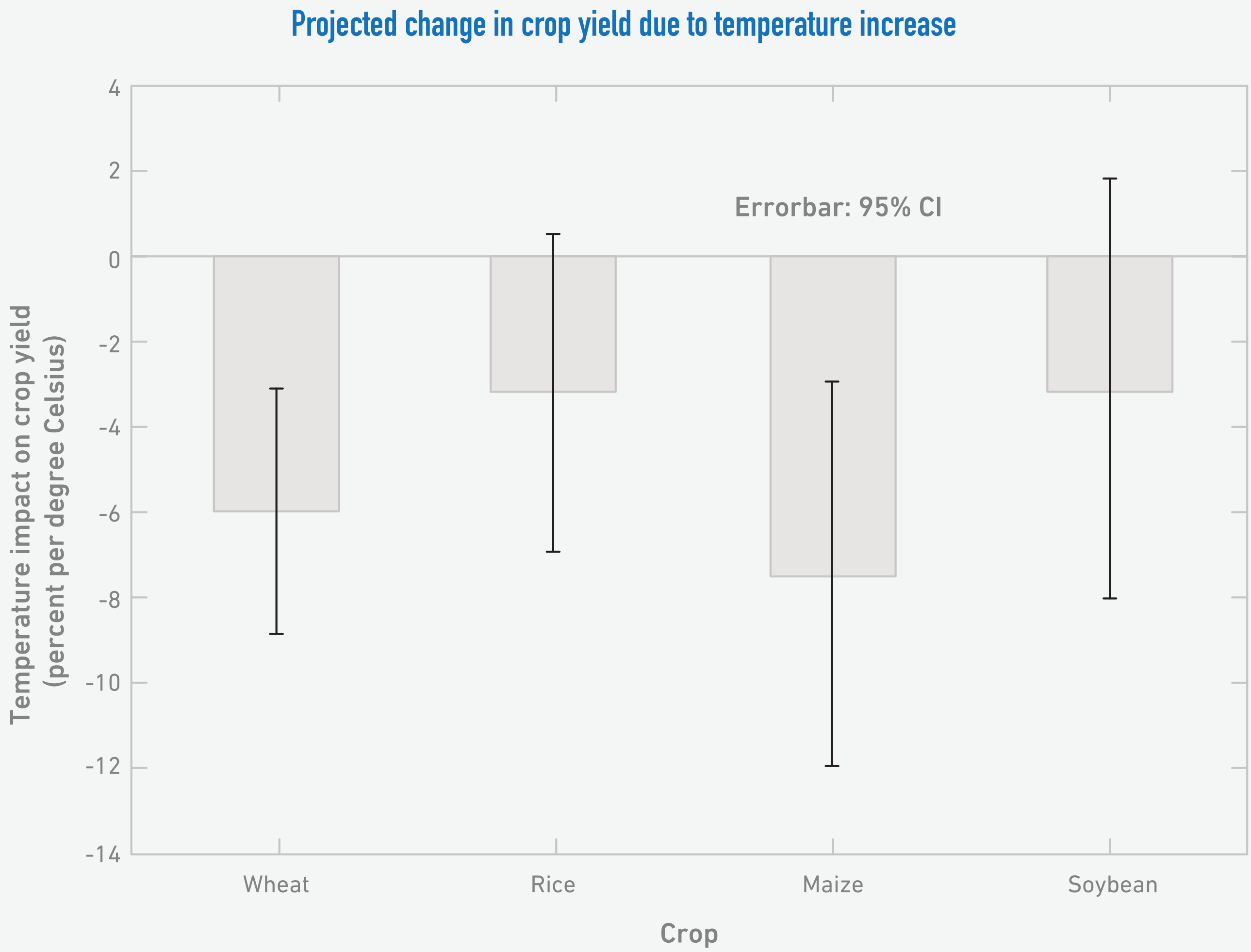


Exhibit 20: Yields of wheat, rice, maize and soybean, which together provide two-thirds of human caloric intake, are expected to decline due to rising temperatures. This exhibit summarizes published estimates based on four analytical methods: global grid-based and local point-based models, statistical regressions and field-warming experiments. Effects of CO_2 fertilization are not included. (Source: Zhao, et al., 2018).

Exhibit 21 details the expected reduction in maize yield in different regions resulting from global temperatures increases of 2°C and 4°C (Tigchelaar, et al., 2018). United States, Brazil, Argentina, and Ukraine, which together account for 87 percent of global maize exports, are the top four maize-exporting countries. The probability that these nations will have simultaneous maize production losses greater than 10 percent in any given year is currently virtually zero. However, the probability increases to 7 percent with a 2 °C increase in temperature and 86 percent with a 4 °C increase in temperature. As such, greater levels of global warming are expected to result in rising instability in global grain trade and international grain prices, which will particularly affect populations living in extreme poverty, who are also the most vulnerable to food price spikes.

Projected change in maize yield due to temperature increase

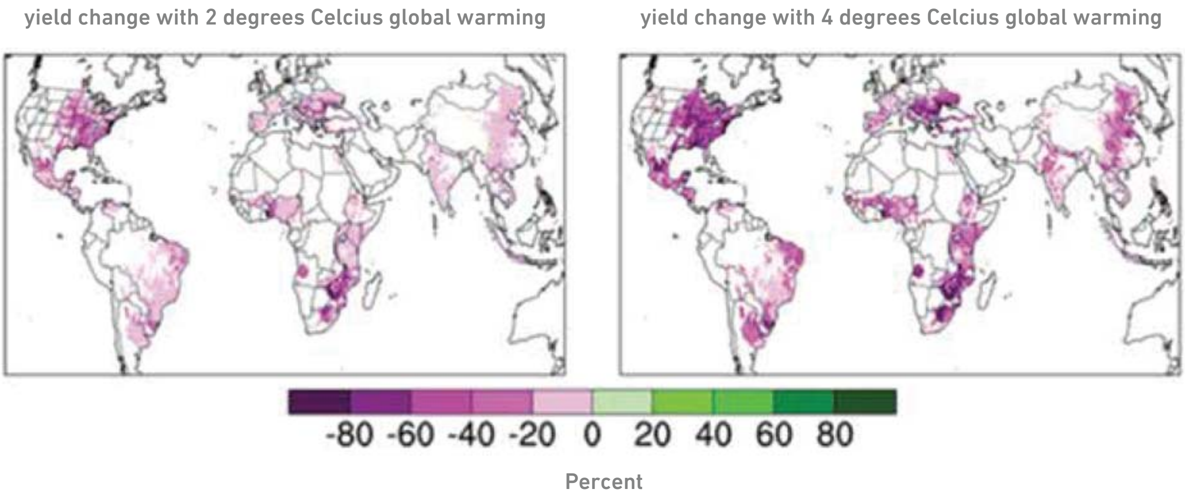


Exhibit 21: Maize yield is projected to decrease globally with global temperature increases. (Source: Tigchelaar, et al., 2018)

4.7. Average long-term precipitation patterns will shift

As the climate warms, the global water cycle is expected to change (IPCC, 2013). Average global precipitation is projected to gradually increase in the 21st century. The global hydrological cycle will intensify due to global warming and mean water vapor, evaporation and precipitation are projected to increase on average. Changes of average precipitation in a much warmer world will not be uniform, with some regions experiencing increases and others decreases or little change.

Precipitation is expected to increase in many wet tropical areas and in high latitudes. Many mid-latitude and subtropical arid and semi-arid regions will likely experience less precipitation. The Asian monsoon is expected to increase in average total precipitation but with greater variation from year to year.

Global climate change will affect our water supplies in various ways. The melting of snowpack and glaciers will affect the amount and timing of water flows in downstream areas. This is critical for Pakistan, where glacial melt contributes more than 40 percent of the total flow of the upper Indus river (Lutz, et al., 2016).

Melting of Himalayan glaciers is projected to alter the Indus River flow in the coming decades, contributing to both floods and droughts (ITT, 2018). Water pollution issues are also expected to increase due to higher water temperature and altered flow patterns. Furthermore, researchers are expecting an upsurge of some vector-borne diseases, such as malaria, in highland regions due to rising temperatures (Siraj, et al., 2014). Armed conflicts fueled by social and political tensions are likely to be exacerbated by the impacts of climate change on water supply, and in particular climate-related natural disasters, such as droughts (Schleussner, et al., 2016).

Climatic conditions play a significant role in forced migration, by affecting drought severity and the likelihood of armed conflict (Abel, et al., 2019).

Despite variability and uncertainty in climate change projections, there is now agreement from a number of different climate models that Africa is at the highest risk from climate change, given the magnitude of existing stresses in the continent (UNDP, 2009). It is highly likely that significant areas of Africa will experience changing rainfall patterns in the coming decades.

Exhibit 22 shows model projections of future changes in average rainfall during rainy seasons in Africa, under global temperature rises of 2 °C and 3 °C (Weber, et al., 2018). Average precipitation is expected to decrease in northern and southern Africa and increase in central and eastern Africa. Similar conclusions were reached by Nikulin, et al. (2018) and Maúre, et al. (2018).

Projected change in precipitation due to climate change

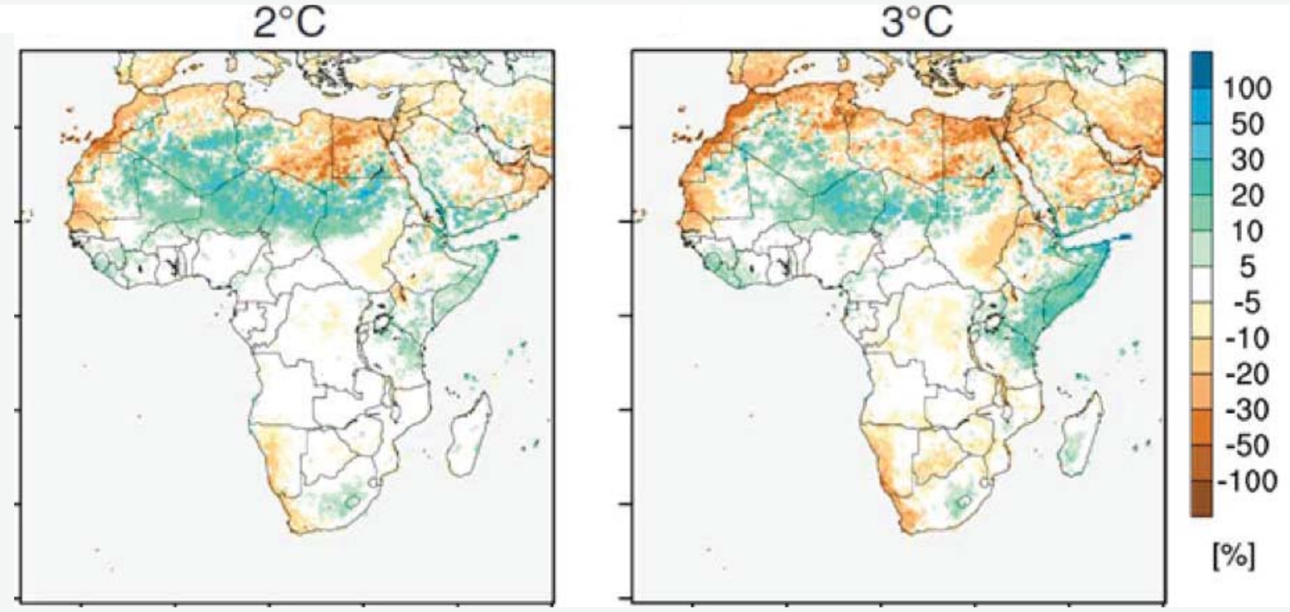


Exhibit 22: Results from climate models suggest that precipitation patterns in Africa will change as global temperature rises. Average rainfall during rainy seasons is expected to decrease in northern and southern Africa and increase in central and eastern Africa. The effect is more pronounced with a temperature rise of 3 degrees Celsius (right) than a rise of 2 degrees Celsius (left). (Source: Weber, et al., 2018)

4.8. Extreme weather events, such as drought, storms and floods will likely become more frequent and more intense

Global climate change is expected to result in more frequent and intense extreme weather events. Warm spells and heat waves will very likely occur more frequently (IPCC WG2, 2014). Storms, such as tropical cyclones, are expected to become more severe, including storm surges in coastal areas.

Precipitation is more likely to occur as heavy rainfall (even in regions that receive less total precipitation), leading to increased erosion, landslides and flooding. Precipitation extremes are projected to negatively affect water quality, due to increased sediment, nutrient and pollutant loadings caused by heavy rainfall, reduced dilution of pollutants during droughts and disruption of treatment facilities during floods.

Frequent and prolonged droughts in some regions are expected to have the most significant impact of extreme weather events on human development. Many climate models project an increased likelihood of agricultural droughts in regions that are presently dry, with extended decreases in soil moisture (IPCC WG2, 2014).

Farmers and pastoralists in drylands with insufficient access to drinking and irrigation water risk the loss of agricultural productivity. This will affect the livelihoods of rural people, particularly those who depend on water-intensive agriculture. There is a corresponding risk of food insecurity and conflict over available water and food resources (UNDP, 2009).

4.9. Sea levels will slowly but inevitably rise in the future, affecting coastal populations

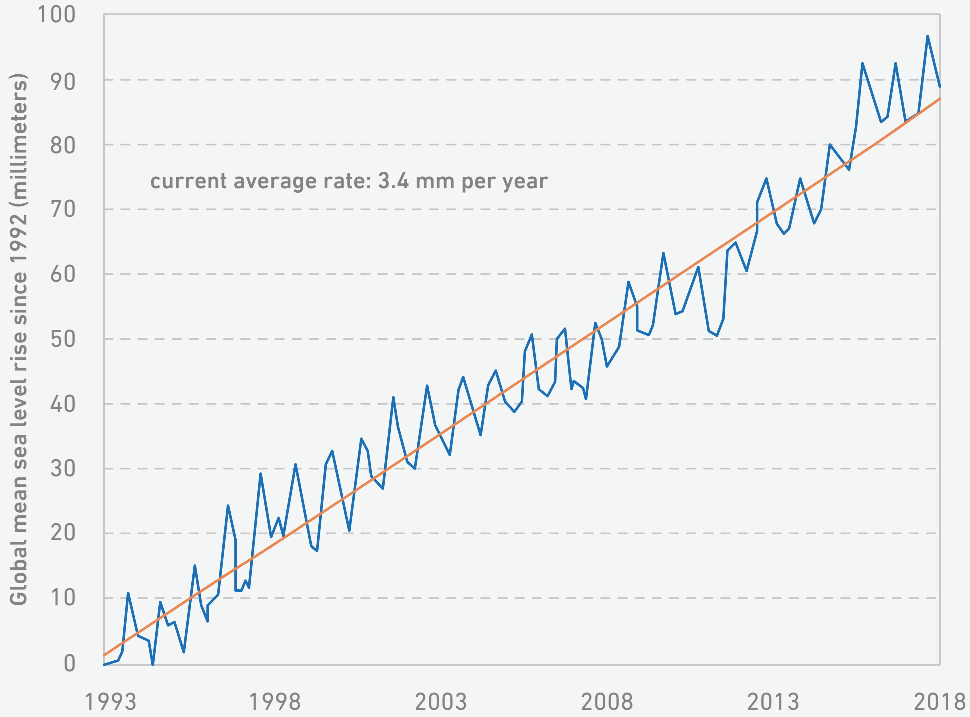
Global mean sea level has risen about 0.2 meters since 1900 at an average rate of about 1.7 millimeters per year (IPCC WG2, 2014). It is currently rising at a rate of about 3.4 millimeters per year (CSIRO, 2018) (**Exhibit 23, top**). Sea level is expected to continue rising at an accelerating pace, depending largely on future greenhouse gas emission levels. While global mean sea level inexorably rises, a variety of factors including tides, gravity and Earth's rotation will continue to influence local sea level in complex ways.

Forecasting future sea level rise is very challenging, though modeling capabilities are improving steadily (Horton, et al., 2014). The 2014 IPCC report projected a sea level rise of about a half meter by 2100 for the low emission climate scenario (RCP2.6), and a full meter for the high emission climate scenario (RCP8.5) (**Exhibit 23, bottom**). Much of this sea level rise is due to thermal expansion of the slowly warming ocean water.

Another, more uncertain, contribution to rising sea levels will be melting glaciers and ice caps. IPCC reports have been criticized for their excessive conservatism, and some experts suggest a sea level rise of at least two meters by 2100 is not implausible (Bamber, et al., 2019).

Sea level rise will affect global development due to permanent or episodic displacement of coastal populations, inundated agricultural land and reduced freshwater supply due to saltwater intrusion into aquifers.

Historical mean sea level rise, 1993 to 2018



Historical and projected mean sea level, 1700 to 2100

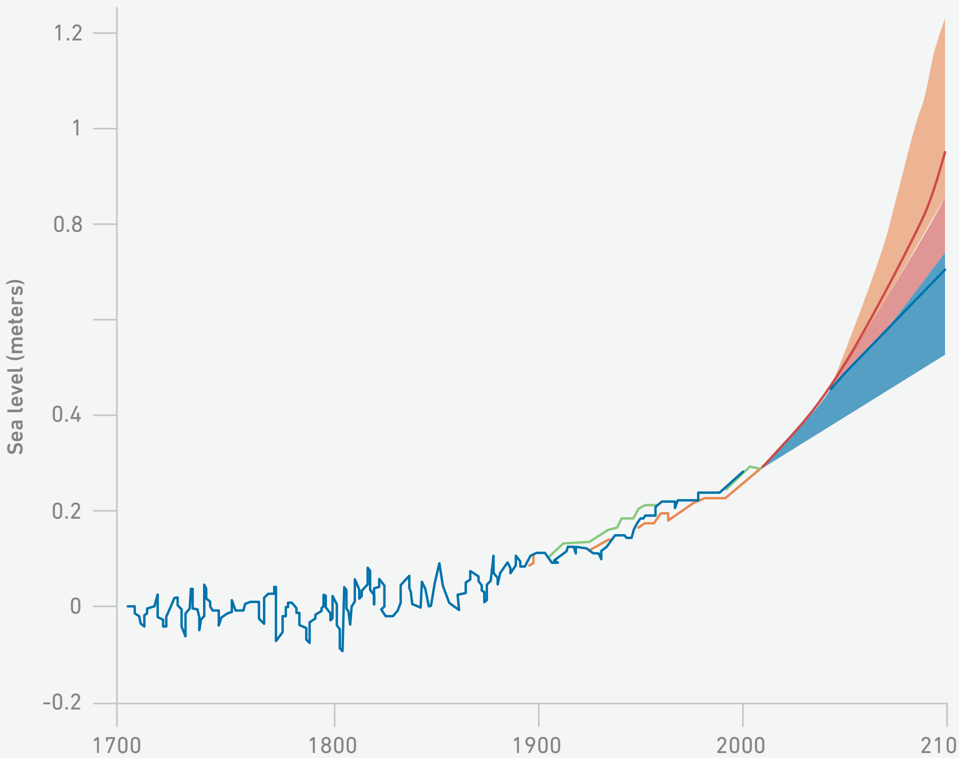


Exhibit 23: Global mean sea level has risen at a rate of about 1.7 millimeters per year since 1900, rising a total of about 0.2 meters since pre-industrial times. It is currently rising at a rate of about 3.4 mm per year (top figure). The mean sea level is projected to continue to rise at an accelerating pace through 2100 and beyond (bottom figure). Future sea level rise is projected for the low emission RCP2.6 scenario (blue) and the high emission RCP8.5 scenario (red) (Sources: top figure: CSIRO, 2018; bottom figure: IPCC WG2, 2014).

Coastal areas are highly vulnerable to extreme events, such as storms and their associated surge, which will be exacerbated with higher average sea levels. Regions that do not experience high tidal variation in water level, located mainly in the Tropics, are projected to experience a doubling of the frequency of flooding due to a sea-level rise of 10 to 20 centimeters, which is expected no later than 2050 (Vitousek, et al., 2017). This will particularly affect the developing economies of equatorial coastal cities and the habitability of low-lying Pacific island nations.

River delta regions are also highly vulnerable to the impacts of climate change, particularly sea level rise and changes in runoff. Many delta plains, especially those in Asia, are very densely populated. Some studies estimate (Ericson, et al., 2006) that by 2050, more than a million people will be directly affected in three megadeltas: the Ganges-Brahmaputra delta in Bangladesh, the Mekong delta in Vietnam and the Nile delta in Egypt.

Their modeling suggests that 75 percent of the population affected by sea level rise live on deltas in Asia and many of the remainder live on African deltas. About 8.7 million people could be affected by coastal inundation by 2050. GIS based models (Dasgupta, et al., 2009) estimate that a one-meter rise in sea level will directly affect more than 56 million people in developing countries.

Several countries are expected to be particularly impacted, including Vietnam and Egypt; both countries could see 10 percent of their population being displaced by a one-meter rise in sea level. Some freshwater aquifers in coastal areas are expected to become brackish due to the intrusion of rising salt water levels (Werner, et al., 2013).

Coastal adaptation practices can seek to protect, accommodate or retreat in response to rising sea levels. Protection efforts can involve ‘hard’ or ‘soft’ measures but will face increasing pressure over time and may ultimately be untenable. Efforts at accommodation focus on reducing damage from high waters through flood-resilient infrastructure or floating agricultural systems, for instance. Retreat options may ultimately be inevitable. This, in populated areas, will result in large numbers of ‘climate refugees’ who will need to permanently resettle elsewhere.

4.10. Ocean water is absorbing atmospheric CO_2 and becoming more acidic, affecting sea plants and animals

As described earlier, the concentration of carbon dioxide (CO_2) gas in the atmosphere has risen from about 280 parts per million (ppm) during pre-industrial times to about 408 parts per million now. Some of the CO_2 that is emitted into the atmosphere is absorbed by the oceans and this has a significant impact on the chemistry of seawater. Carbon dioxide reacts with water to form carbonic acid (H_2CO_3), which increases the acidity of the ocean. Acidity is measured in pH units using a logarithmic scale: a 1 unit decrease in pH corresponds to a 10-fold increase in hydrogen ion concentration, or acidity. Since the beginning of the industrial era, the pH of ocean surface water has changed by about 0.1 unit—from about 8.2 to 8.1, on the full pH scale. This corresponds to a 26 percent increase in hydrogen ion concentration (IPCC, 2013). While not directly related to the changing climate, ocean acidification is caused by the same global drivers and is typically considered a consequence of global climate change.

As oceans absorb additional CO_2 from the atmosphere, ocean acidification is expected to increase in the future, Climate models project a global increase in ocean acidification for all greenhouse gas emissions scenarios (IPCC, 2013). According to projections based on the high emission scenario (RCP8.5), a decrease in the pH of surface ocean water by about 0.3 units is expected by the end of 21st century. Projections show that with the low emission scenario (RCP2.6) the ocean water pH would decrease by only about 0.07 units by 2100.

The consequences of changes in ocean acidity for marine organisms and ecosystems are just beginning to be understood but are expected to affect fundamental biological and chemical processes of the sea. Geological records, as well as results from laboratory, field and modeling studies suggest that marine ecosystems are highly sensitive to changes in ocean acidity. For example, the acidity of seawater largely determines the saturation state of calcium carbonate minerals, which affects the formation of shells for marine animals such as corals, plankton and shellfish. Some marine species like reef fishes and shelled mollusks are expected to be negatively affected by ocean acidification, while other species like crustaceans may fare better (Branch, et al., 2013). Overall effects on primary productivity and food webs will be complex and hard to predict.

4.11. Forest land continues to be converted to agricultural land, especially in Latin America

Deforestation is the removal of trees from a forested area, where the land is then converted to non-forest use. Globally, about 4 billion hectares, or 31 percent of total land area, is covered by forests (FAO, 2015). During the last three centuries, global forest area has decreased by about 1 billion hectares, corresponding to an average deforestation rate of 3.2 million hectares per year (see **Exhibit 5**).

Between 2010 and 2015, forest area decreased by about 3.3 million hectares per year, quite close to the long-term average rate. From 1990 to 2000, deforestation rate rose to an estimated 8.3 million hectares per year. From 2000 to 2010 the rate dropped to an estimated 5.2 million hectares per year, still significantly higher than the long-term average.

Net global decrease in forest area is the result of two opposing processes. First, deforestation occurred at a rate of about 7.6 million hectares per year during the period 2010 to 2015, down from about 16 million hectares per year in the 1990s. Second, afforestation and natural expansion of forests occurred in other areas, at a rate of 4.3 million hectares per year during the period 2010 to 2015.

Globally, much of the increase in forest area occurs in China, where large-scale afforestation efforts increased the forest area by an average of 1.5 million hectares per year during the period 2010 to 2015. Most forest loss currently occurs in Africa (2.8 million hectares per year) and South America (2.0 million hectares per year). **Table 1** lists the countries with the largest annual net loss of forest area between 2010 and 2015.

Countries with the highest loss of net forest area, 2010-2015

Country	Annual forest area	
	Area (thousand ha)	Percent loss per year
Brazil	984	0.2
Indonesia	684	0.7
Myanmar	546	1.8
Nigeria	410	5.0
United Republic of Tanzania	372	0.8
Paraguay	325	2.0
Zimbabwe	312	2.1
Democratic Republic of the Congo	311	0.2
Argentina	297	1.1
Bolivia	289	0.5

Table 1: These 10 countries experienced the largest net loss of forest area between 2010 and 2015. (Source: FAO, 2015)

Around 80 percent of deforestation worldwide is driven by agriculture (Kissinger, et al., 2012). In Latin America, where most deforestation occurs, about 95 percent is caused by agriculture (including livestock), primarily commercial agriculture (**Exhibit 24**). In Africa and subtropical Asia, about 70 to 75 percent of deforestation is due to agriculture, of which about half is commercial and half is subsistence agriculture. In terms of impact on human development, deforestation occurs largely due to conversion of forest area to agricultural land, with corresponding positive implications for food security.

However, deforestation has negative short- to medium- term ramifications like landslides, flooding and loss of access to forest products, as well as potential long-term consequences on biodiversity, habitat for wild species and global climate. The net effect of deforestation on global development is a balance of these forces.

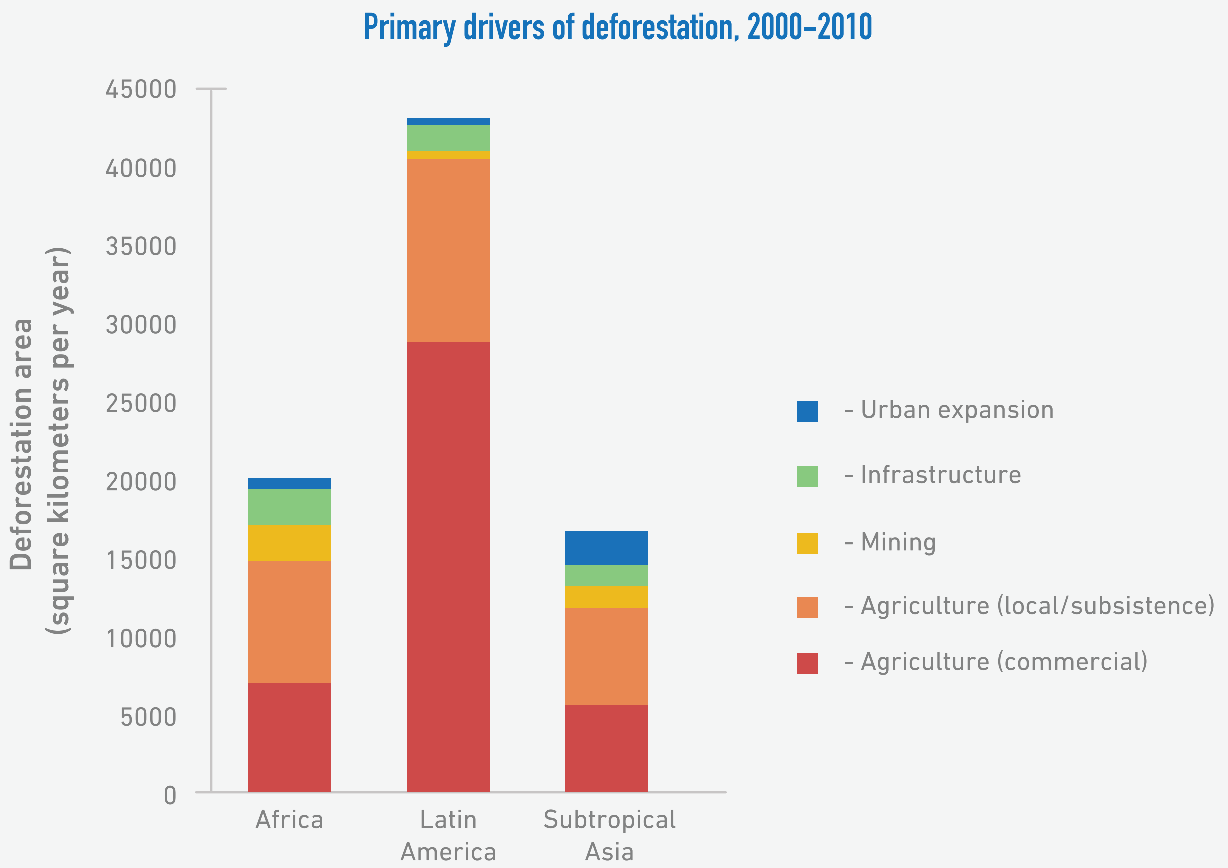


Exhibit 24: Deforestation is driven largely by agriculture. Most deforestation occurs in Latin America, and is largely due to commercial agriculture. Less deforestation occurs in Africa and Asia, where it is driven by both subsistence and commercial agriculture. (Source: Kissinger, et al., 2012)

4.12. Gradual depletion of non-renewable natural resources is increasing their real cost

Non-renewable resource depletion results from human use and dissipation of one-time stocks of natural resources, such as fossil fuels, metal ores and other minerals, that were created over geologic time periods. Public discourse regarding resource depletion is typically polarized. Cornucopians believe that technological innovation and market forces will overcome resource scarcity by developing substitutes or by improving efficiencies of extracting and using the resources.

Neo-Malthusians, influenced by the tone of Thomas Malthus (1798), maintain that our historical success at improving human welfare has resulted precisely from our one-time exploitation of the most concentrated and accessible of these resources. In a broader analysis, elements of both arguments are currently taking effect and expected to continue into the future.

Geologic resources, such as mineral ores and fossil fuels, which have played essential roles in human development to date (for example, the Iron Age), were created in fixed amounts in the Earth's crust over geologic time spans of millions of years. An ore is a rock with a relatively high concentration of some desired element and results from geological and meteorological forces such as plate tectonics, volcanoes, folding, faulting, weathering, erosion and sediment deposition.

For example, the Earth's crust as a whole contains an average of only about 0.004 grams of gold per ton but at particular locations and depths it contains several grams per ton. These locations are prospected and selected to become gold mines. Sites with the highest ore grade are typically exploited first because the cost and effort of mining and processing metal increase as the concentration of metal in the ore decreases. In particular, the energy needed to refine the ore increases exponentially as ore grade decreases (Norgate, et al., 2007).

Exhibit 25 shows historical trends in gold ore grade from 1840 to 2010 in major gold-producing countries (UNEP, 2011). Although gold is not essentially related to global human development, it is a well-documented natural resource for which long-term data is available and serves as a proxy for more functional metals, such as copper, zinc, cobalt and nickel.

The ore grade fluctuates from year to year as individual deposits of gold are exploited but the long-term trend shows declining ore grade in all regions. Clearly discerning the effect of this trend on gold prices and production levels is difficult due to concurrent changes in economic and technological factors, though it has necessarily made the physical exploitation of gold resource more challenging. Similar trends toward lower ore grades are seen for many other industrially-important metals, such as copper and zinc (Harmsen, et al., 2013; Calvo, et al., 2016).

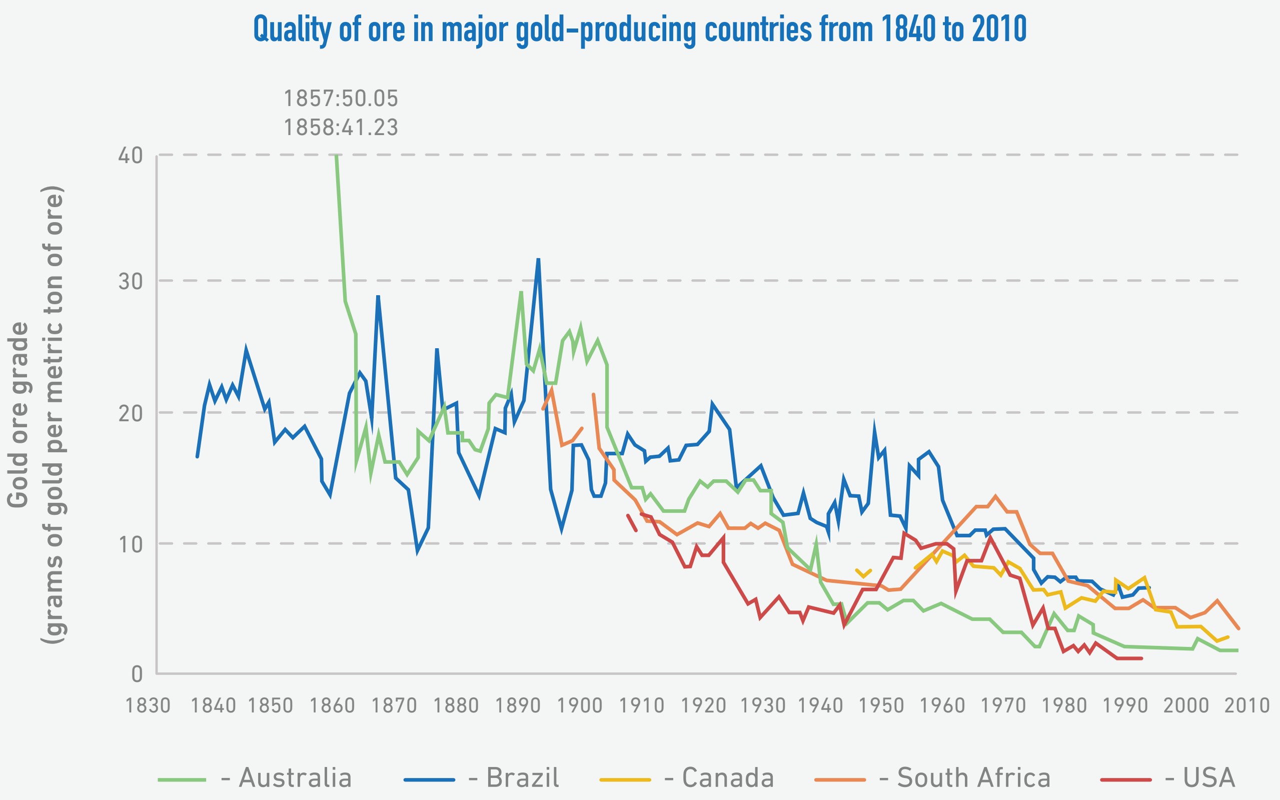


Exhibit 25: The quality of gold ore has decreased considerably since 1840 and high-grade deposits are no longer encountered. (Source: UNEP, 2011)

Another important example is fossil fuel use and sourcing. The three types of fossil fuels—coal, oil and natural gas—supply approximately 81 percent of all global primary energy use (IEA, 2017). Globally, we are heavily dependent on fossil fuels for transportation, electricity, heat and other energy services, such as nitrogen fertilizer production.

Fossil fuels were formed from decayed organic matter that was exposed to heat and pressure in the Earth's crust over long periods of time. Most fossil fuels are made from plants that were alive during the Carboniferous Period some 350 million years ago. As such, fossil fuels are clearly non-renewable over time scales of interest and long-term human development will require a transition to renewable energy sources.

Notwithstanding, the global use of fossil fuels has more than doubled in the last 40 years and overwhelmingly this energy source remains dominant for humans (**Exhibit 26**). Geologic deposits of fossil fuels have declined in quality over time similar in nature to that shown for gold in **Exhibit 25** (Hall, et al., 2014).

However, continued expansion of fossil fuel production has been made possible by a range of advanced technologies, such as deep-water drilling, horizontal drilling, hydraulic fracturing and oil sand recovery. These techniques to exploit unconventional fossil fuel resources come at an economic and energetic cost and are necessary only because the preferred conventional reserves have become increasingly depleted.

Total global primary energy use since 1971

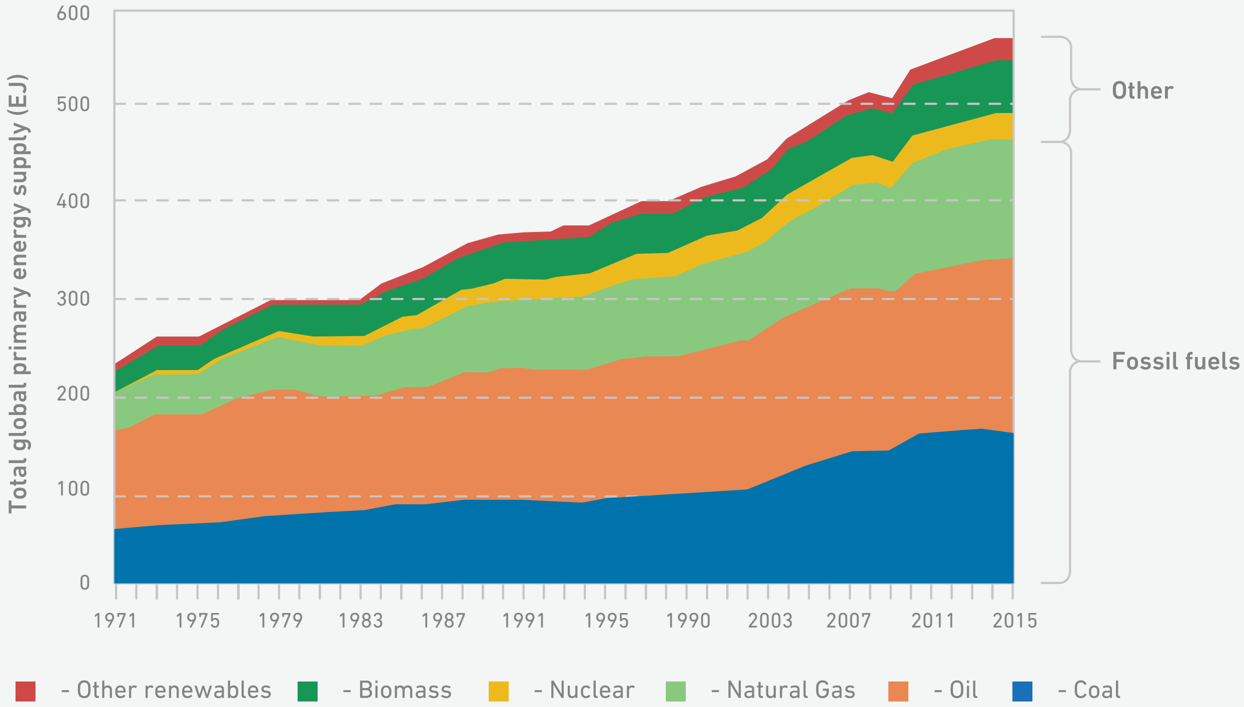


Exhibit 26: The total annual primary energy used globally has more than doubled since 1971; fossil fuels remain the dominant source of energy. Most of the "Biomass" is traditional wood fuel used in developing regions. (Source: IEA, 2017)

As available deposits of natural resources become less concentrated and less accessible, increasing effort must be dedicated to obtain the still available natural resources. Other things equal, this will result in less surplus wealth from the resource that can be applied to improving human welfare (Murphy, 2013). Energy Return on Energy Invested (EROEI) is a useful metric that describes how much societally-useful energy is provided from a source after deducting the energy needed to access and manage the source (Brandt, 2017).

While oil, gas and coal deposits historically provided EROEI values as high as 100 (that is, 100 units of usable energy delivered for each unit of energy needed for production), current unconventional fossil fuel deposits have EROEI values less than 10. As increasingly complex techniques are needed to access and exploit remaining fossil fuel resources, the real cost, including externalities, increases.

This may affect human development by constraining potential solutions that are too energy or resource intensive to scale effectively (Lee, et al., 2012). The concern is less about running out of a resource but of bearing the increasing costs and risks involved with obtaining it. In this light, our increasing use of unconventional fossil fuel extraction techniques (such as hydraulic fracturing and oil sand recovery) is less of an energy revolution and more of an evolution toward the use of lower grade resources.

Prudent planning of human development efforts should not presuppose the existence of indefinitely plentiful natural resources but should anticipate long-term supply shifts. As an example, virtually all nitrogen fertilizer, which is necessary to maintain agricultural yields and global food security, is made with fossil natural gas that is facing gradual depletion.

Similarly, phosphate fertilizer is mined from deposits that took millions of years to form and that are gradually being depleted. The quantities of global phosphate reserves remaining are uncertain (Edixhoven, et al., 2014) and are concentrated in the Western Sahara region of Africa, a disputed region controlled by Morocco. Sustained disruption of phosphate supply, whether due to geological or geopolitical forces, would significantly affect food security (Dawson & Hilton, 2011).

Dynamic resolution of these issues will occur at the intersection of increasing human demand, decreasing geologic abundance and improving efficiency of technologies for extraction and utilization. Early transition to renewable energy sources and production systems will offer increasing benefits over time as the quality of accessible non-renewable resources further declines. Deployment of renewable energy has strong synergies with sustainable development goals (Sathaye, et al., 2010).

5. Environmental changes driven by global and local actions will have impact on human development

The impact of the numerous second-order environmental consequences on human development will vary, and only some of these issues can be fully resolved through actions within developing countries. **Exhibit 27** shows the estimated severity of impacts on human development goals and whether the primary drivers of environmental change are a result of global or local actions.

Some primary drivers like indoor air pollution and soil erosion are clearly local, meaning that these problems could, in principle, be fully solved through local efforts. Other environmental consequences like ambient air pollution and groundwater depletion have regional drivers. To overcome these, some level of regional administration is required.

Some global drivers, including climate change and natural resource depletion, have consequences that will cause local damages regardless of the location of the drivers. These problems require global cooperation for effective mitigation, while local adaptation measures are needed to accommodate inevitable changes, such as sea level rise.

The drivers of other environmental consequences like deforestation are more challenging to localize, in part because local actions such as land clearance may be stimulated by global market forces.

The four quadrants of **Exhibit 27** represent issues with varying severity of impacts and potentials of solution.

- Quadrant A contains high impact problems with local focus of mitigation and/or adaptation.
- Quadrant B contains medium impact problems with local focus of mitigation and/or adaptation.
- Quadrant C contains high impact problems with local adaptation focus. Mitigation, where possible, will require global cooperation.
- Quadrant D contains medium impact problems with local adaptation focus. Mitigation will require global cooperation.

Anticipated impact of environmental change on human development

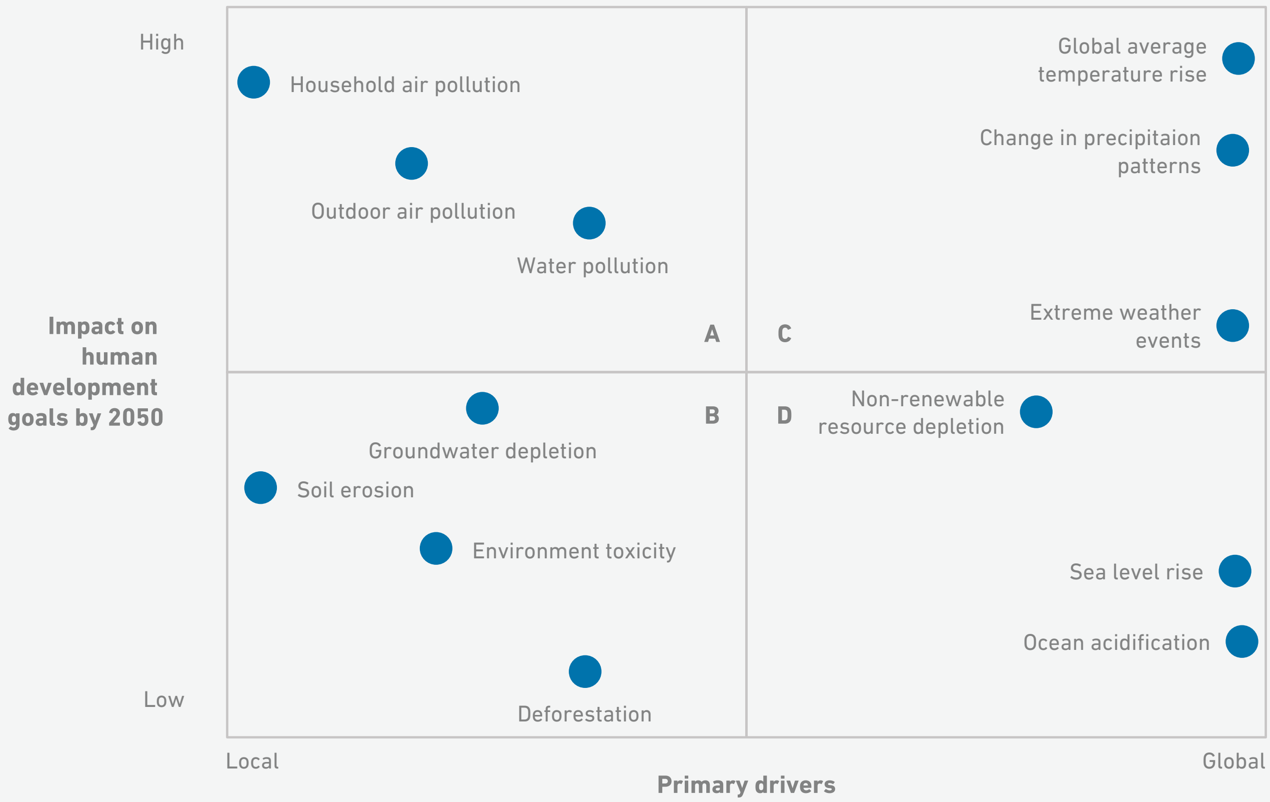


Exhibit 27: Matrix of environmental change consequences, showing anticipated impacts on human development by 2050 on the vertical axis and source of primary drivers on the horizontal axis.

KEY CHALLENGES

Identifying major barriers will help define the constraints and requirements of potential breakthroughs.

Beyond scientific and technological challenges, a variety of hurdles exist that may constrain successful resilience to environmental changes.

1. Many environmental processes are interlinked and problems often have multiple causes that cannot be addressed independently

Advances in one field of human development may cause setbacks in other fields.

2. There is often a time lag between beneficial first-order environmental changes and detrimental second-order consequences

Current political and economic systems, with focus on short-term rewards, are ill-suited to confront these long-term challenges.

3. Many current environmental problems result from externalities of economic activities, meaning the costs are borne by people not involved in the original activities

Externalities are poorly incorporated into current economic metrics of success.

4. Definitive solutions to environmental change issues may also require breakthroughs in human behavior

Many aspects of the lifestyle in industrialized countries remain as aspirational goals for developing country populations, yet are clearly unsustainable at scale.

5. Depending on context, other important barriers may apply

These include the lack of effective regulatory and enforcement mechanisms, lack of adequate economic means to commit to solutions and lack of economic incentives among key decision-makers and stakeholders.

SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

Prescribing solutions to human development problems arising from global environmental change is especially challenging because the changes have occurred precisely due to human efforts towards development.

The approaches successfully used in the past to enable human development, such as the coal-powered Industrial Revolution in Europe and North America in the 18th and 19th centuries, and the resource-intensive Green Revolution in Asia and Latin America in the 20th century, have undoubtedly enabled great advances in human development.

In hindsight, however, the compromises and consequences of these past approaches to development, and their potential threats to long-term human wellbeing, are growing more evident. Future-oriented human development efforts should learn from both the successes and failures of past efforts.

With this historical perspective in mind, we have identified 13 scientific and technology breakthroughs that have strong potential to increase resilience to global environmental change.

Breakthroughs:

1 2 3 4 5 6 7 8 9 10
11 12 13 14 15 16 17 18 19 20
21 22 23 24 25 26 27 28 29 30
31 32 33 34 35 36 37 38 39 40
41 42 43 44 45 46 47 48 49 50

1 A low-cost system for precision application of agricultural inputs, ideally combining water and fertilizer

In some regions like South Asia, the Green Revolution has brought unfortunate consequences including over-exploitation of groundwater resources and over-application of synthetic fertilizers. In other regions like sub-Saharan Africa, the Green Revolution has not arrived and there is under-utilization of groundwater resources and ongoing nutrient mining of soils. There is need for a low-cost, robust, scalable technology to precisely meter and distribute irrigation water and fertilizer to field crops.

This would allow farmers to apply the right amounts of water and nutrients (not too much or too little) at the right time to maximize economic returns and reduce nutrient loss. If made affordable, precision application systems for irrigation and fertilizers, calibrated to local crop type and soil conditions, could be a very effective way to increase agricultural yields, while also reducing negative impacts on the environment.

Enabling better management of the timing and formulation of irrigation and fertilization in cropping systems would ensure that water and nutrients are available where and when needed by the plant roots. Crop yields respond very well with initial inputs of fertilizer, but as additional nutrients are supplied the marginal yield increase becomes smaller.

Optimal results occur somewhere along that gradient, depending on the cost of fertilizer and seeds, land and selling price of harvested crops. For maximum returns, it is necessary to not just apply the right quantity of fertilizer, but to also apply it at the right time and place for optimal nutrient uptake by the plant. This would also protect watersheds and populations downstream from farm fields, by greatly reducing runoff.

The efficiency of using agricultural inputs, such as fertilizer is low in conventional farming. It is estimated that overall efficiency of applied fertilizers is about 50 percent for nitrogen, less than 10 percent for phosphorus and about 40 percent for potassium. The rest is wasted as runoff.

The mismatched timing between availability of nitrogen and crop need for nitrogen is likely the single greatest contributor to excess nitrogen loss in annual cropping systems. Ideally, nutrients should be applied in multiple small doses and when plant demand for them is greatest.

Current State

Development Stage: Engineering

Time to market (years)

<3 4-6 7-10 10+

Deployment: Challenging

Associated 50BT Chapters

Food Security Global Change

SDG Alignment

Impact

Increased Access to Food (# of People)

<1M 10M+ 100M+ 1B+

New Income Generated (# of People)

<1M 10M+ 100M+ 1B+

Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

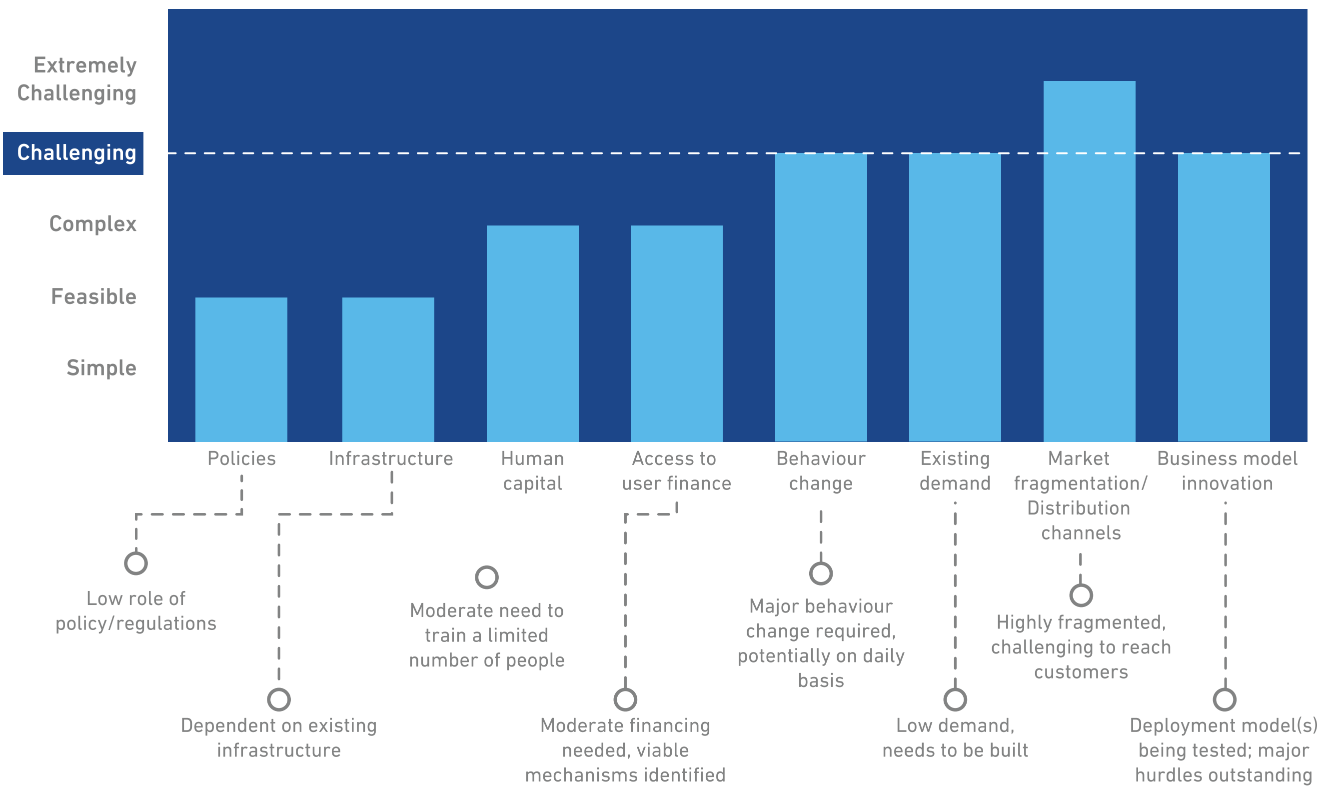
In principle, variations of existing programmable irrigation and fertigation systems used in industrialized countries can be adapted to the needs of smallholder farmers. Already, small-scale drip and sprinkler systems—along with other methods for increasing water usage efficiency—are beginning to emerge in markets like India. Cultivated area under drip irrigation in India has grown from 71 km^2 in 1992, to 2,460 km^2 in 1998, to 18,970 km^2 in 2010, up to 33,700 km^2 in 2015. The cost of such systems will continue to drop as scale of production increases.

This breakthrough would be strongly leveraged by three other breakthroughs, 5 Low-cost shallow groundwater drilling technologies, 6 Affordable solar-powered irrigation pumps, and 9 Low-cost soil nutrient analysis device. Overall, such devices would help farmers better predict crop nutrient requirements, better schedule irrigation and fertilizer applications, and avoid over-fertilization and nutrient runoff. If complemented with adjusted crop rotation patterns and additional biotic complexity, it could improve the plant community's ability to take up more of the available nutrients.

However, there is limited evidence to suggest that users—farmers or otherwise—will be interested in spending money on technologies to conserve water when the resource itself is available free of cost. The potential for saving fertilizer can prove to be a positive incentive, although the current demand for fertilizers is very low in sub-Saharan Africa.

It will face some deployment challenges that are common to the African smallholder farmer market, including structural barriers such as a fragmented market of farmers, limited access to finance for potential users, and lack of training to install, use and maintain the technology. The difficulty of deployment in this case would be CHALLENGING.

Breakthrough 1: Difficulty of deployment



2. A very low-cost scalable technique for desalinating brackish water

This breakthrough focuses on developing and enabling systems for very low-cost, high-efficiency desalination of brackish water resources. Households, industries and farms can utilize such systems to provide additional freshwater supplies for water-constrained regions. The introduction of very low-cost desalinated water could enable sustainable irrigation in vast regions of the world that contain brackish groundwater.

Desalination is increasingly used to provide household and industrial water in regions with scarce freshwater but abundant salt water. Most current desalination facilities are located in the Middle East, use seawater as feedwater and are powered by fossil fuels. The city of Chennai in southern Indian gets about a quarter of its municipal water from reverse osmosis seawater desalination plants.

Conventional desalination methods typically use seawater as feed. Seawater desalination technologies based on membranes, such as reverse osmosis, are approaching the thermodynamic limits of efficiency and have limited opportunity for further improvement. It is unlikely that major technology breakthroughs will fundamentally alter the seawater desalination landscape. Additionally, desalinated seawater is too expensive to use as irrigation water for crop production.

In contrast, there are large potential efficiency gains by using brackish water as feed. There are major opportunities for significant reductions in brackish water desalination cost and energy use through innovative electrochemical or other emerging techniques. The minimum theoretical energy requirement for desalination varies with the salinity of the feedwater—less energy is fundamentally needed to desalinate brackish water compared to seawater. Electromagnetic desalination processes such as electrodialysis (ED) and capacitive deionization (CDI) are limited to low-salinity feedwater, but potentially have much lower cost and energy than pressure or thermal techniques. They offer many advantages when used with brackish feedwater, such as high water recovery and high brine concentrations.

They also require little or no feedwater pre-treatment and membrane fouling can be prevented by reversing the electrode polarities. However, electromagnetic processes only remove ions from the water, leaving organics and colloids in suspension—this is a concern for household water, but less so for irrigation water. Furthermore, the selection and configuration of membranes is currently highly dependent on feedwater characteristics, thus must be adapted to local conditions of feedwater composition and concentration.

Current State

Development Stage: Engineering

Time to market (years): <3 | 4-6 | **7-10** | 10+

Deployment: Complex

Associated 50BT Chapters

Water Security

Food Security

SDG Alignment

Impact

Increased Access to Food (# of People): <1M | 10M+ | **100M+** | 1B+

New Income Generated (# of People): <1M | **10M+** | 100M+ | 1B+

Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

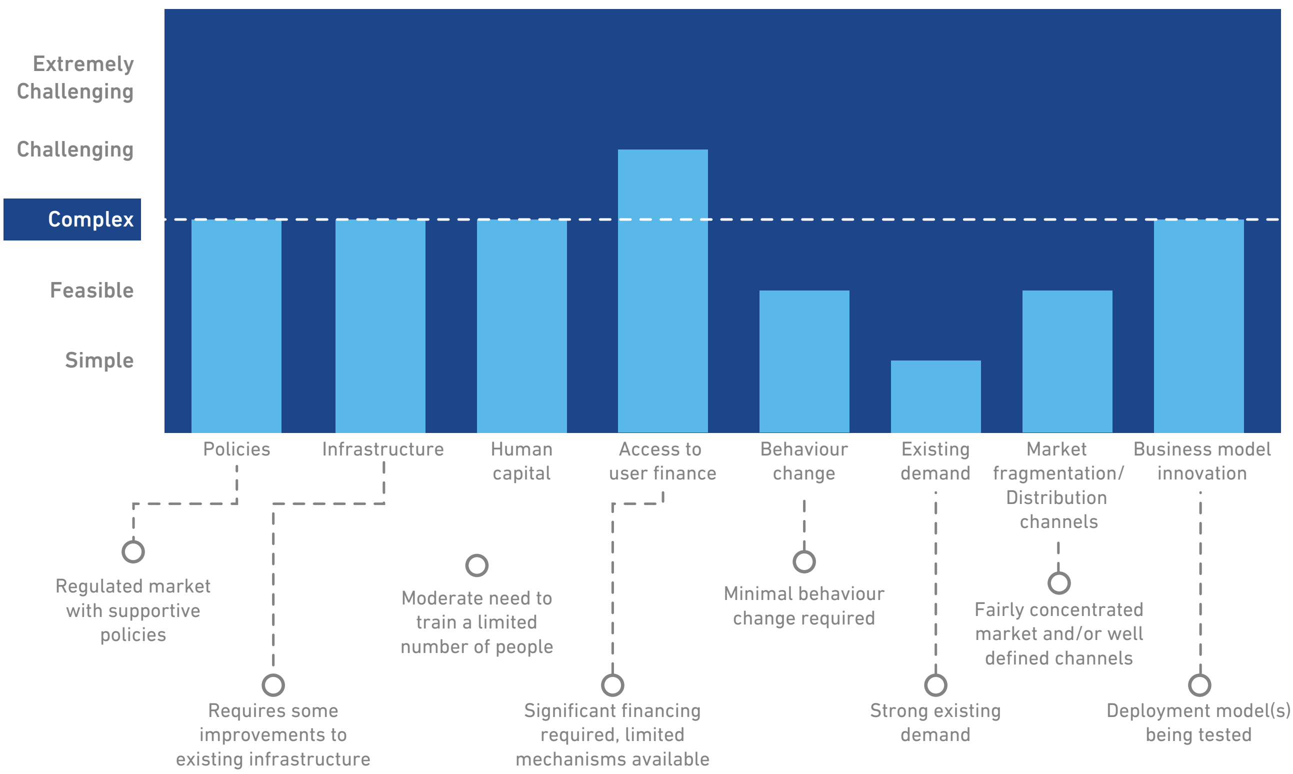
Concerted R&D efforts can overcome current obstacles to enable a major source of low-cost freshwater in regions with brackish resources. The appropriate unit scale of desalination facilities may vary depending on the application (such as household, irrigated farm, urban water utility). The salinity of the product water may also vary depending on the purity requirements of the end uses.

Costs can be further reduced by matching the salinity of the product water to the salinity thresholds for different uses; in other words, removing only enough salt to make the water viable for its intended use. Ideally, facilities will be powered by onsite renewable energy sources, such as photovoltaic solar arrays, to provide reliable and sustainable operation. Developing appropriate business models will be essential to ensure economic sustainability and continuing impact.

End-uses for the desalinated water will include drinking, cooking, washing and other domestic uses and industrial water uses. Efficient techniques for large-scale desalination of brackish water resources will also enable the use of desalinated water for production of agricultural crops using efficient irrigation techniques.

Substantial research and development work is required and we expect that it will take seven to ten years for this breakthrough to be ready. Deployment challenges include access to finance and policies regarding location and discharge streams. We rate the difficulty of deployment, COMPLEX.

Breakthrough 2: Difficulty of deployment



3 Network of low-cost distributed monitoring sensors to measure and map air and water quality

Discharge of pollutants into the air and water is an undesirable side effect of conventional industrialization and development processes. Because many environmental pollutants are invisible, tasteless and odorless, severe cases of contamination often go undetected and unremedied. Detection of environmental pollutants currently requires costly equipment and elaborate sampling protocols, and provides only isolated snapshots of individual places, times and contaminants. To fully understand and solve the problem of environmental pollution of air and water, a more fine-grained knowledge of exposure is required.

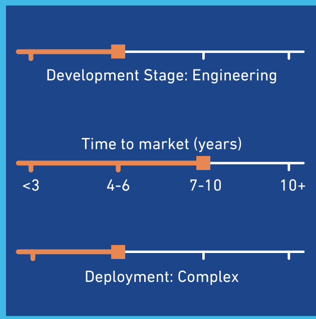
There is an urgent need for the development and widespread deployment of sensors that detect the levels of the most significant pollutants affecting the air and water, and transmit that information to a platform where it is validated and publicly displayed. Sensors will need to identify and measure a broad range of pollutants. Key air contaminants to be measured include particulate matter, ozone and carbon monoxide, while essential water contaminants include E. coli, salinity and arsenic. Though challenging, there is an important and growing need to measure diverse chemical toxins from sources including industry, vehicles and agriculture.

Required technological innovations include integrated sensors for the most significant contaminants that are inexpensive enough for mass deployment, as well as a platform for data collection, validation, analysis and dissemination. The sensors may be hard-wired and provide continuous monitoring of particular locations, or may be portable to conduct mobile geolocated assessments of contamination.

Fixed sensors would likely form the basis of a sensor network, transmitting (continuous or periodic) data to a mapping platform to show changes in quality parameters over time. Issues of sensor performance degradation over time will need to be addressed, to enable robust long-term monitoring. A successful sensor technology will likely not test separately for each individual contaminant, but would scan a sample of air or water and determine quickly and inexpensively its multiple constituents.

For maximum effectiveness, this sensor technology would be integrated with a web-based platform to allow collection and comparison of environmental pollution risks over time and place.

Current State



Associated 50BT Chapters

Food Security

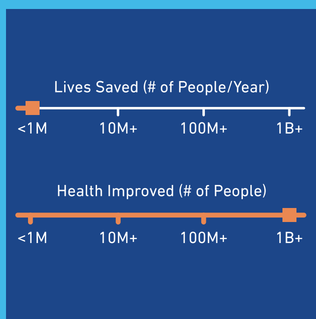
Global Change

SDG Alignment

3 GOOD HEALTH AND WELL-BEING

6 CLEAN WATER AND SANITATION

Impact



Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- Emerging markets potential; requires derisking (sustainable)
- **Non-commercial (unprofitable)**

The linking of improved sensor technology with mobile communications technology would lead to a system for real-time, spatially-explicit, multi-agent exposure monitoring that would create an unprecedented understanding of global air and water pollution, and pathways toward their reduction. Once identified, areas of high risk could be assessed in more detail, and critically contaminated locations in need of remediation can be flagged.

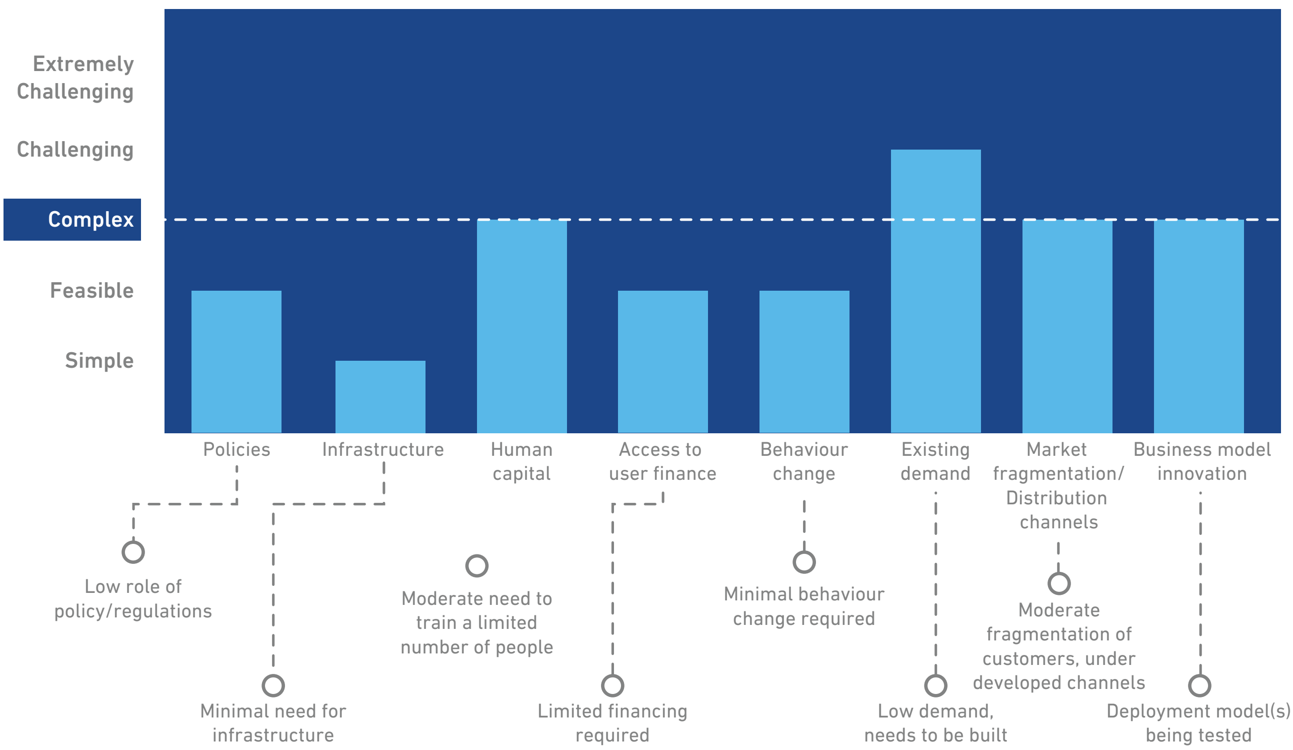
Portable sensing by trained staff using mobile devices with disposable one-time sensors could also be useful to increase the spatial density of measurements. Another approach to mobile sensing is community-based air and water quality monitoring, using low-cost portable sensors connected to smartphones that communicate results to the network.

This approach may face issues with data reliability due to incorrect sampling techniques or fraud, so would require additional validation. The initial cost of the hardware should be modest (less than $500), perhaps taking the form of a plug-in sensor that leverages the computing power of an existing mobile device. Cost of consumables should be low (less than $1 per test), allowing ubiquitous monitoring even in remote sites of low- and middle-income countries.

Progress is being made rapidly in the field of environmental monitoring, though there appears to be little focused effort towards the integrated technology we envision here. A basic form of air quality mapping using near real-time data from a global network of sensors can be found at http://aqicn.org/map/world/.

If sufficient resources were allocated to allow the necessary research and development efforts, we expect that it will take seven to ten years for this breakthrough to be ready for use. A significant deployment challenge is the lack of consumer demand for environmental monitoring. Therefore, deployment is likely to be COMPLEX.

Breakthrough 3: Difficulty of deployment



4 Sustainable, affordable, household-level fecal waste management system

A large share of the population in rural and peri-urban areas of many low-income countries lacks access to household toilets, and is habituated to open defecation. Many others have access to toilets, but of substandard type and capable of contaminating groundwater. This poses serious health risks in the form of diarrheal and other diseases. An effective household sanitation system must provide an initial hygienic separation of the fecal waste, as well as prevent opportunities for secondary exposure to the fecal pathogens such as surface and groundwater contamination. Ultimately, the fecal waste must be made harmless and definitively disposed of.

In rural and many peri-urban areas, the most appropriate sanitation system employs household-level collection and full on-site treatment of waste materials. Household-level sanitation is quite appropriate in rural areas, where extensive sewage networks would be prohibitively expensive due to low population density.

Household sanitation is also widely used in some higher density places such as peri-urban areas, where sewer networks have not reached. A wide range of on-site sanitation technologies have been developed, including pit latrines (single and twin pits), pour-flush pit toilets (with septic tanks, and single and twin leach pits), vermicomposting toilets, dry composting toilets, and anaerobic baffled reactor toilets.

However, existing on-site sanitation methods fall short is some regards. In some cases they do not safely contain fecal waste, instead letting it leak into groundwater aquifers. In other cases, the waste is safely contained in storage only temporarily, but eventually becomes full and must be emptied and can then cause broad contamination.

Despite our long experience accumulated with sanitation practices, there is a large gap for a sustainable, affordable, decentralized, on-site household sanitation solution for low-income households. Of the existing household sanitation technologies, vermicomposting toilets appear to provide relatively high performance at low cost, largely due to enhanced decomposition of fecal matter by earthworms, leading to less waste build-up and less frequent emptying and thus lower maintenance costs.

Current State

Development Stage: In-Market Small Scale

Deployment: Challenging

Associated 50BT Chapters

Water Security

Global Health

Gender Equity

SDG Alignment

3 Good Health and Well-Being

6 Clean Water and Sanitation

5 Gender Equality

Impact

Lives Saved (# of People/Year)

<1M 10M+ 100M+ 1B+

Health Improved (# of People)

<1M 10M+ 100M+ 1B+

Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

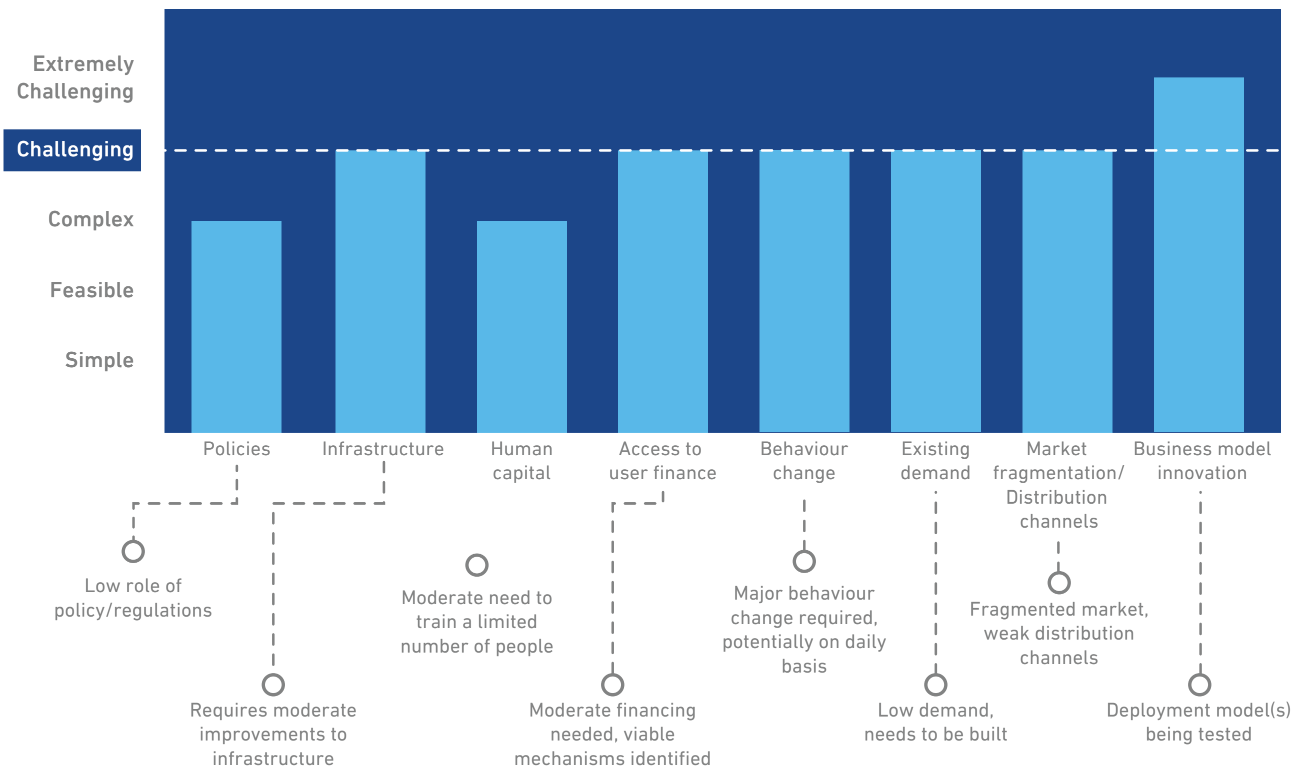
The development of improved on-site household sanitation systems should be viewed as a long-term solution to rural sanitation (and possibly peri-urban sanitation) rather than an interim fix, and should be given a high priority in resource allocation. Sanitation facilities that are merely waste storage repositories, such as pit latrines, must be coupled with mechanisms for regular emptying of fecal sludge and transporting it to appropriate sites for processing or safe disposal. Facilities that include on-site treatment, such as vermi-filtration, generate smaller quantities of residue that must be disposed of.

One potentially useful path may involve additives that facilitate the breakdown of fecal sludge, reducing the need to empty latrines. Researchers are currently developing and testing several options, including addition of higher organisms, microorganisms and hydrolytic enzymes.

In the longer term, opportunities could include use of fermenting organisms, development of new enzymes or facilitation of the current microorganisms involved in digestion. Regardless of the specific path, each step of the sanitation service chain is important to achieve effective waste management, from toilet siting and construction, to final treatment and disposal of waste.

Effective sanitation is challenging where there is no piped water or sewerage, as household toilets must be low-cost, have an effective method to control odor, a system for processing and disposing of waste, and occupy minimal space. Significant experience has been gained on technical aspects of sanitation, but we lack full understanding of the important socio-cultural aspects. Initial technologies are already on the market, but the difficulty of deployment is CHALLENGING.

Breakthrough 4: Difficulty of deployment



5 Medium to large-scale sewage treatment process with recovery of water (and ideally nutrients and energy)

This imperative calls for the development and deployment of novel sewage treatment facilities that are net sources, rather than sinks, of resources. Primarily this applies to water resources, for treating and reusing the wastewater collected in sewer systems. Systems should enable reuse of the treated water for secondary purposes including industrial, recreational and agricultural applications. A secondary focus is on energy resources, where sewage treatment facilities could operate with net zero energy inputs, and could even have the capability to produce energy for societal use. The recovery of nutrient resources from sewage, such as phosphorus or nitrogen, may also be a goal. Integrated sewage treatment can be viewed as a way to harvest clean, renewable sources of water, energy or nutrients while disposing of a waste product.

There is a great need for a low-cost, sustainable and scalable sewage management process for deployment in fast-growing cities in developing regions. In India, for example, less than 38 percent of the sewage that is generated is treated before being discharged into water bodies. The amount of resulting sewage in the environment is contributing to the country's health problems, including diarrheal outbreaks among children and lifelong stunting and wasting.

The massive organic and nutrient loading also has adverse environmental effects and leads to the destruction of ecological productivity of water bodies. Simultaneously, many growing cities have difficulty meeting the water needs of households and industries, due to physical constraints to water supply manifest as closed river basins and depleting groundwater stocks.

The quantities of wastewater generated in major cities are enormous, thus reusing this water for other purposes is a major lever for enhancing water security. For example, if 80 percent of the wastewater collected by urban sewage networks in India were reused, an additional water resource of 18 cubic kilometers per year would be obtained (ITT, 2018). What is lacking is an effective and affordable sewage treatment method that can rapidly scale up in developing regions.

Conventional wastewater treatment methods are a major resource sink, and should not be held as models for scalable sanitation methods for fast-growing cities in low-income countries. In the United States, for example, about 1.3 percent of all electricity is used for sewage treatment. This is a wasted opportunity, because raw sewage contains about six times more chemical energy than the amount of electrical energy required to treat it.

The most appropriate method of treatment for wastewater will depend largely on the intended use of the recycled wastewater and the scale of the treatment facility. Major reuse applications include agriculture (food and non-food crops), industry, and groundwater recharge, for which increasing effluent quality is required, respectively. For agricultural purposes, nutrient removal (or partial nitrogen removal) can be left out of the treatment process, whereas reuse in industrial applications or groundwater recharge requires nutrient and solids removal.

Current State

Development Stage: In-Market Small Scale

Deployment: Challenging

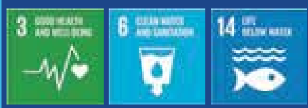
Associated 50BT Chapters

Water Security

Global Health

Gender Equity

SDG Alignment



Impact

Lives Saved (# of People/Year): <1M | 10M+ | 100M+ | 1B+ (marked: 100M+)

Health Improved (# of People): <1M | 10M+ | 100M+ | 1B+ (marked: 1B+)

Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

Groundwater recharge applications may also require removal of micro-pollutants as well as organic carbon. In terms of costs, the higher the quality of treated effluent, the higher the total capital and operational costs are. Generally, larger treatment plants have an increased efficiency, which lowers the lifecycle costs and environmental impacts per cubic meter of treated water.

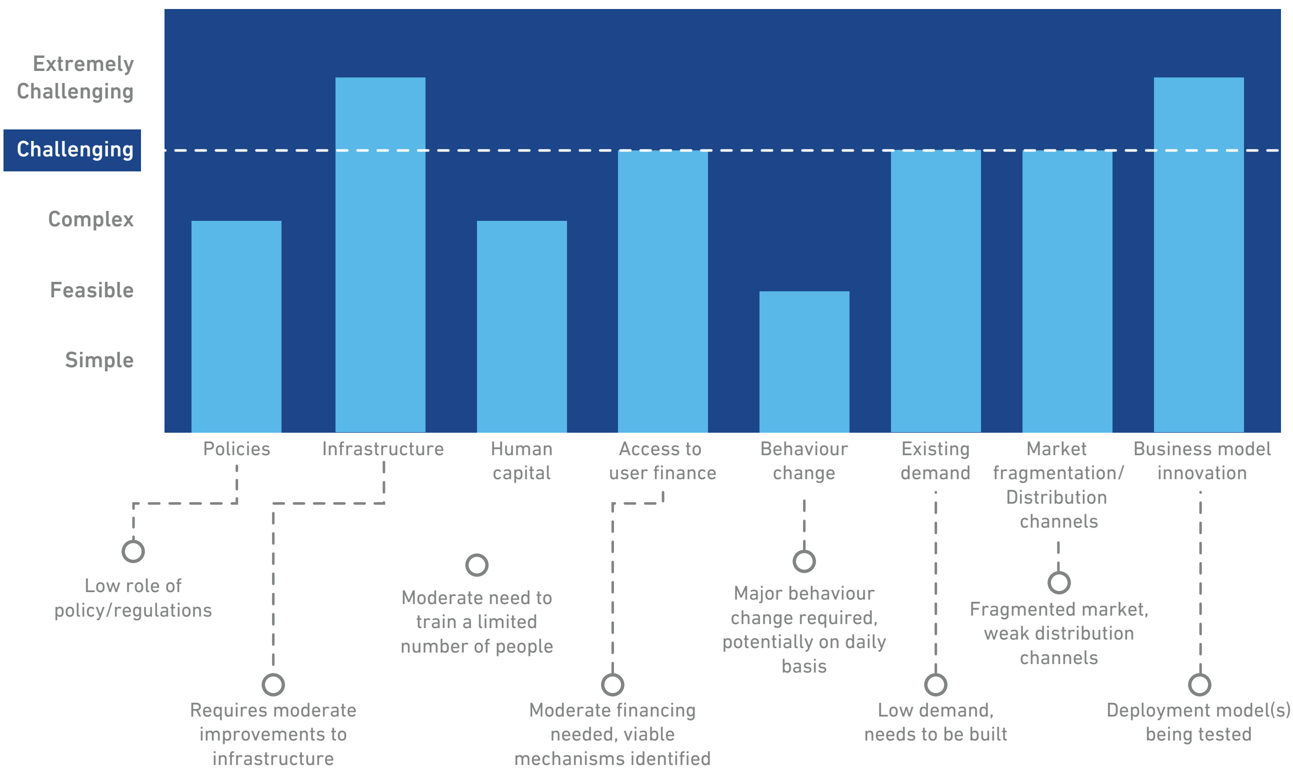
Novel sewage treatment methods followed by wastewater reuse is a potentially important lever for enhancing water security. Reusing wastewater brings two important benefits: less pollution entering water bodies, and less need for freshwater withdrawals. However, in the areas where it is currently practiced, wastewater reuse is typically considered as a temporary solution for acute needs, instead of implemented as a long-term solution to improve water security.

Important criteria for successful treatment technologies include the extent of land area required, the economic resources needed for capital and O&M, and the quality requirements for the reused water. Land area requirements, in particular, may be an impediment to scale-up of some technologies. Different technology solutions may be appropriate for different settings as the scale increases from household to neighborhood and metropolitan level.

There are many challenges to sanitation infrastructure deployment, and business models should not expect to extract high-value content from sewage. Sanitation systems tend to have fairly high up-front costs and require skilled labor to install and maintain. Distribution channels are also poorly defined. In addition, significant public investment is likely to be still required.

Some promising technologies have entered the market, and others should become market-ready in the coming years. Given the lack of proven models and the growing scale of the urban sanitation problem, the level of difficulty for deployment is CHALLENGING.

Breakthrough 5: Difficulty of deployment



16 Alternative meat production system that is affordable, desirable and environmentally sustainable

The environmental consequences of large-scale conventional meat production systems are increasingly evident, such as deforestation and polluted waterways. Alternative meat production techniques are being developed, that if successful could satisfy our growing meat demand with reduced environmental impacts.

Such products are potentially healthier and more efficient alternatives to conventional meat, with lower use of land, water and agricultural inputs. If the conditions for alternative meat production could be sufficiently controlled and manipulated at industrial scale, it would offer safe and affordable food with a healthy nutritional profile, to improve food security and quality of life.

There are two primary avenues for alternative meat production. The first avenue, often called substitute meat or meat analog, involves the conversion of non-animal biomass to have the characteristics of actual meat. This begins with the conventional agricultural production of feedstocks such as soybean, wheat or peas, followed by industrial conversion into a material with texture and taste similar to meat.

A notable example is Impossible Foods, which is primarily made of soybean protein concentrate and vegetable oils, with additional plant-based additives to mimic the flavor of meat. Impossible Foods products were initially introduced in 2016, and in 2019 the firm partnered with Burger King to serve alternative meat burgers in fast-food restaurants throughout the US.

The second avenue, often described as cultured meat, cellular meat or in-vitro meat, involves the managed growth of actual animal cells. This tissue engineering process begins with collection of stem cells from living animals, which are then allowed to grow and reproduce in a bioreactor, a device for carrying out biochemical processes.

The living cells are provided with nutrients in a suitable culture medium, typically composed of water, glucose, amino acids, lipids, vitamins and salts. If the cultured meat is to match or exceed the nutritional value of conventional meat, any nutrients found in meat that are not synthesized by the growing cells must be supplied in the culture medium.

Current State

Development Stage: In-Market Small Scale

Deployment: Challenging

Associated 50BT Chapters

Food Security

Global Change

SDG Alignment

Impact

Increased Access to Food (# of People)

<1M 10M+ 100M+ 1B+

New Income Generated (# of People)

<1M 10M+ 100M+ 1B+

Commercial Attractiveness

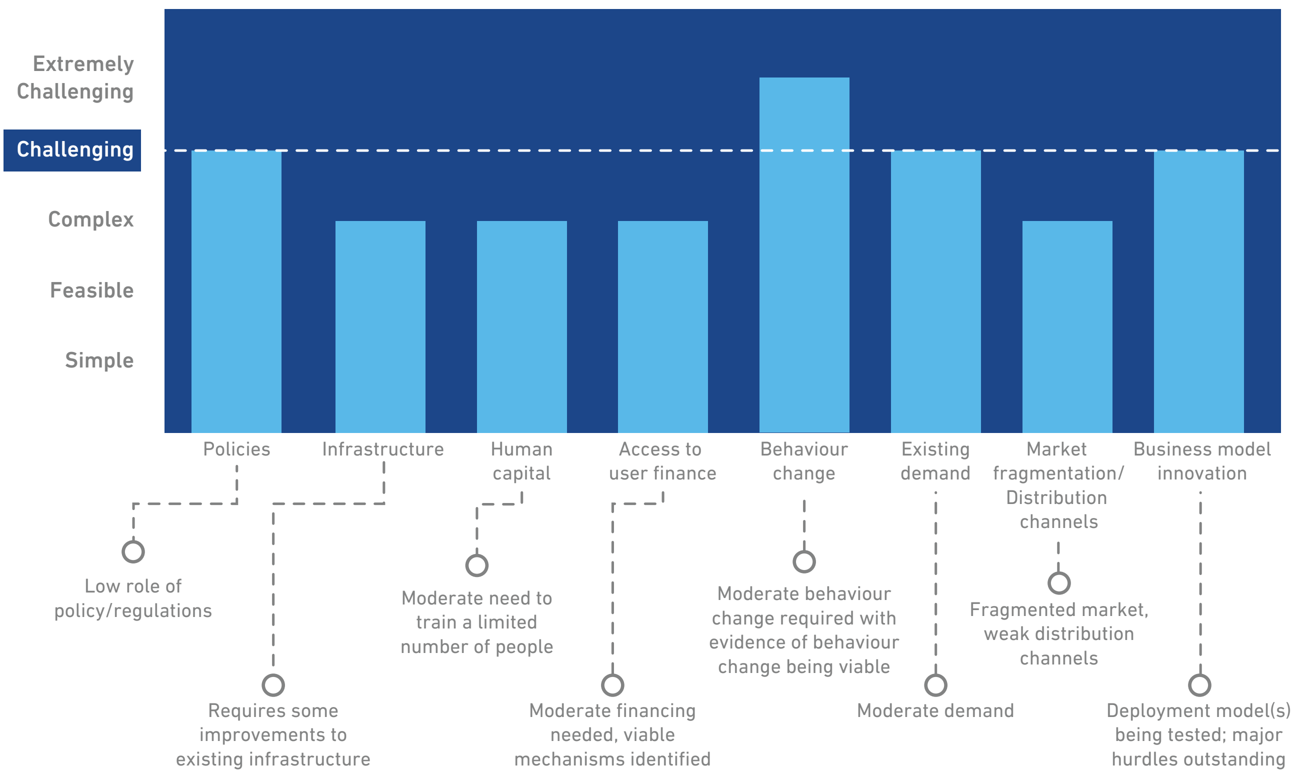
- **Attractive for industrialized markets (high profits)**
- Attractive for emerging markets (lower profits)
- Emerging markets potential; requires derisking (sustainable)
- Non-commercial (unprofitable)

There are many technical challenges to sustainable in vitro meat culturing system on a large scale. The technology now exists to produce in-vitro meat on very small scales, as its major use to date has been regenerative medicine of a variety of tissues and organs.

Current cultured meat processes require large energy input for industrial processes, as biological functions such as digestion and nutrient circulation are replaced by industrial equivalents. The climate implications of cultured meat are complex, and depend on emissions of carbon dioxide, methane and other greenhouse gases from the cultured and reference animal-based systems.

Scaling alternative meat technologies as a global food security solution will depend on many economic, cultural and technical factors. Widespread deployment will face a number of hurdles, primarily along acceptance by consumers and regulators, and limited current demand for alternative meat products. Initial substitute meat products are already on the market, and cultured meat products are likely to be market-ready in three to five years. Large-scale deployment is projected to be CHALLENGING.

Breakthrough 16: Difficulty of deployment



17 New seed varieties that are tolerant to drought, heat, salinity and/or other emerging environmental stresses (ideally using cis-genetic modification)

Agriculture will face numerous stressors during the coming decades, such as droughts due to climate change, salinization of farmland and groundwater, and basin-level limits to water supply. Conventional plant breeding techniques are hard-pressed to develop crop varieties that accommodate such rapid changes. A new generation of crop varieties is needed with tolerance to worsening conditions of drought, heat and salinity. Genome editing techniques such as CRISPR/Cas9 have successfully been used to create variants of maize that have higher grain yield under water stress conditions and have no yield loss under well-watered conditions, compared to conventional maize types. Varieties with tolerance to heat and salinity are also expected, allowing continued expansion of agricultural production despite growing environmental challenges.

Genome editing techniques are capable of precisely and site-specifically (rather than randomly) add, modify or delete genes from plant and animal genomes. Genome editing methods include clustered regularly interspersed short palindromic repeats (CRISPR), zinc-finger nucleases (ZFNs), and transcription activator-like effector nucleases (TALENs) systems.

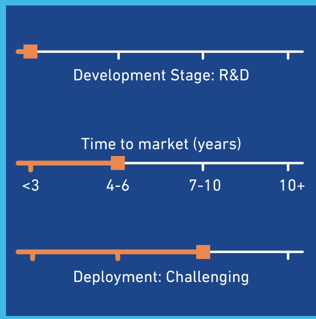
The CRISPR/Cas9 system, in particular, is proving to have many beneficial uses such as increasing crop yield, improving drought tolerance, increasing growth in nutrient-limited conditions, and breeding crops with improved nutritional properties. In this system, the Cas9 nuclease is complexed with a synthetic guide RNA and is delivered into a cell. It then cuts the cell's genome at a desired location, allowing existing genes to be removed and/or new genes to be added.

In water-stressed regions where all available annually-renewable water is fully allocated, CRISPR technology may enable crops that use water more efficiently, producing more biomass per unit of water transpired, to increase total agricultural production. Many farmers do not use irrigation and instead depend on rainfall for crop water needs.

While expanding the use of irrigation is possible in some areas, irrigation is constrained in many regions by lack of water sources or excessive economic costs. Using genetic editing tools to create varieties that make better use of the rainwater that falls on dryland farms, total agricultural production can increase without the need to harness additional water sources.

Importantly, gene editing with CRISPR is cisgenic rather than transgenic modification, meaning that genes are artificially transferred between organisms that could otherwise be conventionally bred. Many consider cisgenic editing to be less controversial than transgenic modification, because the edited organisms could, in principle, have been created through conventional breeding. For this reason, both regulatory procedures and consumer acceptance are proving to be less challenging for cisgenic editing than for transgenic modification.

Current State

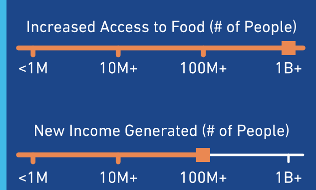


Associated 50BT Chapters

Food Security

SDG Alignment

Impact



Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

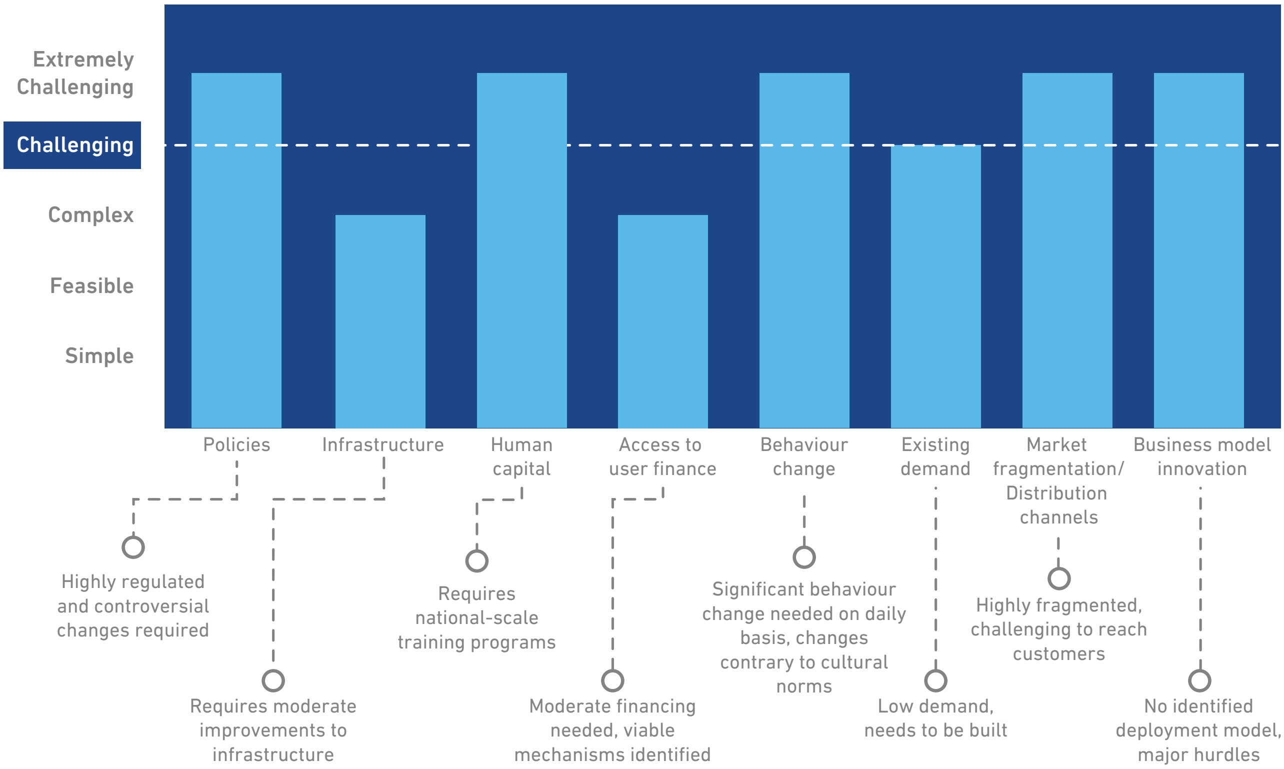
Of more immediate concern may be the asymmetric economic relationship between the producers and planters of edited seeds, as genetically modified organisms have typically been produced and marketed by large multi-national corporations with narrow interests.

The global seed industry is undergoing consolidation, and four firms are now estimated to control over 60 percent of global proprietary seed sales. Structures should ensure that improved seeds are accessible to all farmers in need, to avoid further widening social inequalities. The production of seeds within low-income countries, by existing and emerging biotechnology centers, would provide opportunity for local control. It will also be important to take steps to avoid unwanted second-order environmental effects of edited seeds.

Initial genetically edited varieties with some drought tolerance already exist for crops like maize, and it is reasonable to believe that more can be developed for other staple crops within four to six years assuming there is interest and funding. One important constraint to the pace of genetic editing breakthroughs is the polygenetic nature of many of the traits we would like to breed into plants and animal, which are determined by many different genes in ways that are not yet well understood.

Furthermore, there are significant barriers with respect to adoption by farmers and governments alike, which makes deployment CHALLENGING.

Breakthrough 17: Difficulty of deployment



19 Affordable healthy homes that are resilient to extreme weather events

Shelter is a fundamental human need, but a large segment of the world's population is either homeless or lives in very poor housing conditions. Almost 70 million people are refugees or displaced persons who have been forced to flee their homes and find shelter elsewhere. More than 800 million people reside in urban slums, often living in improvised dwellings with insecure land tenure. Long-term trends towards urbanization suggest that the urban population in less developed regions, currently less than 3 billion, will exceed 5 billion people by 2050. Creating adequate housing to accommodate this number of people will be challenging.

A growing challenge is the increasing frequency and intensity of extreme weather events, due to global climate change, which are expected to alter the habitability and safety of homes. A comprehensive and lasting solution to the problem of inadequate shelter requires concerted action in the political, economic and technological spheres. In particular, technology-related advances are needed to develop robust, affordable and environmentally compatible housing materials and designs that can scale-up to meet global demand.

Constructing housing with traditional building materials used in rural areas, such as grass and earth, cannot scale up sufficiently in urban areas with much higher population densities. The only option for poorer segments of the population is to create provisional shelter from found materials such as cardboard and plastic sheets. Due to their exposure to physical insecurity and unsanitary living conditions, life is precarious for this segment of the population.

A breakthrough is needed to develop a functional and very low-cost housing system accessible to the global poor that is resilient to extreme weather events. Applied research is needed to identify appropriate types of building materials and the scale and location of manufacturing facilities in different social, geographical and cultural contexts.

Trade-offs may exist between large-scale centralized production versus smaller-scale decentralized production closer to end users. Trade-offs may also exist between production automation and local employment opportunities. The potential use of locally-available raw materials suggests that various geographically specific solutions may exist.

Current State

Development Stage: Engineering

Time to market (years)

<3 4-6 7-10 10+

Deployment: Complex

Associated 50BT Chapters

Global Change

Gender Equity

SDG Alignment

3 GOOD HEALTH AND WELL-BEING

11 SUSTAINABLE CITIES AND COMMUNITIES

Impact

Improved Quality of Life (# of People)

<1M 10M+ 100M+ 1B+

Health Improved (# of People)

<1M 10M+ 100M+ 1B+

Commercial Attractiveness

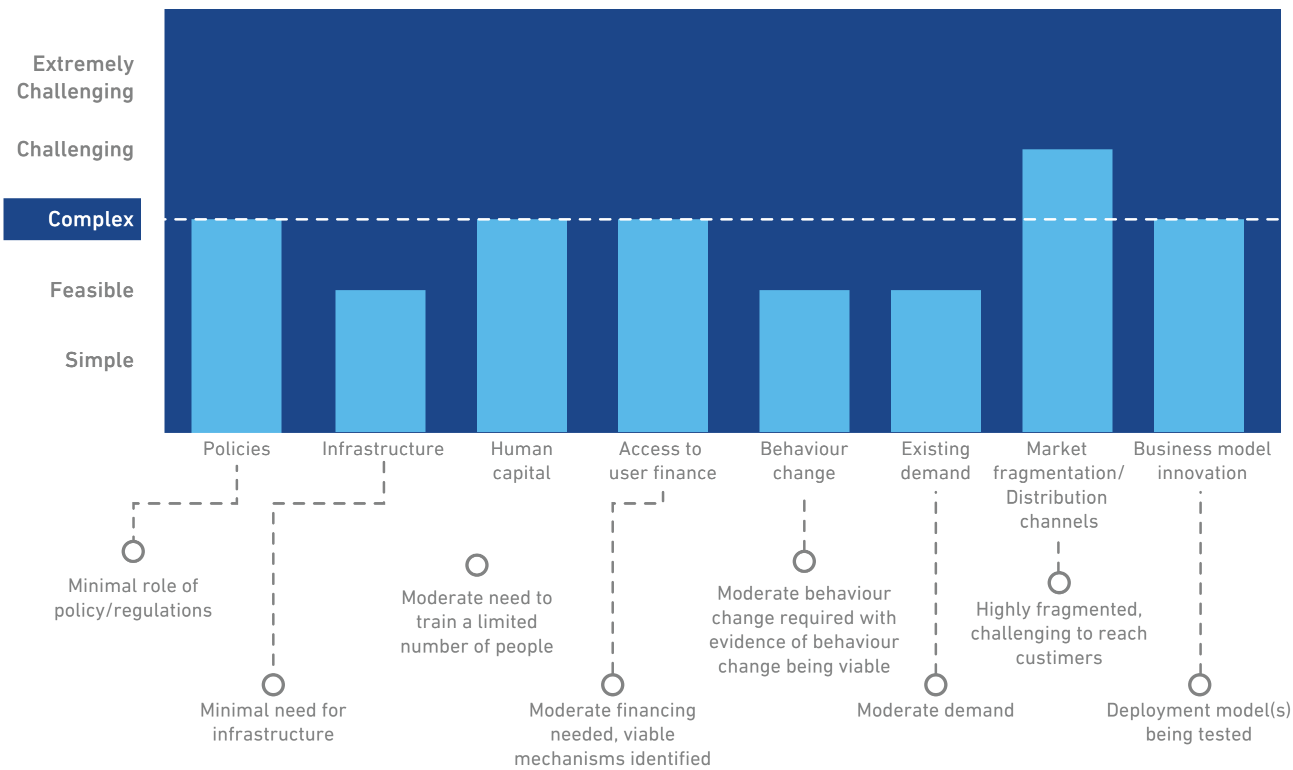
- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

Beyond material properties, sensitive design work is required to produce robust, efficient, comfortable and culturally-appropriate housing solutions that can scale to the extent needed. Potential integration of renewable energy technologies, such as photovoltaic or solar-thermal collectors, could allow synergies between human development goals.

While broad in scope, if resources were allocated to allow adequate research and development efforts, we expect that it will take five years for this breakthrough to be deployment ready.

Significant deployment challenges include a fragmented building industry with multiple actors and components, access to finance for both producers and end users and municipal and national policies supporting urban poor. The difficulty of deployment would be COMPLEX.

Breakthrough 19: Difficulty of deployment



43 A standardized, solar mini-grid system that makes it simpler, cheaper and faster to set up and operate mini-grids

Making solar mini-grids inexpensive and easy to install will significantly help scale these systems up. The key drivers of capital expenditures for solar photovoltaic (PV) mini-grids are the PV modules and the balance-of-system (BOS). The BOS comprises both equipment, such as power electronics like inverters and racking structures, and soft costs like labor, site preparation and licensing fees.

BOS costs vary widely by geography, primarily because of soft costs. While PV modules, lithium ion batteries and power electronics are all experiencing steady declines in costs, there exists potential for optimizations in the BOS costs.

Currently, the installation process for solar mini-grids is a time consuming, unpredictable and challenging process involving a highly fragmented supply chain. Many components need to be procured, transported and integrated in hard-to-reach places without supporting infrastructure or adequate skilled labor.

A standardized system, which is easy for technicians (with some training) to install in a few days and simple to maintain on an ongoing basis, will significantly improve the economics of rural mini-grids.

In addition to reducing the balance-of-system costs, a standardized system will minimize the need for technical expertise for operations by simplifying operations and maintenance (which is another major hurdle to the proliferation of mini-grids).

Current State

Development Stage: In-Market Small Scale

Deployment: Complex

Associated 50BT Chapters

Access to Energy

SDG Alignment

Impact

New Income Generated (# of People)

<1M | 10M+ | 100M+ | 1B+

Improved Quality of Life (# of People)

<1M | 10M+ | 100M+ | 1B+

Commercial Attractiveness

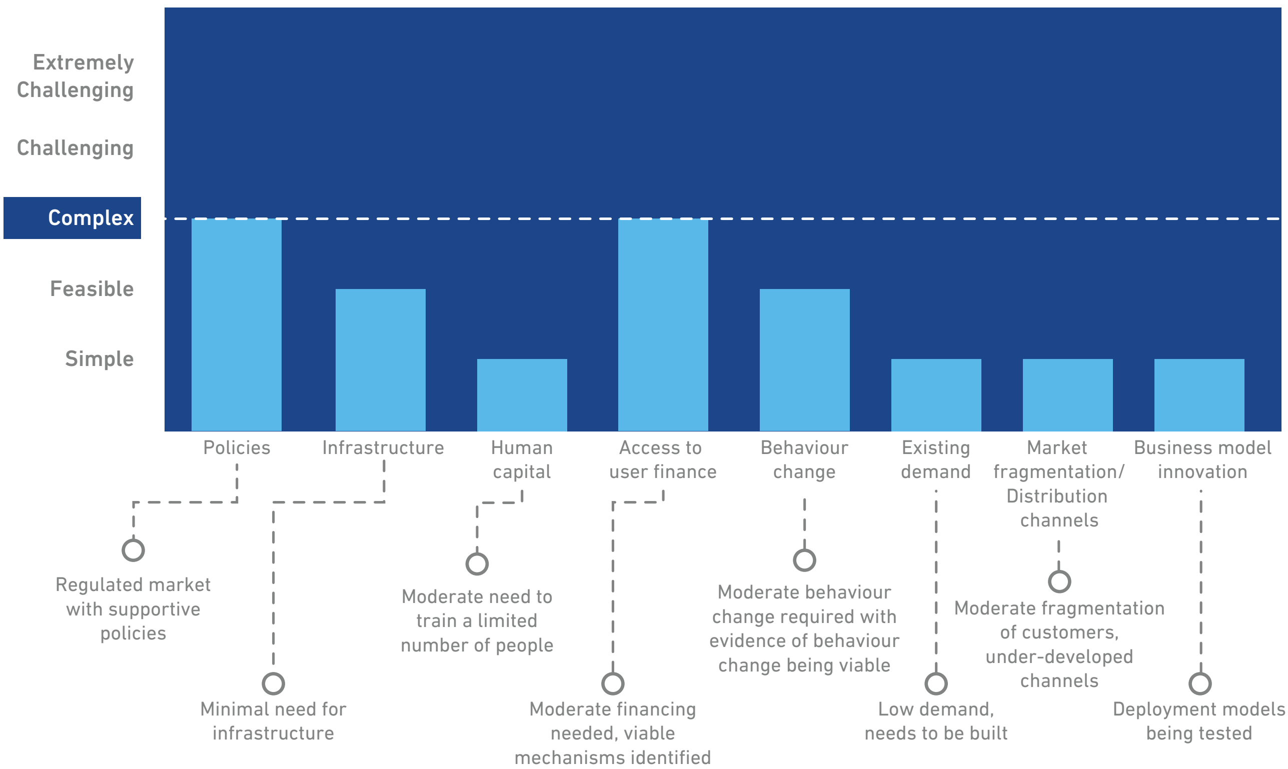
- Attractive for industrialized markets (high profits)
- **Attractive for emerging markets (lower profits)**
- Emerging markets potential; requires derisking (sustainable)
- Non-commercial (unprofitable)

Such a system should include all the key components of a decentralized renewable energy mini-grid for generation, storage and grid management. Standardization and self-help tools for installation, O&M and troubleshooting will be key.

Similarly, modularity and configurability—to meet the specific power demands of a particular installation—will be crucial to ensure adequate capacity and maximum capacity utilization. An early version of such a technology is currently being deployed by ITT after several years of design, integration and standardization of components.

Deployment challenges include limited current demand, challenging market economics and a lack of skilled technicians to install and maintain the systems. As such, deployment will be COMPLEX.

Breakthrough 43: Difficulty of deployment



46 Advanced biomass cookstoves that are desirable, affordable, robust and very clean

Biomass such as wood, straw and dung is the primary cooking fuel for about 2.5 billion people, or a third of the world's population. Household air pollution caused by these fuels causes millions of deaths each year, due to illnesses such as lower respiratory infection, lung cancer, ischemic heart disease, stroke and chronic obstructive pulmonary disease. Despite major initiatives to extend access to cleaner cooking fuels like gas and electricity, more households currently use solid fuels for cooking today than at any time in human history, due to growing population size. It is likely that billions of people will continue to cook with biomass for the foreseeable future, due to economic, logistical and cultural barriers to change.

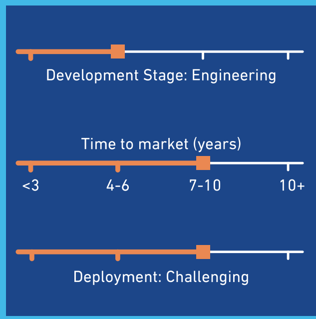
Design and deployment of improved biomass cookstoves has been an important goal of global development efforts for many decades. A wide range of biomass cookstove improvements have been proposed and trialed, with significant reduction in emissions of air pollutants like particulate matter and carbon monoxide. Some of these improved stoves have reached moderate levels of deployment in low-income countries.

However, recent research has shown that the exposure-response relationship for household air pollution is non-linear, thus the large reduction in emissions from current improved stoves brings only a modest decrease in health risk. To effectively eliminate the serious health risk of household air pollution, stove emissions must be reduced much further than is possible with current biomass stove designs.

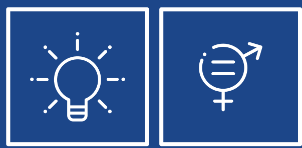
A new generation of advanced biomass cookstoves is needed, with greatly reduced emissions so they have low health risk that is comparable to other clean cooking solutions like gas and electricity. Advanced biomass cookstoves typically use complex, multiple stage combustion methods in order to burn fuel efficiently and minimize harmful emissions.

Current versions of advanced biomass cookstoves often have high upfront costs, offer less cooking flexibility, need pre-processed fuels and require an electricity supply to power built-in fans, yet still do not reliably achieve emission levels low enough to eliminate health risk in people's kitchens.

Current State



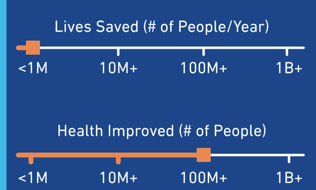
Associated 50BT Chapters



Access to Energy
Gender Equity

SDG Alignment

Impact



Commercial Attractiveness

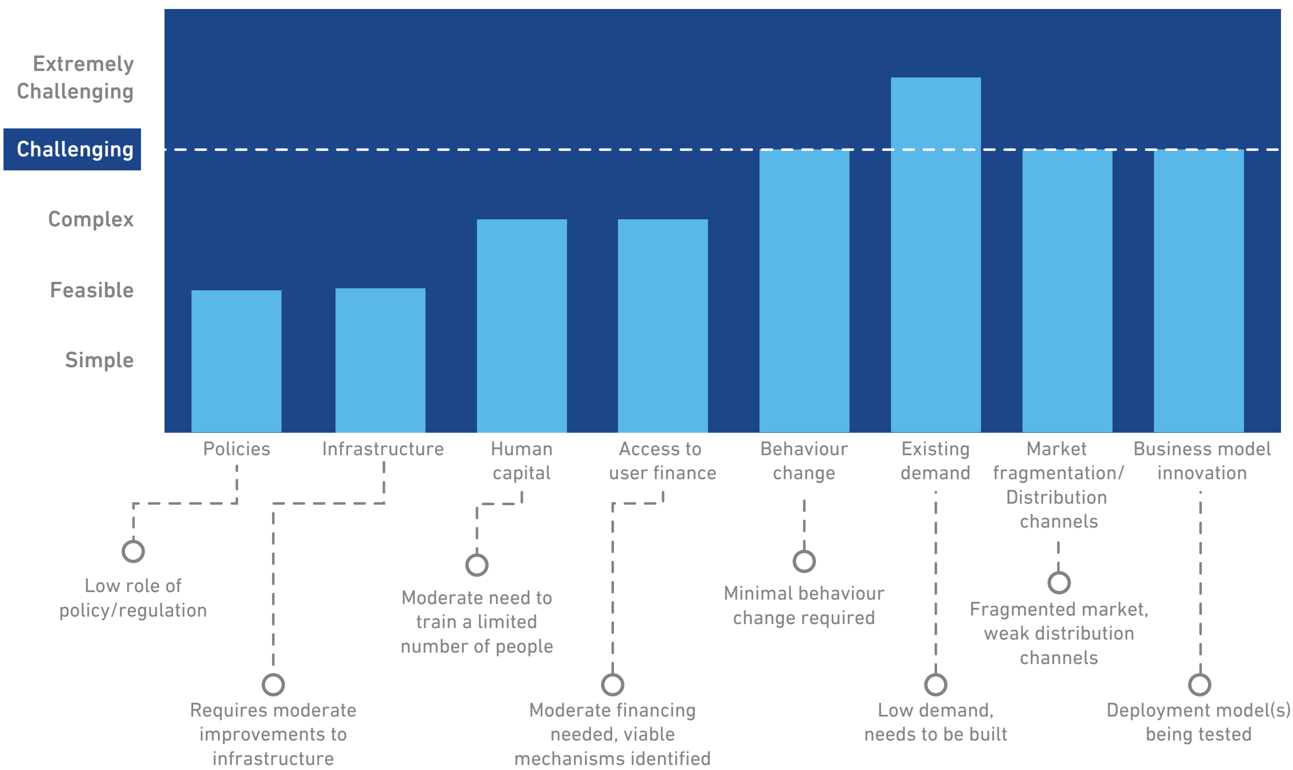
- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

An effective advanced biomass cookstove must be durable, low-cost and low maintenance. It will preferably use unprocessed fuel, or fuels that can be processed locally with available equipment. It will be compatible with traditional foods and cooking styles and not require major behavioral change by the users.

Above all, it must employ extremely efficient combustion processes and emit very low levels of dangerous pollutants. This breakthrough will require significant advances in thermodynamic and combustion sciences, as well as outstanding user-centric design.

Innovative business models will be required, and significant outreach will be needed in some regions to ensure sufficient demand. The projected time to market readiness of a breakthrough advanced biomass cookstove is five to seven years, and the difficulty of deployment is CHALLENGING.

Breakthrough 46: Difficulty of deployment



48 A mechanism to remove particulate emission from old trucks and other heavy-duty vehicles

Particulate emission from heavy duty vehicles like trucks and buses are a major source of outdoor air pollution in low-income (UNEP, 2014). In Delhi, India, for example, 23 percent of all particulate emissions come from the transport sector (Sharma, et al., 2016). This is mainly due to the large number of operating older vehicles coupled with poor vehicle maintenance, inadequate infrastructure and low fuel quality.

Vehicles in developing countries are typically older than those in industrialized countries. The average age of the vehicle fleet in Tanzania is about 15 years, and in Kenya and Uganda it is about 13 years (UNEP, 2009). Some vehicles, especially diesel-powered trucks and buses, operate for more than 40 years.

These older heavy-duty vehicles are responsible for a high percentage of air pollution, despite their low fleet numbers. These vehicles continue to operate because of the high cost of new vehicles, and the existence of strong maintenance and supply lines for older technology. Due to the inherently slow turnover of vehicle fleets, and the limited economic means of many truck and bus owners to obtain cleaner replacements, existing heavy-duty fleets are likely to remain in operation for many years.

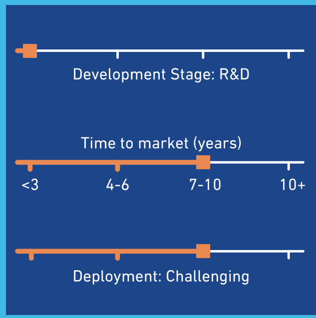
In the longer term, many improved technologies may enable cleaner urban transport systems. These include electric battery and fuel-cell vehicles and prioritized rapid urban transit with light rail or other modes. Having a cleaner transport system requires an appropriate regulatory framework and involves economic and behavioral trade-offs.

Long-term policies and investments are needed to support cleaner transport as a means to reduce urban outdoor air pollution. In the medium term, cleaner diesel fuels (with reduced sulfur and lead content) should be used, as well as incentives toward renewal of the heavy-duty vehicle fleet such as subsidies and inspection regimes. Nevertheless, many authorities are reluctant to force older heavy-duty vehicles off the road because of the national economic importance of the logistic services they provide. There is a need for an immediate alternative.

Urban air pollution could be significantly improved if these older vehicles could be easily and inexpensively retrofitted with a technology to reduce particulate matter emission. A number of retrofit emission technologies currently exist for heavy-duty diesel vehicles, such as catalyzed diesel particulate filters, which remove 95 percent of particulate matter from exhaust but cost up to $10,000 per vehicle (UNEP, 2009).

Particulate filters are mandatory on new diesel trucks in Europe, North America and other industrialized regions, costing about $3000 each. Current particulate filters impose an energy penalty on the vehicle, increasing diesel fuel consumption by about 3 percent (Reitz, 2013). Existing particulate emission controls are too expensive for widespread adoption by existing fleets in low-income countries.

Current State



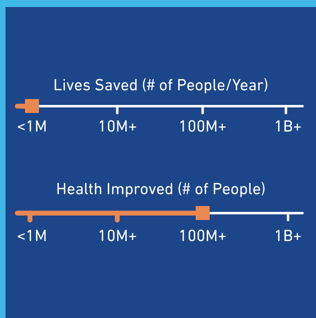
Associated 50BT Chapters

Global Health
Global Change

SDG Alignment

3 GOOD HEALTH AND WELL-BEING
11 SUSTAINABLE CITIES AND COMMUNITIES

Impact



Commercial Attractiveness

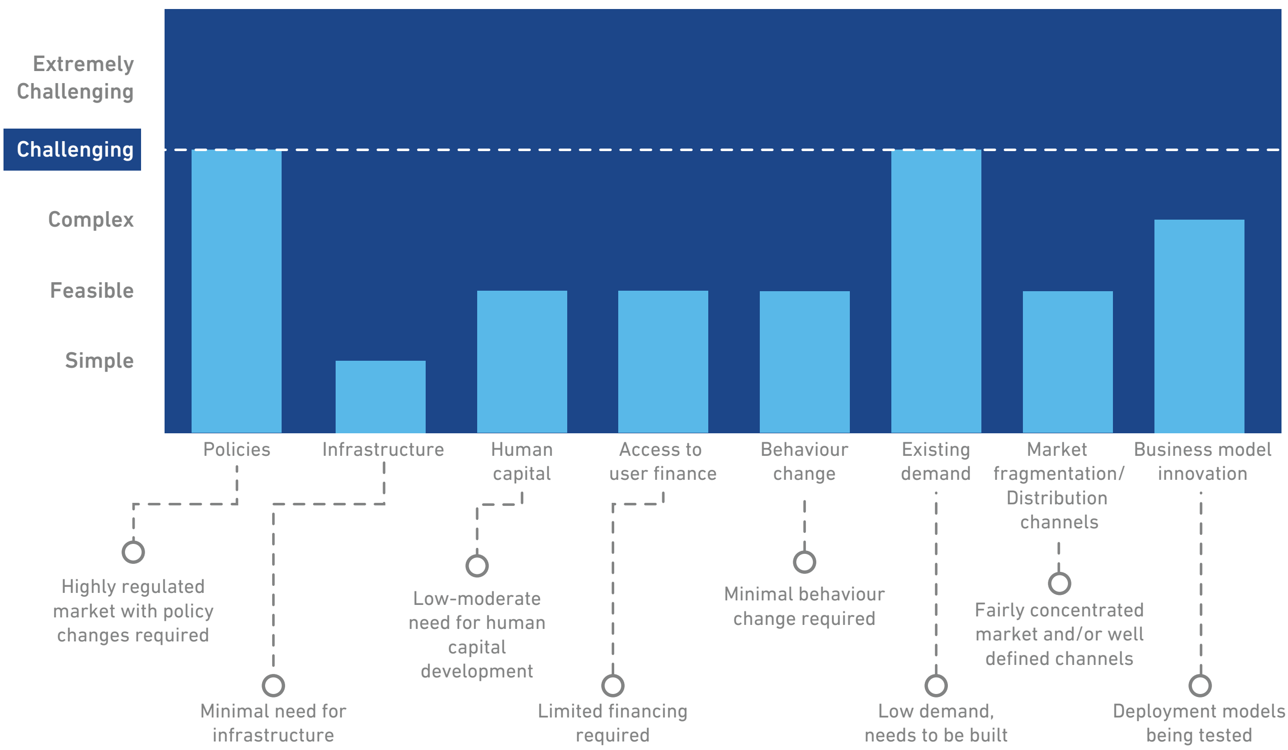
- Attractive for industrialized markets (high profits)
- **Attractive for emerging markets (lower profits)**
- Emerging markets potential; requires derisking (sustainable)
- Non-commercial (unprofitable)

There is a need for a robust, low-cost device that can be retrofitted onto old heavy-duty diesel vehicles to reduce particulate matter exhaust. This engineered solution must be inexpensively produced—less than $1,000—with simple retrofitting onto existing fleets of trucks and buses. Operation of the device must not impose significant load on the vehicle, in terms of exhaust back pressure or electricity demand.

A successful breakthrough technology would use inexpensive and abundant materials (for example, no expensive catalysts), would require only simple installation and maintenance and would produce no harmful byproducts. A range of technical approaches may be appropriate, including filtration, electrostatic precipitation and wet scrubbing (EPA, 1979; Roy, et al., 2011).

Assuming adequate level of support to achieve this breakthrough, we expect that it would take less than five years to be market ready. A major deployment challenge is the lack of demand within the current market structure. Some level of policy incentive must be created to encourage vehicle owners to install such a device. The difficulty of deployment in this case would be CHALLENGING.

Breakthrough 48: Difficulty of deployment



49 Small-scale waste incinerators with efficient combustion and clean emissions

The challenge of urban waste management remains unmet in many cities in low-income countries. Mounds of household rubbish often accumulate uncollected, spreading disease vectors and increasing health risks to community residents. Fast-growing cities lack adequate truck fleets for waste collection and haulage, and existing landfills are often poorly operated and filling rapidly.

Facing the lack of centralized waste management, households and communities typically burn their garbage in uncontrolled open-air fires. This leads to the emission of particulate matter, volatile organic compounds and toxins such as dioxin, with serious adverse health impacts on residents. Refuse burning is responsible for 10 percent of all PM2.5 particulate emissions in all of India, 12 percent in the city of Delhi, and 14 percent in the state of Uttar Pradesh (Sharma, et al., 2016).

An important lever to solve the solid waste problem in low-income cities is well-engineered, appropriately-sized, incineration plants that safely combust waste materials (Silva & Lopes, 2017). Breakthrough designs will be needed to ensure consistently safe air emission levels, even with diverse feedstock.

Existing guidelines on small-scale incineration, for example of medical waste (MMIS, 2010), are unlikely to meet the necessary high standards for air emission quality. Siting of multiple small-scale incineration plants will facilitate collection of waste at local disposal centers. Mobile incinerators moved between collection points may allow higher capacity utilization and improved economics.

Current State

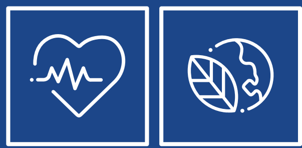
Development Stage: R&D

Time to market (years)

<3 4-6 7-10 10+

Deployment: Challenging

Associated 50BT Chapters



Global Health Global Change

SDG Alignment

Impact

Lives Saved (# of People/Year)

<1M 10M+ 100M+ 1B+

Health Improved (# of People)

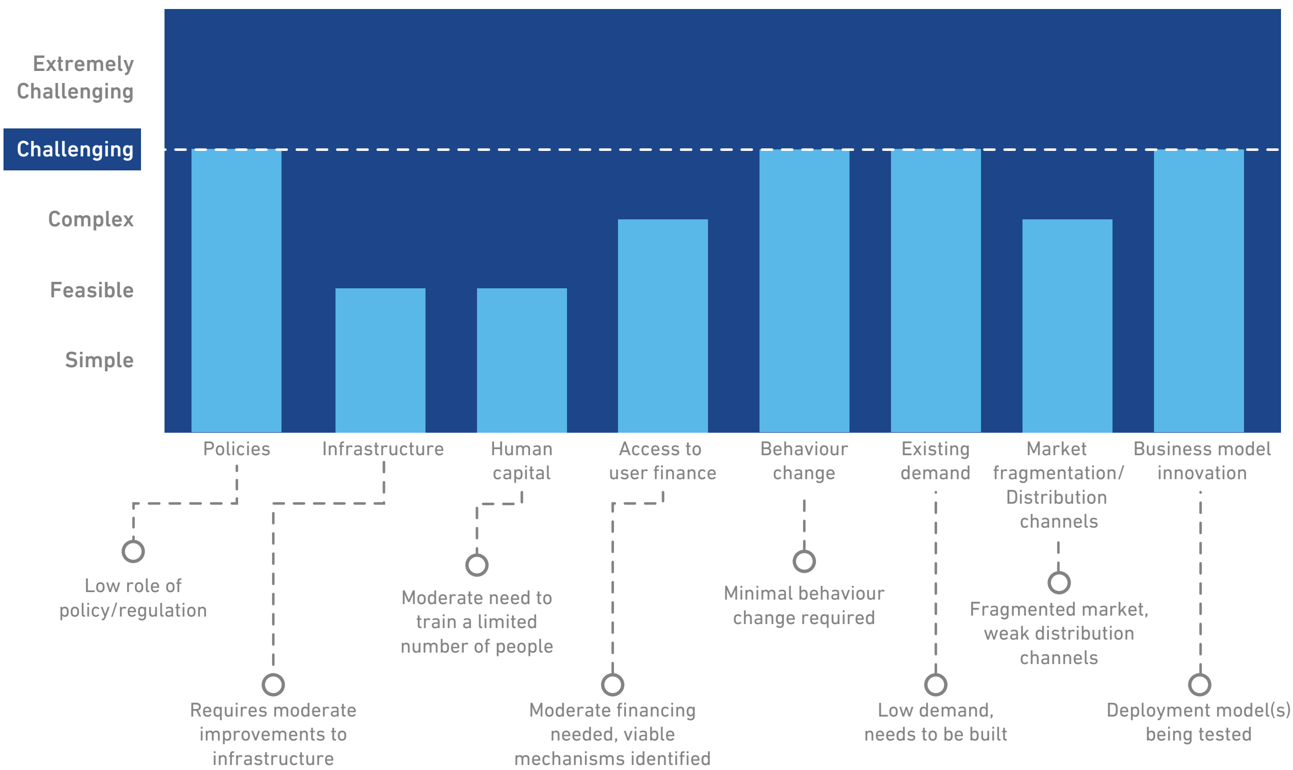
<1M 10M+ 100M+ 1B+

Commercial Attractiveness

- Attractive for industrialized markets (high profits)
- Attractive for emerging markets (lower profits)
- **Emerging markets potential; requires derisking (sustainable)**
- Non-commercial (unprofitable)

With resources and dedication, this breakthrough could be market-ready in three to five years. However, it faces strong challenges in terms of political and regulatory acceptance, and lack of demand, and business model innovation. Widespread deployment of this breakthrough is therefore CHALLENGING.

Breakthrough 49: Difficulty of deployment



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EMERGING TECHNOLOGIES

INTRODUCTION

Popular attention is increasingly focused on a number of emerging technologies, some of which are purported to possess transformational potential for human wellbeing in the near future.

Some have been proposed as leapfrog technologies that can help achieve Sustainable Development Goals (SDGs). Here we critically examine seven emerging technology areas to assess their realistic potential for human development, within the 2030 timeframe and beyond.

Assessment of emerging technologies is challenging--essentially to determine the future importance of systems that do not yet exist at scale. A multi-disciplinary approach is required, with consideration of various spatial and temporal scales, and an emphasis on managing uncertainties and variables. Such an assessment can be rewarding, and is driven by several motives.

First, we want to identify and support technologies with strong positive net future impacts. Early adoption of favorable emerging technologies drives collective progress as industry players learn through experience (Wright, 1936; McDonald & Schrattenholzer, 2001).

Secondly, we want to avoid early lock-in of technologies with negative potential. Adoption of emerging technologies carries the risk of establishing technological, economic and social momentum behind a particular path, before the potential impacts and future alternatives are fully understood (Liebowitz & Margolis, 1995).

Finally, we seek early-stage feedback loops that provide strategic guidance for policy-makers, investors, scientists and entrepreneurs on the realistic potentials of emerging technologies. Investments in developing and deploying one technology will compete with investments in other potentially beneficial technologies. Strategic decision-making should be informed by a realistic forward-thinking understanding of the technologies' ultimate potentials and limitations.

Many novel technologies are currently in varying stages of discovery, development and deployment. Here we focus on seven areas of technology advancement that have achieved high profiles in popular conversation. There is substantial overlap between some of the areas.

- Artificial intelligence and big data
- The Internet of Things
- Robotics
- Drones and remote sensing
- Blockchain and distributed ledgers
- Genetic editing and CRISPR
- Nanotechnology and nanomaterials

In this chapter we briefly describe and assess each of these seven areas, with emphasis on their potential contributions to global human development efforts within and beyond the 2030 SDG timeline. **Table 1** summarizes our assessment of the potential impact of these seven technologies on global human development efforts within both the SDG timeline of 2030 and the longer-term perspective of 2045. It is important to reiterate that the table shows the potential of the technologies, but is not a forecast of what will occur.

Nine development sectors are distinguished, each of which are covered in detail in other chapters of this report: water security, food security and agriculture, education, gender equity, human rights, global health, digital inclusion, access to energy, and resilience to global change.

Potential benefits to human development of select emerging technologies

	Water security (By 2030 / By 2045)	Food and agriculture (By 2030 / By 2045)	Education (By 2030 / By 2045)	Gender equity (By 2030 / By 2045)	Human rights (By 2030 / By 2045)	Global health (By 2030 / By 2045)	Digital inclusion (By 2030 / By 2045)	Access to energy (By 2030 / By 2045)	Resilience to global change (By 2030 / By 2045)
Artificial intelligence and big data	Analysis & management		Individual teaching		Remote sensing analysis	Discovery & diagnostics	Teaching & services	Analysis & management	Analysis & management
The Internet of Things	Sensing & automation	Sensing & automation		Safety & services	Data collection	Wearables & monitoring		Sensing & automation	Sensing & automation
Robotics									
Drones and remote sensing	Watershed sensing	Multispectral sensing			Monitoring & alert	Environmental monitoring		Environmental sensing	Multisectoral sensing
Blockchain and distributed ledgers				Identification & services	Knowledge security		Secure knowledge		
Genetic editing and CRISPR	Drought tolerant crops	Genetic productivity				Humans & ecosystem		Biofuel productivity	
Nanotechnology and nanomaterials	Water purification					Environmental health		Energy capture & storage	Cleaner production

no benefit | little benefit | some benefit | much benefit

Table 1: Potential beneficial impacts of seven emerging technologies on global human development efforts within the SDG timeline of 2030 and in the longer term.

In addition to their potential benefits, emerging technologies also may carry risks. These may include risks to human health, such as the use of genetically modified pathogens as bioweapons (Tucker, 2013). Another risk is that of environmental disturbance, perhaps due to an aggressively invasive species resulting from genetic editing (Taleb, et al., 2014). There are also risks to privacy and broader human rights, brought on by the historically unparalleled gathering of information by some technologies.

This also contributes to risks of excessive centralization of control and power, enabled by asymmetrical access to information and by high returns to scale. A further important risk is failure of complexity, due to decreasing and eventual negative returns to increasingly complex problem solving (Tainter, 1988). **Table 2** summarizes our assessment of the potential risks of these seven technologies, within both the SDG timeline and the longer-term perspective of 2045.

Potential risks of select emerging technologies

	Human health		Environmental		Privacy and rights		Centralization and Control		Failure of complexity	
	By 2030	By 2045	By 2030	By 2045	By 2030	By 2045	By 2030	By 2045	By 2030	By 2045
Artificial intelligence and big data					They know everything		Knowledge control		Virtual vs. physical	
The Internet of Things					Mass data collection		Data collection		Network complexity	
Robotics							Capital vs. labor		Goal formation	
Drones and remote sensing					Eye in the sky		Data collection		Support systems	
Blockchain and distributed ledgers									Systemic collapse	
Genetic editing and CRISPR	Unintended consequences		Rogue organisms				Intellectual property			
Nanotechnology and nanomaterials	Nanotoxins		Nanotoxins							

no risk | little risk | some risk | much risk

Table 2: Potential risks of seven emerging technologies within the SDG timeline of 2030 and in the longer term.

The seven technology areas are discussed in detail in the remainder of this chapter. For each area, we briefly introduce the historical context and provide an overview of the workings of the technology. We then describe the potential applications of the technology in low-income countries, and their relevance for achieving the SDGs.

We discuss important prerequisites and barriers to scale that must be overcome, and we mention the potential downsides or risks that adoption of each technology brings.

ARTIFICIAL INTELLIGENCE AND BIG DATA

Artificial intelligence and big data will likely have little impact on the SDGs by 2030 except in the education sector. AI has the potential to improve educational outcomes in developing countries via smart text books using individualized teaching methods. In the longer term, AI and big data may contribute to global health efforts through improved discovery and diagnostics methods. They also have potential to improve analysis and management methods to enhance water security, access to energy and environmental resilience. Nevertheless, they present substantial and well documented risks to privacy and human rights, and enable greater centralization of power and control of information. Overall, while many interesting tools will be developed, AI and big data are unlikely to significantly impact SDG achievement.

CORE FACTS AND ANALYSIS

The rapidly growing presence of Artificial Intelligence (AI) in many aspects of life in the industrialized world has led to important questions of the mechanisms with which AI can help achieve the SDGs by 2030.

An influential report (ITU, 2017a) from a "AI for Good" summit asserted "a firm belief that AI will help to solve some of the most pressing challenges to our planet and its people," and stated that "AI will be central to the achievement of the Sustainable Development Goals and could help solve humanity's grand challenges." A 2018 report (PWC, 2018) claimed that "there is enormous potential to create AI-enabled 'game changers' in which the application of AI ... has the potential to deliver transformative solutions."

AI researchers and developers have made great advances in recent decades, driven by three factors.

First, computational power and memory, following Moore's Law, have become exponentially more compact and inexpensive, making it possible to process significantly more data and calculations in a fraction of the time and space it took just a couple of decades back.

Second, the sheer volume of transactional data captured on individuals and their interactions with other individuals, vendors, institutions and their environment has increased by several orders of magnitude.

Third, the proliferation of an extraordinary range of sensors capturing digitized data—from GPS trackers, to cameras, IoT devices, satellites, drones and medical diagnostic devices, has enabled analytical engines to incorporate hitherto unfathomable data types, and model extraordinarily complex patterns and relationships across a large (and ever-growing) number of dimensions.

Several decades ago, the financial services sector was an early adopter of AI and data analytics to improve risk profiling, product pricing and customer targeting. **Exhibit 1** illustrates the methods used by banks, credit card companies and insurance providers to move from relatively simple statistical models to early-generation AI in the 1990s and early 2000s. This shift was precipitated by the increasing availability of numeric/digital data and the emergence of the data aggregation industry.

The principal analytical tools—such as neural networks—had hitherto been only used in AI research settings. Within a few years, the vast majority of financial services providers in the developed world adopted such tools, which quickly became accepted as conventional analytics, indeed even the bare minimum level of sophistication required to function in the industry.

The advent of data analytics

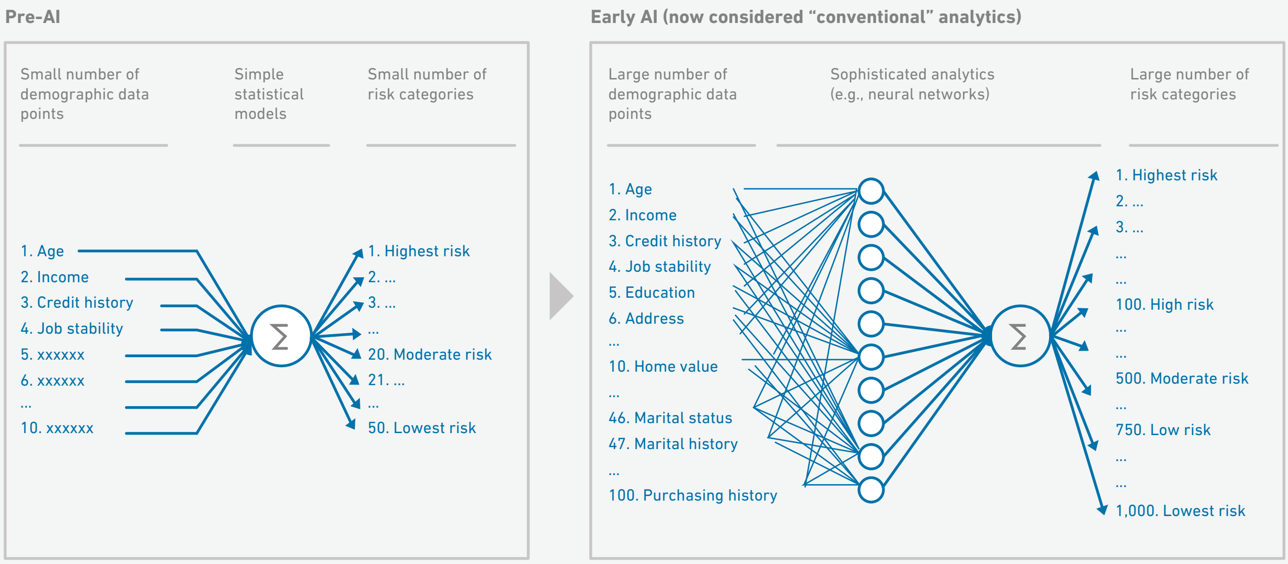


Exhibit 1: The financial services industry was among the early adopters of sophisticated data analytics and early-generation AI for risk scoring. Before the availability of a breadth of data types and data points, financial services companies used rudimentary models to determine customer risk. As digitized numerical data became available, early movers in the industry quickly adopted neural networks and other analytical/ AI tools hitherto used only in academic research to make much more precise predictions about customer profiles. By the turn of the century, such tools became commonplace in a number of industries, and were no longer considered AI. (Source: ITT, 2018)

The period between 2005 and 2010 marked the advent of the big data era (Bryant, et al., 2008).[1] With the dramatic increase in data sources enabled by smart phones and devices (like fitness trackers), social networking platforms, increased sophistication of search engines like Google, and continued growth of the data aggregation industry, the amount of available data—as well as the variety of data—on consumers increased by orders of magnitude (Press, 2013).

Not surprisingly, this allowed financial services providers (and, increasingly, companies in many other sectors) to become much more sophisticated in identifying potential customers, understanding their profiles and tendencies and marketing to them with highly customized advertisements, pricing and post-sales customer relationship management.

[1]Note that the phrase “big data” was coined about a decade earlier, reportedly by Cox & Ellsworth (1997).

In order to fully utilize the newfound breadth and volume of data, the analytical engines also needed to become more powerful, which led conventional neural networks to evolve into deep learning neural networks capable of extracting many more patterns and relationships.

Exhibit 2 illustrates the power of the new-generation AI tools over those from the previous generation.

Increasingly sophisticated data analytics and artificial intelligence

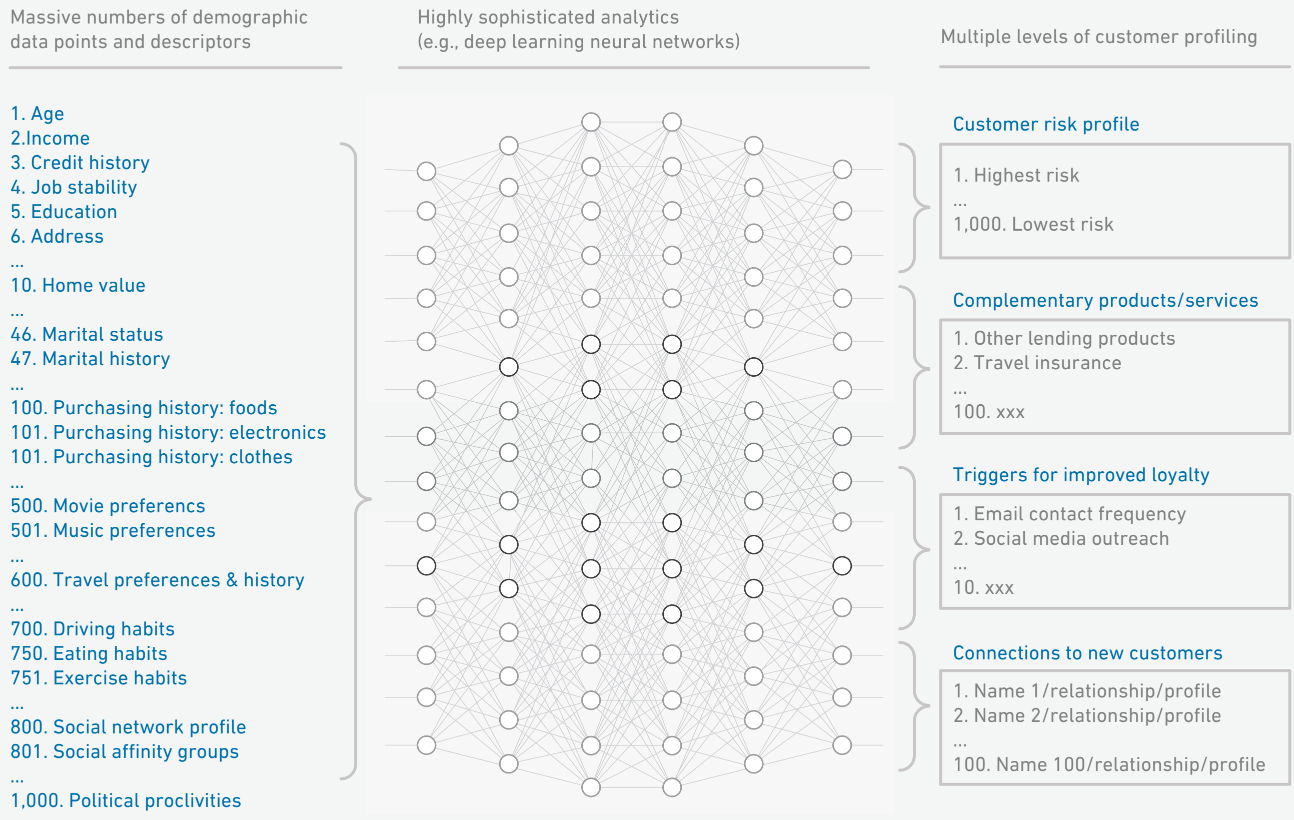


Exhibit 2: By 2010, the amount and type of data began to vastly increase due to the proliferation of smartphones, social media platforms and other data sources. By using this data and even more powerful analytical tools than those used in previous decades, companies in many industries are able to model consumer behavior and preferences with an astonishing degree of precision. (Source: ITT, 2018)

It is important to distinguish between AI and conventional analytics in current nomenclature, as forums focused on human development have tended to conflate the two. The phrase "big data" is often used anytime data—big or small—is aggregated for analysis; similarly, the phrases "deep learning" and "AI" are used, even when the statistical optimization tools are now squarely in the realm of conventional analytics. Sophistication of the analytical tool should be appropriate to the underlying volume and richness of data.

Just as analytical tools that are too simplistic for the underlying data will lead to erroneous conclusions, so will using tools that are too complex. Indeed, data complexity theory shows that using analytical models with too many degrees of freedom can lead to errors due to over-fitting (Li & Abu-Mostafa, 2006).

KEY CHALLENGES

While data analytics and AI are capable of bringing societal benefits, there are a number of legitimate concerns about government and corporate surveillance of citizens, targeting of specific groups (based on religion, ethnicity, political proclivities, sexual orientation, or other oft-discriminated-against traits) and other forms of exploitation and persecution (Access Now, 2018).

Malicious use of AI could threaten digital security, such as through improved hacking or socially engineering performance; physical security, like through weaponized consumer drones; and political security, such as through automated and targeted disinformation campaigns (Brundage, et al., 2018).

A number of recent high-profile scandals related to big data and AI have provoked much discussion about the risks of the technologies (The New York Times, 2018), yet appear to have led to a general acceptance of the risks in industrialized countries with ostensibly robust policy ecosystems and legal protections (Rand Corporation, 2017).

As potentially problematic as these risks are in countries with robust legal protections, the challenges are likely to be significantly higher in regions without such protections. There is strong evidence to suggest that lower-income countries tend to have weaker governance and rights protections (this is detailed in the Human Rights chapter).

Indeed, today, even without robust data infrastructure, governments of the poorest countries can use any of a number of commercially available tools to surveil the communications of their citizens.

While there are a number of forums dedicated to these concerns and the necessary protections, it is unclear when appropriate legal frameworks will be put in place and whether such protections can effectively eliminate abuse.

BREAKTHROUGH APPLICATIONS

Numerous examples of using AI for human development have been cited in various forums in the fields of health, agriculture, energy, conservation and others.

Potential health applications include medical diagnostic devices with automated decision-making, and analysis of medical imaging to identify tumors and other anomalies. AI has been used to inform discoveries in genetics and molecular medicine (Hamet & Tremblay, 2017), and combined with mass spectrometry data to screen for patients with Zika virus (Melo, et al., 2018).

Other potential applications in global development include hyper-local weather analysis to inform farming decisions, optimized forecasting and management of energy systems, modeling and predicting extreme weather events, real-time translation between multiple languages, learning system with personalized content and pace and utilizing data on fishing vessels to identify potential violations of ocean conservation agreements (ITU, 2017a; PWC, 2018).

While data analytics can play a meaningful role in achieving the SDGs, most of the major interventions required to achieve the SDGs do not need sophisticated data analytics (ITT, 2018).

Instead, critical interventions in food security, health, energy access and education in low-income countries mainly depend on infrastructure (such as for energy access), physical tools (for increased crop production), innovative business models (for education and healthcare) and other on-the-ground programs (**Exhibit 3**).

Although data analytics could help inform and optimize these programs, it constitutes only a small portion of the overall solution space.

The most impactful technologies across four development sectors, and their dependence on advanced analytics and artificial intelligence

	Limited dependence on data-driven analytics	Conventional analytics and decision-making tools	AI and big data
FOOD SECURITY	• Affordable on-farm implements for irrigation and weed removal • Steady supply of fertilizer (conventional or via alternative mechanisms) • Post-harvest loss reduction including dry storage and refrigeration • Processing equipment for key cash crops • Livestock vaccines for key diseases/ pathogens and cold-chain-enabled artificial insemination • High-nutrient animal fodder	• Crop market information: pricing and match-making between sellers and buyers • Training content (customized generation and dissemination) on optimal agronomic practices • Crop [micro-] insurance • Granular data for improved agricultural policy-making • Funds for financing smallholder farmers and agricultural processors	• Improved seeds for drought and heat with robust models for understanding impacts on ecosystems
HEALTH	• Reliable vaccine cold chain equipment or thermostable vaccines • Suite of point-of-care primary care diagnostic devices • New generation of pharmaceuticals: vaccines for HIV/AIDS, malaria and TB; single dose or short course TB anti-bacterial • Large primary care networks with high quality standards and broad/deep reach • Long-lasting, low cost non-chemical spatial repellents for mosquitoes and other vectors • Nutrient-dense, culturally appropriate infant foods • Decentralized toilets (e.g. composting)	• Rules-based clinical protocols based on patient demographics, medical history, diagnostics, etc. • Customized training and certification tools for clinicians • Large-scale (ideally government-run) health insurance programs • Granular data for improved policy-making, incorporating local health data and trends • Diagnostics for image-based data (x-ray, retinal scans, etc.) using existing AI-based automation	• New generation of AI-based diagnostic techniques, bypassing conventional biomarkers • Epidemiological/outbreak tracking and forecasting
ENERGY ACCESS	• Productized modular "drop-in-place" solar mini-grid systems with reduced installation cost and time • Commercially viable clean cook stoves and cooking fuels • New generation of affordable energy-efficient appliances, especially for productive uses • Storage solutions for mini-grids that leverage supply chains for automobile batteries • Large renewable electric utilities based on public-private partnerships and capital subsidies	• Data and predictive models on community energy usage so that utilities can plan capacity and regulators can develop appropriate policies	
EDUCATION	• Large networks of branded, low-cost private schools at all education levels: primary, secondary and vocational	• Incentive programs for schools and teachers, linked to improvements in quality access and educational outcomes • Student loan programs, especially for vocational training and entrepreneurship • Conditional cash transfers and other incentive programs for families to invest in education	• Intelligent teaching systems enabled by semi-automated content curation, automated grading to dynamically adjust learning speeds and content, and interfaces for both students and teachers

Exhibit 3: Mapping of the potential impact of AI and big data on food security, health, energy access and education in low-income countries. About half of the major interventions required to achieve the SDGs do not need data analytics, and instead depend on infrastructure, physical tools, innovative business models and other on-the-ground programs. (Source: ITT, 2018)

There are a number of important interventions that depend heavily on data and analytics, but the vast majority of these interventions can be implemented with conventional analytics solutions, the likes of which have been in commercial use for at least two decades in industrialized countries.

Advanced AI can offer powerful solutions in a small number of specific targeted areas, such as automated health diagnostics. In most other cases, AI risks being a distraction from more fruitful pursuits involving on-the-ground physical action.

Undoubtedly there is value in collecting, analyzing and utilizing reliable data, to glean insights, make better decisions and automate certain tasks.

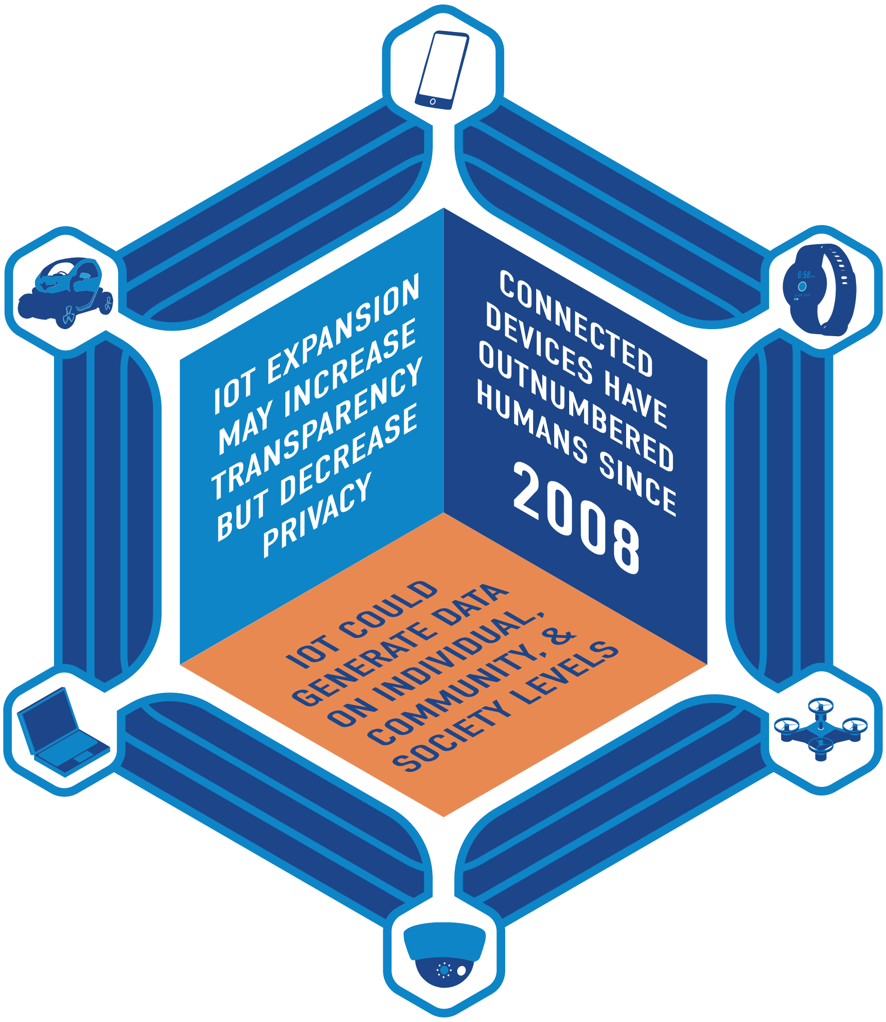
However, in the context of human development—especially within the 2030 timeline of the SDGs—there is much more foundational work that needs to be done before sophisticated data and AI tools can be used for effect.

For example, while there is tremendous value in automated diagnosis from X-ray and ultrasound images, it will only have impact if there are enough affordable X-ray and ultrasound machines being deployed within reach of target populations.

Similarly, while it will be very valuable to develop accurate risk models for crop insurance, the models will have limited impact without enough cash reserves to provide insurance and without mechanisms to deliver and administer insurance policies.

Therefore, it is important to fully understand the deployment context for such tools before investing heavily in them.

For stakeholders whose primary focus is on vertical SDG areas, such as food security and health, data and AI strategies should only be considered as a part of integrated strategies for the vertical areas, so that there are clear linkages translating the improved information to better execution of direct interventions.



THE INTERNET OF THINGS

The Internet of Things (IoT) has a number of targeted applications that may affect the SDGs, though penetration will likely be low by 2030. It has strong potential to improve access to energy, for example through smart electricity grids, and increase environmental resilience by sensing and documenting pollution sources. It also can improve sensing and automation capabilities that can enhance water and food security. IoT wearables and monitoring devices can provide data and services to help improve health outcomes. It has the potential to improve gender equity and human rights, by identifying and documenting threats. However, the massive collection of IoT data also carries risks to privacy and human rights, and asymmetric data access may enable greater centralization of power. Overall, slow deployment of IoT infrastructure will limit its impact on SDGs by 2030, but there is great potential for longer term impact in many sectors.

CORE FACTS AND ANALYSIS

The Internet of Things (IoT) is an evolving integration of components that link the physical world and the virtual (computer-based) world. While there is no universally acceptable definition of IoT, it has been described as "the growing range of Internet-connected devices that capture or generate an enormous amount of data every day along with the applications and services used to interpret, analyze, predict and take actions based on the information received" (USDC, 2017).

IoT has the potential to generate a huge number of data points in sectors as diverse as water, health, energy and agriculture. The positive and negative impacts of such data collection on societal wellbeing is less clear.

IoT is not a single device or a product, but an integrated structure that includes tangible items like sensors and actuators as well as intangibles like software and data.

The technological components of the IoT include building blocks like machine-to-machine interfaces and protocols, microcontrollers, RFID technology and other wireless communication, sensors, actuators and software (CERP-IoT, 2010). A host of synergistic technologies can potentially add value to the IoT, such as machine vision, robotics, user interfaces, biometrics, geo-tagging and others (**Exhibit 4**).

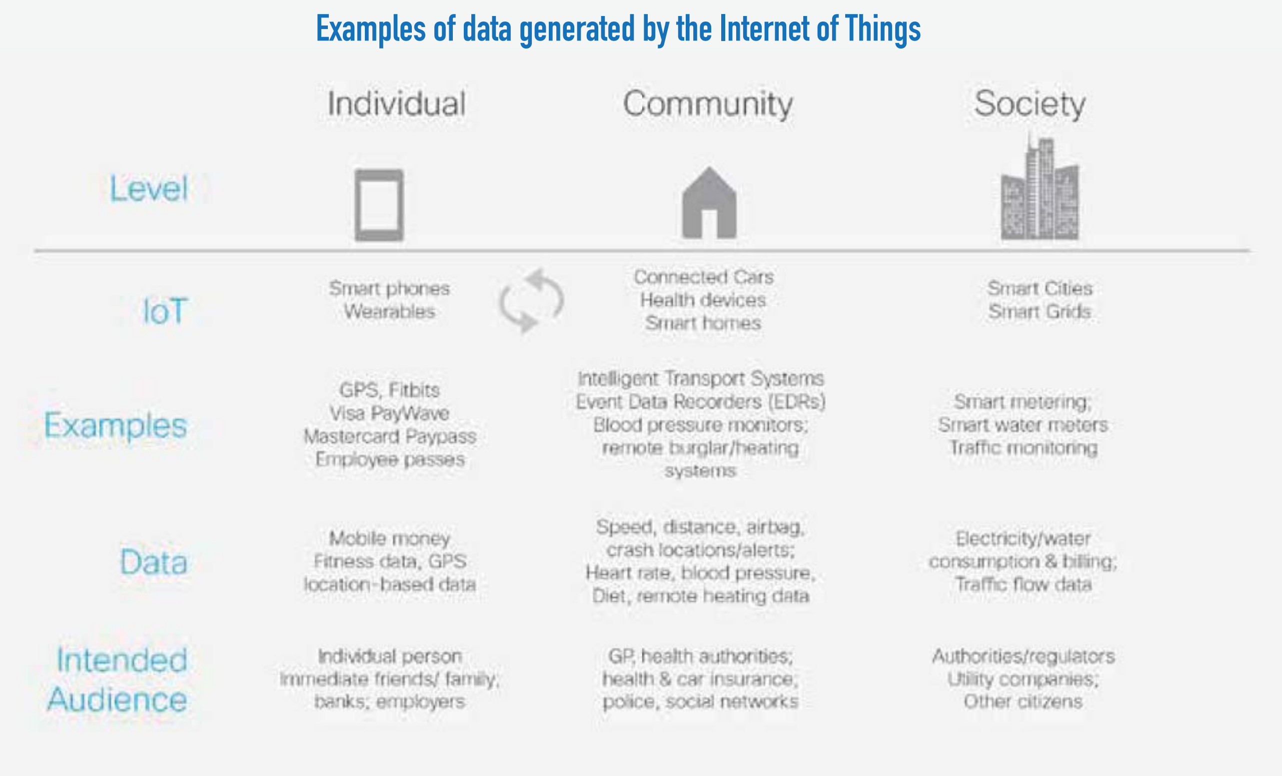


Exhibit 4: The Internet of Things could generate a wide range of data at the individual, community and society levels. (Source: ITU, 2016)

The objective of IoT is to expand knowledge and control of the world, by integrating data processing with physical devices that sense and influence their surroundings. IoT communication channels include machine-to-machine, as well as person-to-machine and machine-to-person to enable human interfacing with the IoT. Person-to-person communication is generally not considered IoT.

Global connectivity is expanding rapidly: the total number of connected devices surpassed the number of people in about 2008, and is now estimated to exceed 20 billion (**Exhibit 5**). The biggest driver for this growth is machine-to-machine communication such as connected cars, homes and healthcare devices. Researchers estimate that IoT will contribute more than 14 trillion dollars to the world economy by 2025 (McKinsey, 2015).

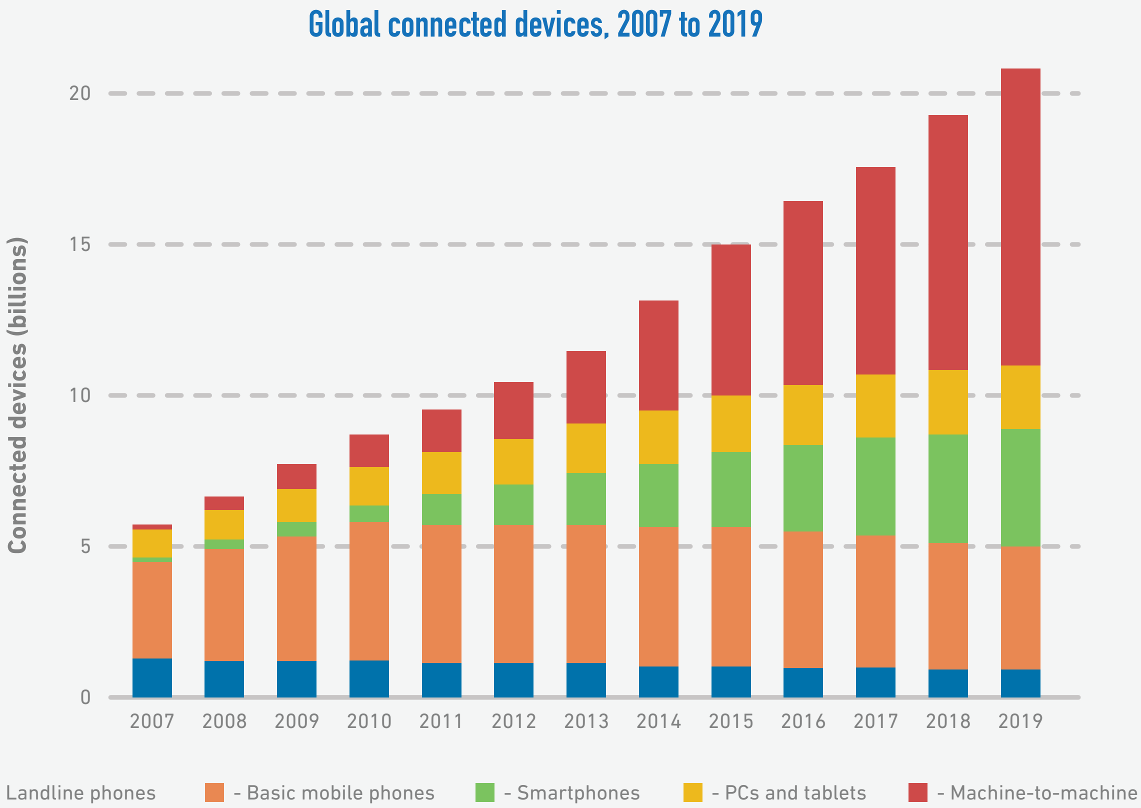


Exhibit 5: The number of connected devices continues to increase rapidly, and the fastest growing segment is machine-to-machine communication that forms the core of the Internet of Things. (Source: ITT analysis based on Gartner, 2017; GSMA, 2017; ITU, 2017b; Newzoo, 2018; IoT Analytics, 2018; Ericsson, 2018; Cisco, 2019)

The World Economic Forum projects that 84 percent of IoT deployment has the potential to address challenges surrounding the SDGs (WEF, 2018). An estimated 75 percent of these IoT projects concentrate across five SDGs: industry, innovation and infrastructure (25 percent), smart cities and communities (19 percent), clean energy (19 percent), good health and well- being (7 percent) and sustainable consumption (5 percent).

The contribution of IoT to social and environmental sustainability is complex and still not fully understood. For example, in the energy sector, a commercial application of IoT sensors used to track energy consumption can have downstream benefits like energy use reduction, development of conscientious users and cost savings for utility companies. Nevertheless, such benefits will have to extend to the poorest members of society, for IoT solutions to have a tangible impact on achieving SDGs.

KEY CHALLENGES

Even though the expansion of internet and mobile broadband coverage has been quite rapid in many low-income countries, some key challenges will have to be addressed for IoT to achieve its potential impact.

First, economic sectors in low-income countries are more labor intensive and may not use IoT-enabled devices to conduct their day-to-day operations. Investments would need to be made in behavior change and awareness activities that can lead to adoption at scale.

Second, connectivity may be available only at a basic level to operate applications on a small scale, and the full range of IoT services might not be accessible in some areas.

Furthermore, concerns have been raised that increasing interconnection of devices leads to heightened risk of lethal disruption by hackers (Schneier, 2018).

For example, malicious hackers could cause automated cars to crash, implanted medical devices like pacemakers to fail and electrical power grids to go offline.

Despite these challenges, IoT technologies, especially those attached to sensors for environmental toxicity, health and other under-documented aspects of society in lower-income settings, have the potential for significant democratization of information, transparency and accountability.

As such, they have the potential to make a sizeable contribution to the SDGs and beyond. While expansion of IoT is expected to increase transparency, it is also expected to decrease privacy.

BREAKTHROUGH APPLICATIONS

Two trends have influenced the increasing utilization and integration of IoT to provide services in low-income countries. First, more people in low-income countries have access to telecommunication services than basic services like sanitation, water and electricity.

In 2015, for example, more than 95 percent of the world's population lived in areas with network coverage of 2G or better (ITU, 2016). Second, the cost of ICT infrastructure development has significantly decreased over the last decade and supply chains continue to be simplified. There has been a proliferation of service delivery applications that leverage these reduced costs to make basic services accessible to the poor.

Sectors where IoT application is showing promising impact include healthcare, agriculture, water security, energy access and human rights.

In the healthcare sector in some low-income countries, sensors are being used to monitor cold chain supply networks to monitor and track the temperature at which vaccines are stored. Mobile based thermal sensors record the temperatures in real time and a warning is issued to the responsible person if the temperatures exceed a threshold level.

IoT technologies are also being used to address immediate health challenges in humanitarian response, such as the Ebola outbreak in West Africa. The United States Agency for International Development (USAID) has supported and employed IoT solutions via connected wearable technologies. Sensor Technology and Analytics to Monitor, Predict, and Protect Ebola Patients (or STAMP2 for short) has been tested on Ebola patients in the United States and is being scaled up to meet the needs of government agencies such as USAID for its Ebola treatment strategy in Liberia (ITU, 2016).

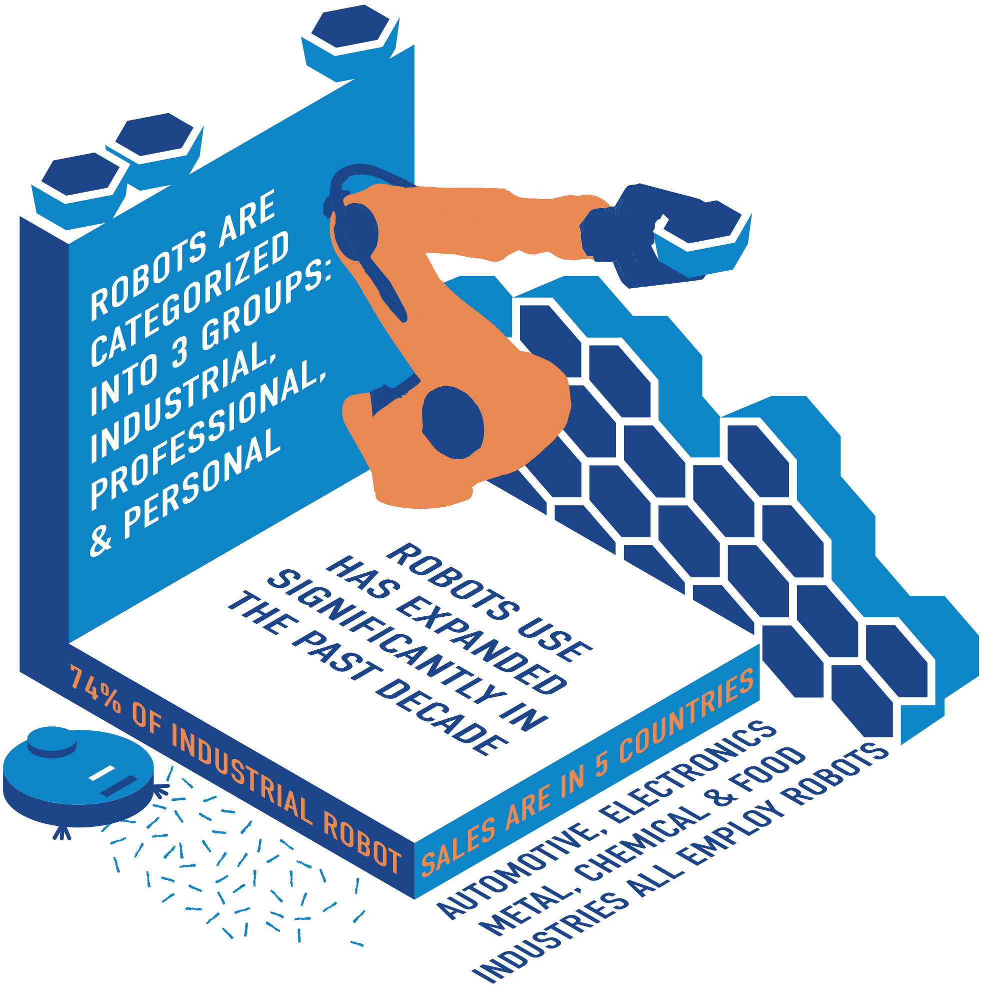
In the agriculture sector, IoT technologies can be used to monitor soil moisture, pH value and nutrient levels to inform farming decisions such as irrigation and fertilization. Micro-weather stations are using IoT technologies to monitor and predict weather more accurately, and to transmit the information to smallholder farmers for them to plan farming activities. Post-harvest losses could be reduced by IoT monitoring and feedback of storage and handling conditions.

Many waterborne toxins are invisible, tasteless and odorless, thus severe cases of contamination often go undetected and unremedied. Detection of water and other environmental toxins currently requires costly equipment and elaborate sampling protocols, and provides only isolated snapshots of individual places, times and contaminants.

There is a need for the development and widespread deployment of IoT sensors that detect the levels of the most significant environmental toxins affecting water quality, and transmit that information to a platform where it is validated and publicly displayed. Required technological innovations include integrated sensors for the most significant contaminants that are inexpensive enough for mass deployment, as well as a platform for data collection, validation, analysis and dissemination.

Energy access may be enhanced by the introduction of IoT-enabled smart grid systems, which would solve many management and billing challenges facing electricity suppliers in low-income countries and globally. Smart power meters can continuously monitor electricity use, and can curtail service to individual households in case of excessive power draw or non-payment of bills.

Human rights could be enhanced by wearable devices, or smart electronic devices that can be incorporated into clothing or worn on the body as implants or accessories. Such IoT devices have the potential to capture significant information and evidence to shed light on transactions involving corruption and human rights violations. However, they also have the potential to be used in violations of privacy.



ROBOTICS

The use of robots has very little realistic potential to improve SDG outcomes by 2030 or in the longer term, barring major shifts in social structures and power dynamics. Indeed, robotics carry risks to global development, as tasks once done by low-income people are instead done by capital-intensive machines, leaving poor populations with more tenuous livelihoods.

CORE FACTS AND ANALYSIS

The general objective of robotics is to shift physical activities from humans to machines. A further goal is to extend activities beyond human capabilities, for example with faster or stronger abilities. The tool to achieve this is a robot, a machine that can carry out a diverse set of actions, either in a pre-programmed sequence or in response to sensed stimuli.

Robotics is distinct from other forms of automation because robots 1) are digitally controlled, 2) perform physical tasks, and 3) vary tasks depending on control instructions.

In contrast, software automation is limited to the virtual (non-physical) realm, for example diagnosing diseases from medical images. Mechanized devices, for example heavy equipment such as diggers and loaders, are controlled by people not computers. Simple automation, such as dedicated tools on an assembly line, can perform a single task excellently but can do nothing else.

There are various categories of robots, and there is no strict definition of the term. The International Federation of Robotics, an industry association, recognizes three groups: industrial robots, professional service robots and personal service robots (IFR, 2018a, 2018b).

More broadly, self-driving cars can be considered robots, and drones (discussed in the next section) with automated capabilities are flying robots.

About 375,000 industrial robots were sold globally in 2017. The use of robots for automation of industrial tasks has expanded strongly in the past decade (**Exhibit 6**). China is the largest market for industrial robots, followed by South Korea, Japan, the United States and Germany. Together, these countries represent 74 percent of industrial robot sales (IFR, 2018a). While, the automotive and electronics industries are the greatest users of robots, the metal, chemical and food industries are also employing significant numbers of robots.

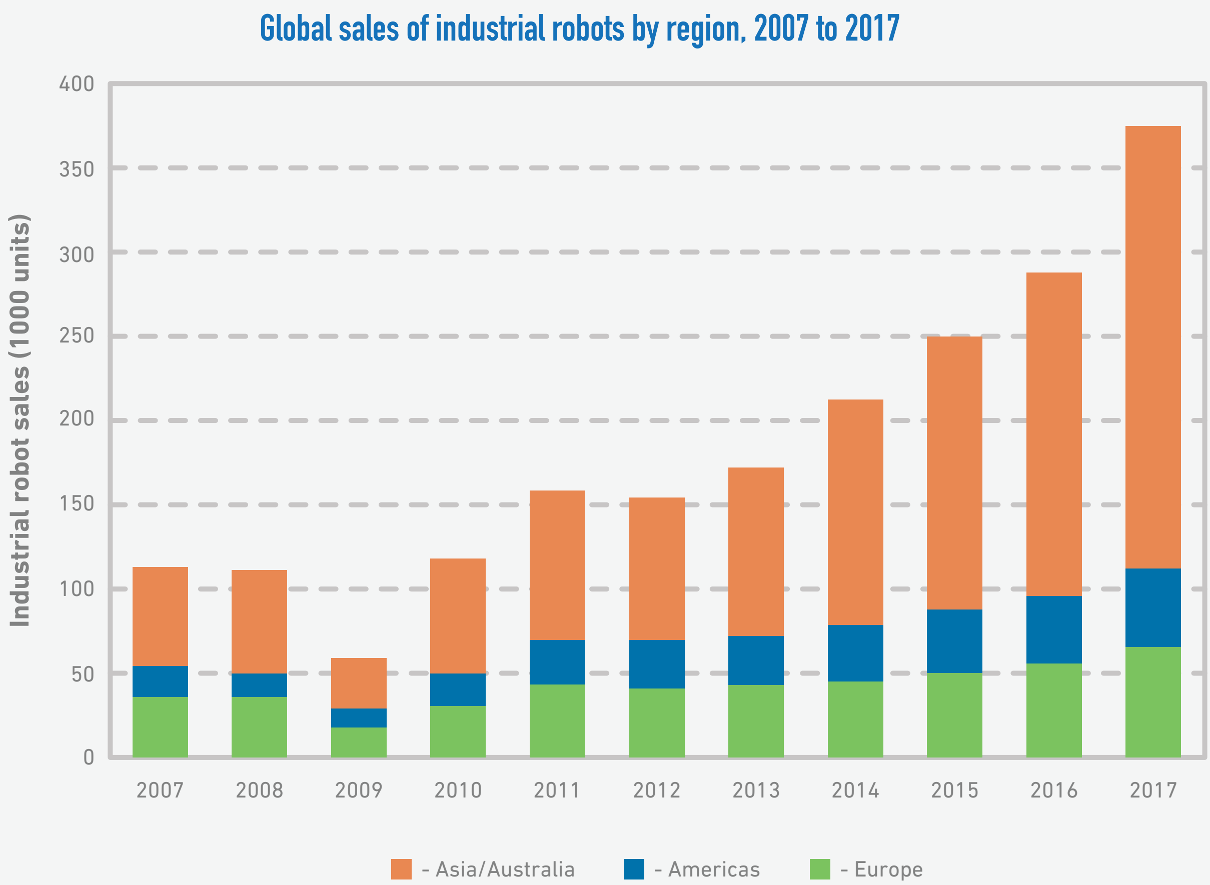


Exhibit 6: Industrial robot shipments have been increasing globally in recent years, particularly in China. (Source: IFR, 2018a)

Service robots can be used for professional or personal purposes.

There is a wide range of professional service robots, and about 110,000 units were sold in 2017 (IFR, 2018b) (**Exhibit 7**). More than half were logistical robots, which are automated guided vehicles to carry loads in manufacturing and non-manufacturing environments.

About 11 percent of professional service robots were military robots, mainly unmanned aerial vehicles as well as some unmanned ground-based vehicles.

The remaining professional service robot types sold include public relation robots such as telepresence robots and mobile guidance and information robots, automated milking machines and other farm-based robots, powered human exoskeletons used for rehabilitation and ergonomic support, and medical robots that conduct robot assisted surgery or therapy. Drones for commercial and personal use are discussed in a later section of this chapter.

Personal service robots are the most widely used type of robot, with 8.4 million units sold in 2017 (**Exhibit 7**). About two-thirds were household robots such as vacuum and floor cleaning and lawn-mowing robots. The remaining were entertainment and leisure robots including toy, hobby and education robots.

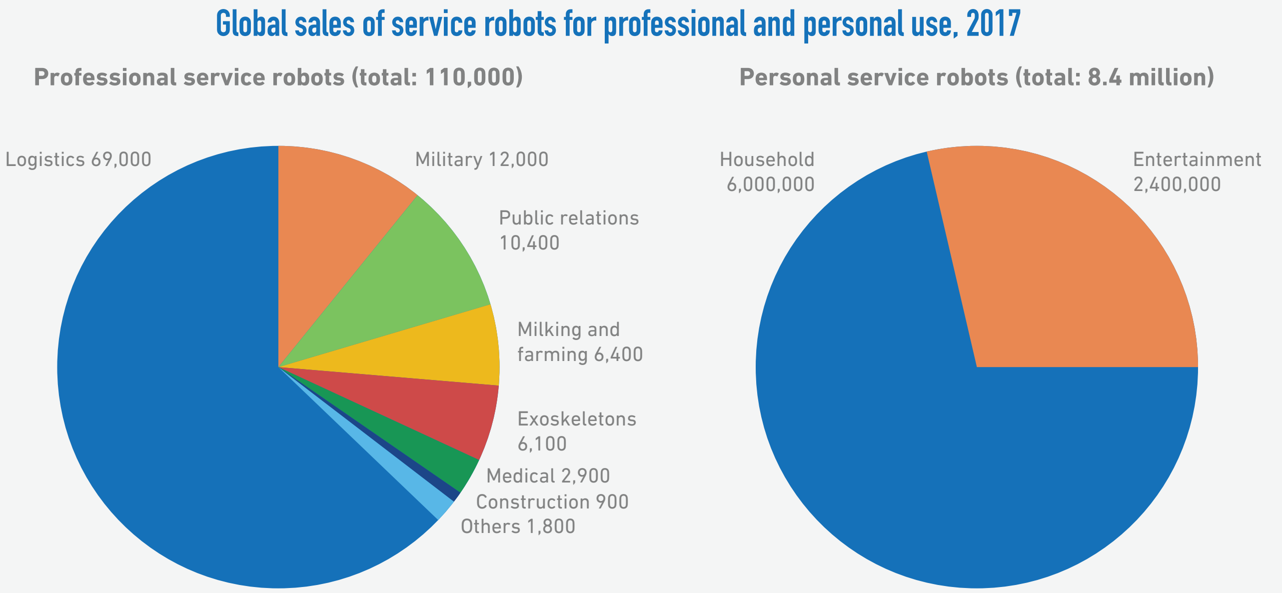


Exhibit 7: About 110,000 service robots for professional use were sold in 2017, while 8.4 million personal service robots were sold. (Source: IFR, 2018b)

KEY CHALLENGES

The intuitive appeal and long-promised benefit of robotics is to automate arduous tasks, thus allowing people more free time for personal enjoyment. Economist Keynes famously suggested that our response to technological improvements would be to “spread the bread thin on the butter—to make what work there is still to be done to be as widely shared as possible” (Keynes, 1930).

Whether that outcome is realized is a question of societal goals and structure, not of technical sophistication of robotics. Automation practices to date appear to be driven not by desire for broad human wellbeing, but for continued concentration of resources.

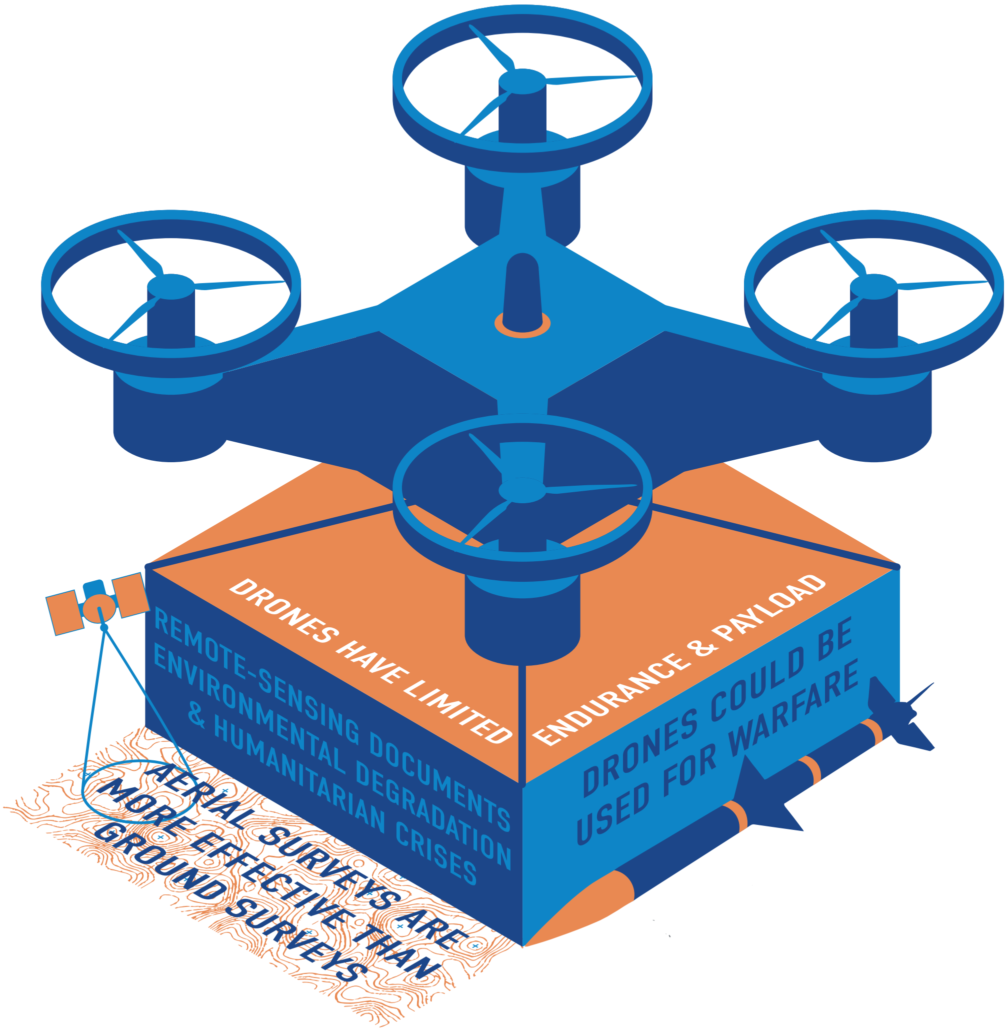
BREAKTHROUGH APPLICATIONS

Numerous application areas have been proposed for robotics to improve human welfare. In the field of healthcare, for example, IoT-connected robots could provide some care for elderly and disabled persons, monitor and track medical equipment and maintain complex medical and communications equipment.

Rescue operations could also benefit from robots in disaster areas where it is hard for humans to reach. Agriculture could also benefit, for example greater accuracy in spraying pesticide thus cutting its use. Farm jobs like harvesting could be automated, using robots with scanning and imaging technology allowing them to identify and handle the varying shapes of individual fruits and vegetables.

In general, however, robotics appears to have little opportunity to help achieve the SDGs by 2030 or beyond. Optimistic technology-centered projections may foresee greater human benefits from robotics, but transformative development effects are unlikely in practice due to nontechnical limitations.

Most robots are largely inappropriate for the resource-limited settings of low-income countries. Robots are more likely to aid global development effort when they extend human abilities (such as drones providing remote sensing) than when they replace human ability (including most “labor-saving” applications).



DRONES AND REMOTE SENSING

Drones and remote sensing are increasingly used to gather data for improved management and decision-making in the military and environmental sectors. The emergence of lower-cost satellite systems is making remote sensing data more widely available for more applications. The spatial and temporal resolution of remote sensing platforms is improving steadily. As multi-spectral imaging capabilities of drones and satellites improve in the near future, and data processing and artificial intelligence capabilities grow, remote sensing will likely play increasing roles in many sectors including water and food security, global health and access to energy. Remote sensing data can support the monitoring and alerting of human rights violations. However, drones and remote sensing carry significant risks to privacy, due to ubiquitous monitoring of activities. Overall, the impact of drones and remote sensing on SDGs by 2030 will be limited, but the longer-term impact on global development can be substantial.

CORE FACTS AND ANALYSIS

Within the last several years there has been rapid development of technologies to collect image-based information from aerial platforms including aircraft, satellites and drones. This information can be used for various commercial, military and humanitarian purposes.

The collected information can be in the form of conventional photographs, or may use other parts of the electromagnetic spectrum like hyperspectral images (such as infrared or ultraviolet) or LIDAR (Light Detection and Ranging using pulsed laser light).

Satellite-based remote sensing has traditionally been very expensive and restricted to government uses. Current satellite imagery comes with challenges like relatively low image resolution and visibility that is dependent on cloud cover.

However, some organizations are developing lower cost satellites and improved sensing options. For example, Planet Labs lowered the cost of satellite imagery by building mini-satellites with off-the-shelf sensors and inexpensive smartphone components. Small satellites were launched at a development cost of $7,000. The company's current fleet of 200 satellites captures around 1.4 million images of the Earth per day, covering an expansive (though not universal) area at a resolution of three to five meters (Planet Labs, 2018). Governments and private companies can now access the data for various uses, such as monitoring the health of crops and creating risk models for flood zones.

Drones, also known as unmanned aerial vehicles (UAVs), are related to earlier radio-controlled airplanes used by hobbyists. Drones, however, have many technological advancements that have made it possible to fly them from very large distances. Pilots can fly drones without having direct visual access to the full flight path thanks to the ability of drones to acquire GPS signals. Furthermore, sophisticated algorithms enable semi-autonomous control of drones with limited need for real-time input from human pilots.

Statistics on drone sales and usage are sparse, confounded by varying definitions of what constitutes a drone across a range of products from toys to professional instruments.

The Economist (2017) estimated that about 200,000 commercial drones were in use in 2017, and about 3 million personal drones. equipment such as diggers and loaders, are controlled by people not computers. Simple automation, such as dedicated tools on an assembly line, can perform a single task excellently but can do nothing else.

Traditionally used for military operations, applications of drones in the commercial sector is growing. The United States has been a strong growth driver. The country's value of investments in UAV sector grew from $40 million in 2012 to $1 billion in 2017 (McKinsey, 2017).

It is forecast that commercial applications of drones will increase the United States' GDP by $46 billion by 2026. It is unclear if low-income countries will invest as heavily in UAV technology as the United States, but there is potential for applications that could benefit people in emerging economies.

The purchase price of drones has significantly decreased over the past several years. Basic drones with low-resolution cameras are available in the market for as low as $99 and drones with features like GIS and high-resolution imagery capabilities are available from $600 (Nixon, 2018).

Ready to fly UAVs, which can be used for monitoring health crop, checking on livestock and land surveillance, are now available from $12,000.
It is expected that this cost will significantly drop as more investors allocate resources towards technological innovations to improve the components.

KEY CHALLENGES

There are several challenges to large-scale applications of remote sensing technologies to benefit the underserved. Many countries have strict regulations regarding use of airspace by UAVs. Governments should take responsibility for developing guidelines for appropriate use of UAV technologies to address violation of privacy, unauthorized access and public nuisance and safety concerns. As use of drones increases further, large-scale investments will be needed to develop systems that can manage such air traffic.

Furthermore, existing drone technologies have limited flight endurance and payload capacities. To achieve impact at scale, these capabilities need to be developed further, while keeping the costs affordable to users.

There are also physical limitations to the sensing abilities of drones and satellites. For example, satellites can only provide overhead images, which can be blocked by buildings or trees.

Importantly, remote sensing information is often necessary, but not sufficient, to stop undesired actions from occurring. The knowledge obtained by remote platforms must be complemented by robust on-the-ground presence to actually thwart activities like illegal logging and fishing.

An additional challenge is the use of such technologies by governments and other entities for warfare and terrorism. For example, military drones, also known as unmanned combat aerial vehicles, such as the Predator and Reaper drones operated by the US armed forces, have become integral to modern warfare. Furthermore, explosives-laden drones were used in a recent assassination attempt in Venezuela, charting new territory for asymmetric warfare (BBC, 2018).

BREAKTHROUGH APPLICATIONS

There are several promising application areas for remote sensing and drones to impact SDGs. While recognizing the major privacy concerns raised by the proliferation of consumer satellites and drones, the technologies will be valuable in improving transparency and documentation as part of the broader IoT paradigm.

In agriculture, drones or satellites are able to accurately measure plot-level farm yields and communicate with sensors for better agricultural decision making. For example, sensors could communicate data like soil moisture levels to better understand on-farm processes that affect crop production.

Multispectral images that extend beyond the visible wavelengths (about 400 to 700 nanometers) can distinguish between healthy crops that are actively photosynthesizing and those that are stressed due to biotic or water constraints, before such differences can be detected by conventional visual inspection.

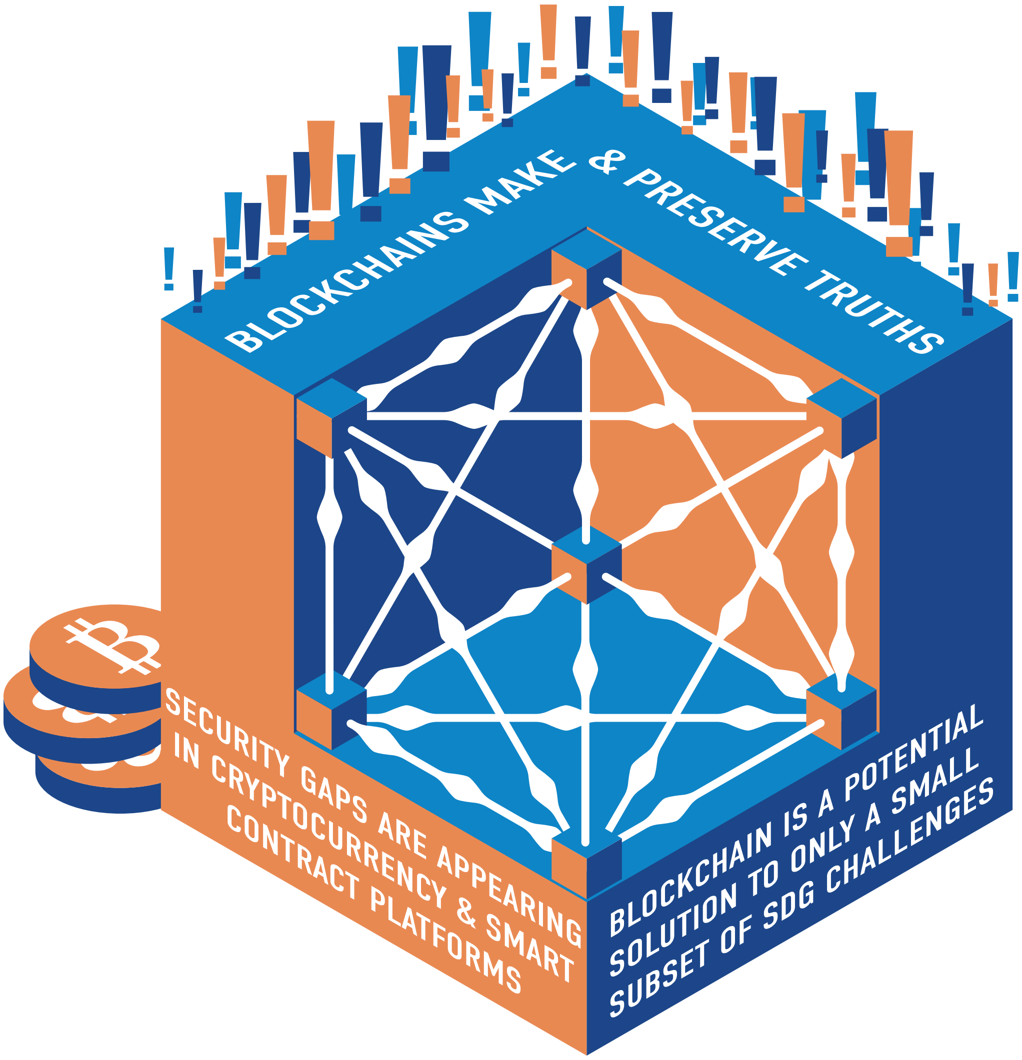
Remote-sensed images have been identified as being very useful for documenting humanitarian crises and environmental degradation (see the Human Rights chapter). Drones or satellites can be deployed to monitor violation of human rights, and communicate information to authorities for timely action to be taken. However, such knowledge is only effective if accompanied by the political will and on-the-ground presence needed to thwart the violations.

Drones can be effective in hard to reach areas and to reduce the risk of corruption by local authorities. Aerial surveys are often cheaper, faster and more effective than ground surveys.

For example, using satellite imagery of a rural area of western Kenya, researchers were able to estimate household level wealth with 62 percent accuracy, based on visible indicators such as the size of buildings within a family compound and the amount of bare land within and surrounding a homestead (Watmough, et al., 2018).

Drones can be used to improve manufacturing and infrastructure development. Builders can use low cost drones to monitor safety, document and capture site progress and to identify issues before they become hazards. UAVs/Drones can also be deployed to effectively monitor compliance at mining sites.

In the healthcare sector, drones can potentially be used to deliver small amounts of vaccines, blood or other time-sensitive supplies to health facilities in remote locations. The global leader in this space is Zipline, currently using drones for medical deliveries in Rwanda and Ghana (Zipline, 2019). Payloads are limited to small, high-value items, and drones are not expected to replace conventional supply chains of medical supplies.



BLOCKCHAIN AND DISTRIBUTED LEDGERS

Blockchain and distributed ledgers have received much attention in recent years, but realistic analysis suggests that the technologies are unlikely to contribute significantly to realizing the SDGs. While potentially useful for some lucrative applications, they are unsuitable for many social impact applications and run the risk of bad data input locking in "garbage in, garbage out" problems. Blockchain and distributed ledgers may play a minor role in improving human rights, gender equity and digital inclusion, if appropriate platforms are developed and widely used. Two potentially useful application of blockchain technologies are in establishing digital identification systems, and reducing fees on remittance transfers sent by migrants to relatives in their home countries. Overall, the impact of blockchain and distributed ledgers on the SDGs will be minimal.

CORE FACTS AND ANALYSIS

Blockchain has gained popular attention recently because of its role in Bitcoin, the cryptocurrency that briefly commanded a price of more than $19,000 in late 2017 (**Exhibit 8**). Bitcoin was devised in 2008 by pseudonymous Satoshi Nakamoto and is the first decentralized, peer-to-peer cryptocurrency to gain traction (Nakamoto, 2008). Blockchain is the underlying technology supporting Bitcoin, providing the digital ledgers that record all transactions taking place.

Such distributed ledgers offer a way for people who do not know or trust each other to create a record of events that will compel the assent of everyone concerned. Blockchains are thus "a way of making and preserving truths" (The Economist, 2015) with potential applications in various sectors, particularly where there is an absence of a trusted data repository.

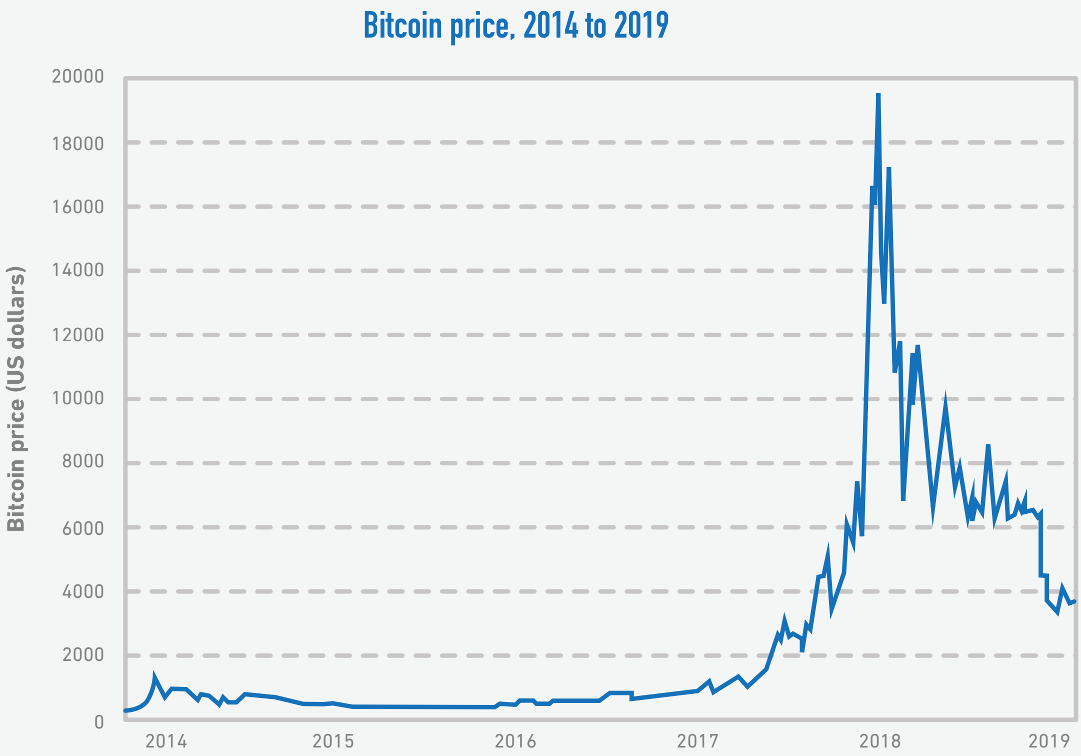


Exhibit 8: The Bitcoin cryptocurrency was introduced in 2008, but had very little exchange value until 2017. It reached a peak price of more than $19,000 in December 2017. (Source: Coindesk, 2019)

Blockchains are a type of database that sequentially records transactions among users within a decentralized peer-to-peer network. Cryptographic tools are used with blockchain technology. All nodes and users must use public key cryptography to be part of the network and interact with each other.

A blockchain is a ledger that records all transactions taking place on its network. Every network node stores a current copy of the data, and updates are automatically transferred among all nodes. A key innovation of blockchain technologies is the interlinking of records. Each block of transactions has a unique identifier that is mathematically linked to the previous block.

Changing or deleting blocks in the database is nearly impossible, as it would require changing all records in the chain. Adding new blocks of data requires consensus among all nodes of the network. This is achieved with a proof-of-work algorithm which nodes must run. The outcome of proof-of-work is shared among network nodes that can then validate the result, and the block is then added to the existing blockchain.

KEY CHALLENGES

Low-income countries face numerous challenges when implementing blockchain technology. IDRC (2017) analyzed the potential impact of blockchain technology on human development, considering infrastructure, capacity development, policy and regulation and institutions and governance.

Globally, about four billion people do not have access to the internet. Most of these people live in low-income countries, and are unlikely to benefit from blockchain technology as end users.

Nevertheless, end users do not need to directly use the technology to benefit from it, if indirect access to cryptographic tools is made available through community-based organizations, small enterprises or local governments.

However, the policies and procedures needed to secure the electronic transfer of information is not yet in place in many low-income countries, making it more challenging to use cryptographic tools.

Proof-of-work computations are energy intensive- the digital mining of cryptocurrencies such as Bitcoin, Ethereum, Litecoin and Monero consumes more energy than the physical mining of copper, gold or platinum metals, to produce the same value of product (Krause & Tolaymat, 2018).

While blockchains were once considered fully protected from malicious hacking, security gaps are appearing in cryptocurrency and smart contract platforms. For example, "51 percent attacks" have been used against some cryptocurrency exchanges including Verge, Monacoin, Bitcoin Gold, Vertcoin and Ethereum Classic (Orcutt, 2019). Such attacks are made by gaining control of a majority of the network's mining power, and creating alternative versions of the blockchain in which the same cryptocurrency can be spent multiple times.

The complex infrastructure requirements (bandwidth, connectivity and high operating costs) of blockchain technology will likely prove challenging for low-income countries (IDRC, 2017).

Best practice for low-income countries is to use blockchain technology to complement or supplement ongoing programs, rather than replacing existing initiatives or initiating new ones on standalone blockchain platforms. Entry barriers would be lower, and the sustainability of initial investments in blockchain technologies would be improved.

Furthermore, blockchain has an inherent scalability challenge due to the tendency toward centralization with a growing blockchain. As the blockchain grows larger, the requirements also become larger for storage, bandwidth and computational power spent by nodes in the network. This leads to a risk of centralization, if the blockchain becomes so large that only a few nodes are able to process a block (James-Lubin, 2015).

BREAKTHROUGH APPLICATIONS

Enthusiasts have proposed numerous potential applications of blockchain. Closer analysis suggests that blockchain is a potential solution to only a small subset of human development challenges, and not a universal solution as some proponents argue.

A potentially useful public sector application of blockchain is digital identification (ID) systems. The leader in this field is ID2020, a public-private partnership committed to improving lives through digital identity (ID2020, 2019). Led by Accenture and Microsoft, ID2020 seeks to harness the power of blockchain to provide digital identity for the displaced. ID2020 works on a model in which it brings together development organizations, private sector companies, governments and NGOs around a pooled fund, used to implement high-impact digital identity programs.

Private sector applications include services such as validation of finance and logistics commitments. Another proposed application is smart contracts, which execute themselves automatically under the right circumstances. Smart contracts are computer protocols intended to digitally facilitate, verify or enforce the negotiation or performance of agreements.

Blockchain technologies also offer several advantages for identity services, such as decentralization and immutability. However, the technologies also face several challenges, including security issues such as lack of key management, and a lack of established standards (Cooper, 2016).

To date, blockchain technologies have been used mostly in the fields of finance and logistics. Specific to human development, they have the potential to reduce fees on remittance transfers. Globally in 2016, migrants sent an estimated $574 billion in remittances to relatives in their home countries (PRC, 2018).

SDG 10 includes the goal of limiting remittance cost to three percent of the amount sent, which appears feasible using a cryptocurrency-based transfer mechanism. The global average cost of transacting remittances is almost seven percent, and is higher in Africa than in any other region (World Bank, 2018). Using traditional banks entails higher costs, averaging 10.5 percent.

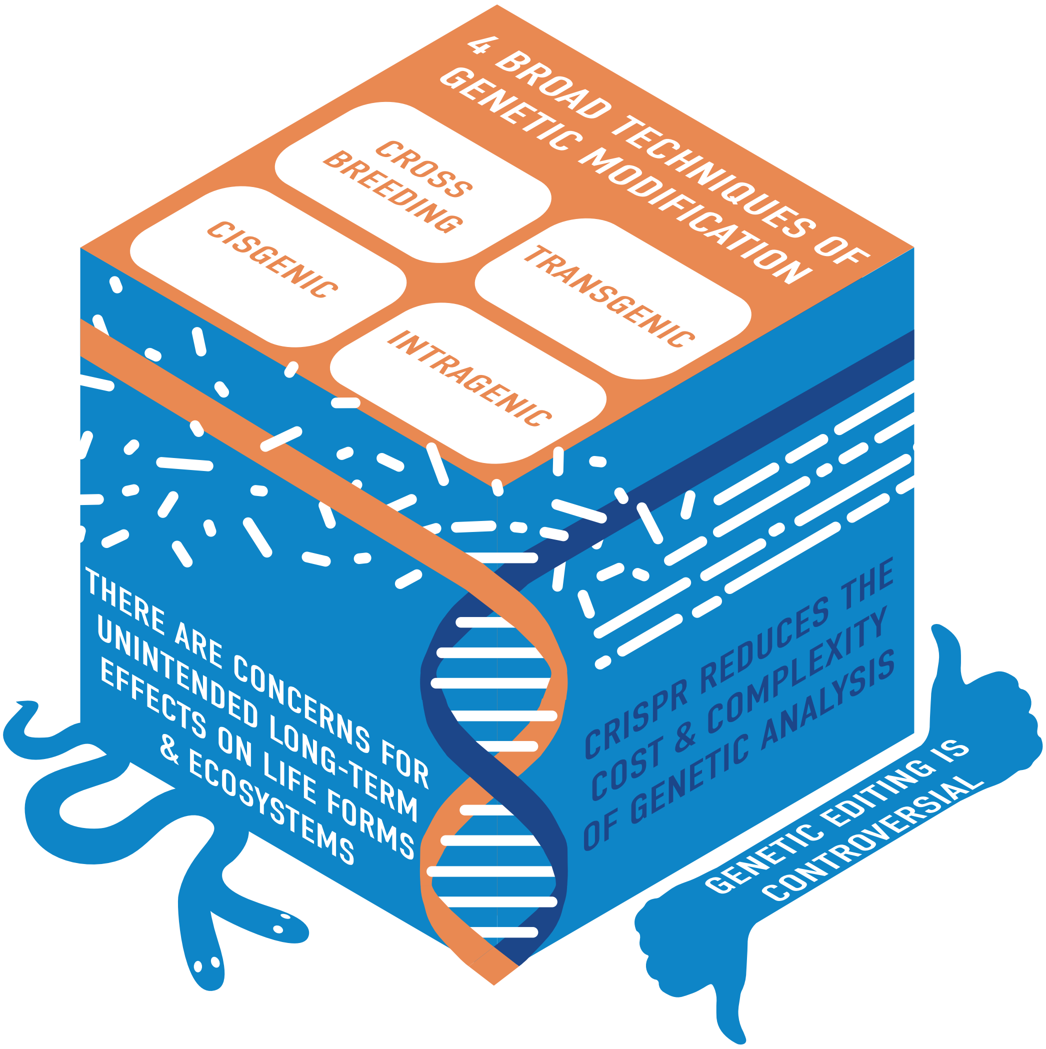
Blockchains are very effective at maintaining immutable records of events, once the information is entered into the ledger. However, they are incapable of distinguishing the veracity of the entered data. Many human development challenges play out in extremely remote and harsh locations, where the precise binary control of blockchain has little influence.

For example, blockchain has been proposed to ensure the logistical control of humanitarian aid distributions (Galen, et al., 2018). While blockchain may be initially effective as aid supplies move through major port, rail and road infrastructure with reputable management, blockchain's control of on-the-ground processes becomes more tenuous as the environment turns more chaotic.

Effective chain of custody of humanitarian commodities ultimately requires documentation of the final handover to needy beneficiaries, which often occurs in difficult conditions of weather and insecurity. While digital documentation may be entered into a blockchain, there is no guarantee that the aid has actually traveled the last mile into beneficiaries' hands, due to numerous actors such as corrupt authorities and warlords with opportunities to divert the commodities.

Similarly, blockchain technology has been proposed to control and validate electoral processes (Galen, et al., 2018). While a blockchain may ensure against fraud occurring after voter data has been entered into the database, it will have no influence on the many social, economic and cultural sources of electoral fraud that may affect the quality of the data that is entered into the chain.

Blockchain has also been proposed as a mechanism to ensure the transparency and veracity of land title transactions. Such a mechanism would require the active cooperation of government land registration agencies, however, who are themselves a major cause of land title irregularities. Thus, blockchain could not be imposed from outside to reduce land fraud, but would need to be embraced by the authorities. However, if authorities were truly interested in reducing fraud, a host of simpler methods would suffice.



GENETIC EDITING AND CRISPR

Genetic editing and CRISPR techniques have potential to make substantial long-term contributions to global development, but will have minimal impact on the 2030 SDGs due to limited physical scaleup. Once deployed at scale, the technologies can significantly improve food security by creating crop and animal varieties with increased resilience to emerging environmental stresses including heat, drought and salinity. They may also improve global health outcomes by expanding research capabilities on genetic disorders, directly modifying human genomes to avoid diseases, and reducing environmental threats such as disease vectors. Nevertheless, genetic editing brings health and environmental risks due to unintended consequences of altering complex systems, and the risk of increasingly asymmetric economic relationships between seed producers and poor farmers. Overall, slow deployment will limit its impact on SDGs by 2030, but longer-term impacts of genetic editing and CRISPR can be considerable.

CORE FACTS AND ANALYSIS

There is substantial controversy over genetic editing (GE) and its role in human development efforts (Freedman, 2013; Doudna & Sternberg, 2017; Kuzma, 2018). Each year, new articles are published in support of GE, and seemingly just as many opposing their use.

Some meta-analyses have found GE in agriculture to be largely beneficial to farmers (Klümper & Qaim, 2014), while others have found evidence to the contrary (Fagen, et al., 2014). These controversies have not prevented GE from becoming a part of the mainstream food systems in industrialized countries like the United States (which accounts for more than 40 percent of land area growing GE crops worldwide).

In Asia, India, China and Pakistan are major producers of GE cotton. In Africa, the only countries where GE crops are grown commercially are South Africa, Egypt, Burkina Faso and Sudan (CRS, 2018).

Recent advances in genome editing technology have created powerful new tools that expand the ability of humans to alter genes. New genome editing techniques are capable of precisely and site-specifically (rather than randomly) add, modify or delete genes from plant and animal genomes.

These gene editing methods include clustered regularly interspersed short palindromic repeats (CRISPR), zinc-finger nucleases (ZFNs) and transcription activator-like effector nucleases (TALENs) systems.

The CRISPR/Cas9 system, in particular, is proving to have many potentially beneficial uses, such as increasing crop yield, improving drought tolerance, increasing growth in nutrient-limited conditions and breeding crops with improved nutritional properties (Barrangou & Doudna, 2016).

Historically, gene editing mechanisms have only been available to advanced labs, focusing in issues affecting higher-income populations. By reducing the cost and complexity of genetic analysis and manipulation, CRISPR can significantly increase the number of topics being researched, as well as the number of scientists conducting the research.

As such, it could be truly transformative in the agriculture and health sectors, especially in the long run. In the 2030 timeline, however, it is unclear how much of that potential will be realized.

An important constraint in the pace of GE applications is the polygenetic nature of many of the traits we would like to breed into plants and animal, which are determined by many different genes in ways that are not yet well understood.

Broadly, there are four techniques used for genetic modification:

Conventional cross-breeding: Seed genetics have been modified through cross-breeding since the earliest days of agriculture. After harvesting a crop, farmers would save and sow the seeds from plants with desired characteristics, and use the rest as food.

Gregor Mendel, the father of modern genetics, formalized this technique in the mid-1800s. In this approach, the primary cultivar is bred with another variety of the same crop (a relative), but one that has some desirable traits. The first generation of the breeding will likely result in a new variety with some undesirable traits from the relative, as well as a loss of some desirable traits from the primary cultivar.

The first-generation variety is then bred with the primary cultivar to produce a variety that is closer to the target variety. This process of breeding each new variety with the original cultivar, is continued until the target variety is achieved. This type of conventional breeding was used to develop the seed varieties that launched the Green Revolution, and is currently used in a broad range of contexts to strengthen seeds. It is uncontroversial.

However, the main disadvantage of this process is that the improvements are limited to the best traits among the varieties of the same family of crops; if no known variety of the crop has the desired trait, it will not be possible to incorporate that trait into the crop. The process is also very slow, taking many years to develop an improved seed variety.

Transgenic modification: The phrase 'genetically modified organism" (GMO), in common parlance, typically refers to transgenic modification. Introduced in the 1990s, this process involves the insertion of genetic material from unrelated organisms—which cannot be crossed by natural means—into the genes of target crops.

One well-known example of transgenic modification in the low-income country context is Bt-Cotton, developed for use in India and China to combat bollworms, a particularly destructive pest. In this process, a portion of the gene of the *Bacillus thuringiensis* (Bt) bacterium is inserted into the gene of locally grown cotton.

The results in countries like India and China appear to be mixed, compared with results from similar enhancements in industrialized markets. In China, for example, cultivation of Bt-enhanced cotton appears to have led to a resurgence of secondary pests (Wang, et al., 2008), largely eroding initial benefits from the enhanced seeds. In Kenya, trials of Bt-enhanced maize have shown diminishing economic returns for smallholder farmers after the third year of planting enhanced seeds (Gouse, et al., 2006).

These studies highlight the main concerns about transgenic modification. First, unforeseen disruptions of the ecological system, especially from second-order and third-order changes that are not immediately perceptible, and occur only over time. Second, economic losses for the farmers beyond any initial gains that they may achieve. As a result, GMOs are facing considerable policy hurdles, with the majority of African countries placing significant controls or outright bans.

Cisgenic modification: Cisgenic modification involves the alteration of genetic material from organisms of the same broader species (a relative). CRISPR is the most widely discussed example of cisgenic modification. In this system, the Cas9 nuclease is complexed with a synthetic guide RNA and is delivered into a cell. It then cuts the cell's genome at a desired location, allowing existing genes to be removed and/or new genes to be added. Many consider cisgenesis to be less controversial than transgenic modification, because the edited organisms could, in principle, have been created through conventional breeding, while offering the benefit of rapid and targeted improvements (Holme, et al., 2013; Singh, et al., 2015; Moradpour & Abdullah, 2017).

For this reason, both regulatory procedures (Sprink, et al., 2016) and consumer acceptance (Delwaide, et al., 2015) may prove to be less challenging for cisgenic editing than for transgenic modification. The United States authorities have considered the risks of cisgenesis to be similar to those of conventional breeding, rather than of transgenesis (USDA, 2018). However, the European Court of Justice ruled in 2018 that all forms of mutagenesis, including those conducted using CRISPR and related methods, would be subject to the requirements made for transgenic GMOs (European Court, 2018)

Intragenic modification: Intragenesis involves in vitro rearrangement of the genetic structure of the cultivar. While this technique also restricts modifications to the same gene pool available for conventional breeding, a European Food Safety Authority study found that the risks associated are similar to those with transgenesis (EFSA, 2012). However, other studies suggest that the public as well as regulatory agencies will view intragenesis more like cross-breeding than transgenesis (Holme, et al., 2013).

KEY CHALLENGES

There are some serious concerns about the role of GE crops in low-income countries. An important concern is the economic burden that is placed on low-income farmers who may come to depend on expensive GE seeds, which have to be purchased annually.

Other concerns, which are equally relevant for industrialized countries, include the potential impacts on neighboring farmers whose non-GE crops are accidentally cross-pollinated with GE seeds used in the vicinity, and unintended long-term effects on different life forms in the ecosystem, even if the seeds are used as intended.

Furthermore, the opportunity cost of investing development funds in creation of one-off GE products will be substantial, compared to more systemic investments in strengthening agricultural ecosystems.

In industrialized countries, all other the avenues for increasing yields had already been exploited before market pressures led to the demand for additional measures like GE. In low-income regions of the world, there are still many lower risk mechanisms that can be implemented to increase yields, such as irrigation, fertilization, pest management, and adoption of conventionally-bred improved seeds.

The yield gains of the Green Revolution in Asia and Latin America were achieved without GE (although, in hindsight, a number of the practices were very damaging to the environment). With the benefit of this hindsight, it should be possible to improve yields in sub-Saharan Africa (as well as the parts of South Asia not impacted by the Green Revolution) through more sustainable intensification without relying on GE.

We believe that in most cases, smallholder agriculture will benefit much more from foundational and systemic improvements, such as access to irrigation, on-farm implements, extension services, electricity and local processing facilities rather than using GE.

A further concern regarding the use of genetically edited seeds is the asymmetric economic relationship between the producers and planters of the seeds. Genetically modified organisms have typically been produced and marketed by large multi-national corporations, driven by shareholder priorities.

Past experience shows a lack of transparency, oversight, and openness to concerns of citizens The global seed industry is undergoing consolidation, and four firms are now estimated to control over 60 percent of global proprietary seed sales (Howard, 2018).

If genetic editing is to be used effectively for agricultural development, structures should be put in place to ensure that improved seeds are accessible to all farmers in need to avoid further widening of social inequalities.

BREAKTHROUGH APPLICATIONS

GE will likely have the greatest impact in the fields of health and agriculture. In health, there is potential for GE technology to reduce or eliminate populations of mosquitos that spread malaria, either via gene drives that directly affect the fertility of mosquitos (Kyrou, et al., 2018), or via a genetically-modified fungus that delivers toxins to the mosquitos (Lovett, et al., 2019).

CRISPR may also play a role in eliminating flaviviruses, such as yellow fever, West Nile, dengue and Zika viruses (Richardson, et al., 2018). It may also be adapted to study which genes are targeted by particular antibiotics, providing important information to develop new drugs or improve existing ones (Peters, et al., 2019).

In agriculture, there are numerous potential roles for GE in enhancing food security in low-income countries. Improving tolerance to environmental stressors is likely to be an important focus of GE work in the coming decades.

Successful GE techniques could enable the development of novel crop varieties with enhanced tolerance to heat, drought and salinity, allowing continued expansion of agricultural production despite growing environmental challenges. It will be difficult for conventional plant breeding techniques to develop crop varieties to accommodate such rapid changes during the coming decades, such as droughts attributed to climate change, salinization of farmland and groundwater and basin-level limits to water supply.

CRISPR/Cas9 techniques have successfully been used to create variants of maize that have higher grain yield under water stress conditions and have no yield loss under well-watered conditions, compared to conventional maize types (Shi, et al., 2016).

Varieties with tolerance to salinity are also expected. Researchers expect recent sequencing of the wheat genome to help develop wheat varieties resilient to emerging environmental challenges (IWGSC, 2018).

Nevertheless, as discussed in the Water Security chapter, most of sub-Saharan Africa is facing economic water scarcity rather than physical scarcity, and there appears to be sufficient shallow renewable groundwater that can be accessed for irrigation in the region. In such areas, we believe there are many more benefits to be gained from sustainable solutions to irrigation and nutrient management, rather than the introduction of GE crops.

This is particularly true considering that irrigation solutions will impact multiple crops, whereas GE varieties will likely be available only for a small number of crops. In addition, irrigation solutions will help the cultivation of high-nutrient crops like vegetables, which can also lead to higher farmer incomes. It is important to note that providing access to irrigation has proven very difficult, though the expansion of electricity supply and affordable pumps will likely lead to increased use of irrigation.

That said, in parts of the world (for example, South Asia) that are now facing long-term water shortages associated with demographic and economic growth, GE may be needed to maintain high yields if improvements are not possible through other means. CRISPR and other GE technologies could potentially enable crops to use water more efficiently, producing more biomass per unit of water transpired, to increase total agricultural production in regions facing hard limits to basin-level water supply, including depleting groundwater and river basin closure.

Furthermore, an important share of global agricultural production does not use irrigation, and instead depends on rainfall for its water needs. While expanding the use of irrigation is possible in some areas, irrigation is constrained in many regions by lack of water sources or excessive economic costs. By using GE technology to make better use of the rainwater that falls on dryland farms, farmers could increase total agricultural production without the need to harness additional water sources.

Another application of GE in agriculture is enabling tolerance to specific herbicides or pests. One of the documented risks with modifications of seeds against particular pests is the possibility of unintended second-order consequences, such as the proliferation of secondary pests when the seed is modified to deter primary pests (Rodenburg & Demont, 2009).

If such modifications are deployed without a full understanding of their effect on the various forms of life in the ecosystem, the results could severely damage the environment. The rich and complex ecosystems in tropical countries make it extremely difficult to analyze all the direct, second-order and subsequent impacts with sufficient rigor.

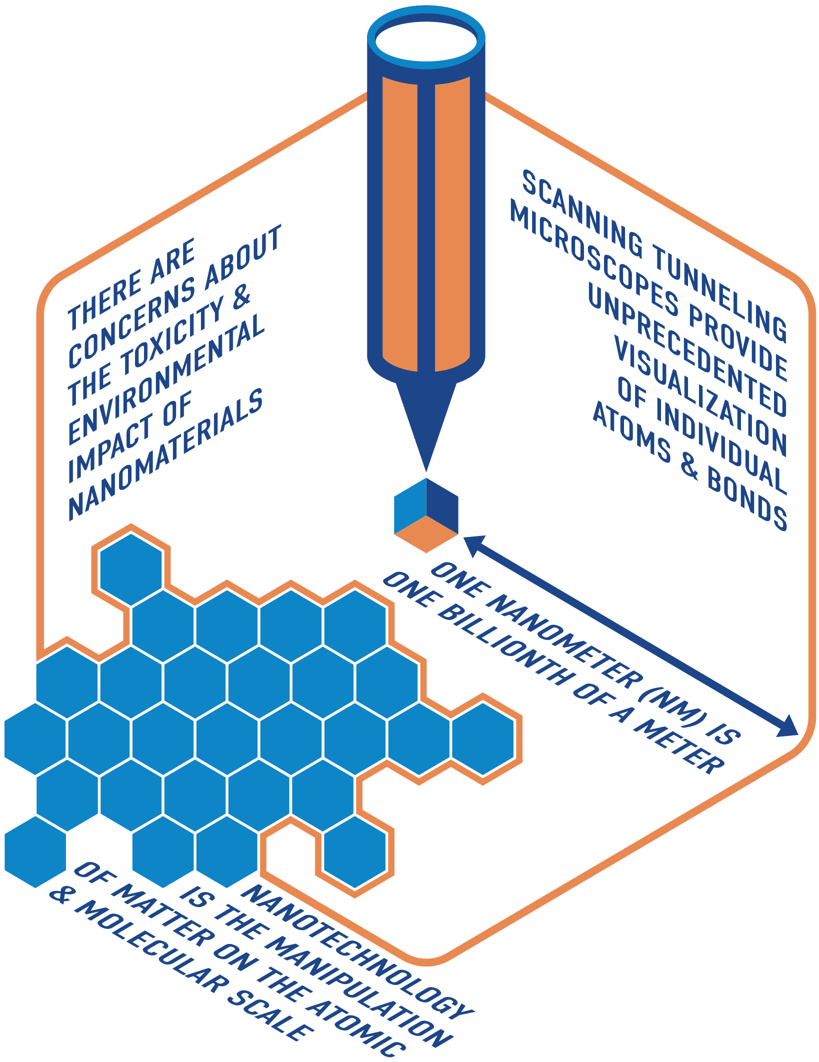
Another application is the fortification of crops with nutrients. For example, vitamin A is one of the key micronutrients missing from the diets of many millions of low-income individuals in South/Southeast Asia, sub-Saharan Africa and Latin America.

Transgenically enhanced golden rice offers the possibility of addressing that deficiency without the need for food sources that naturally contain vitamin A, such as carrots and green vegetables (IRRI, 2018). The problem, however, is that there are several other nutrients which these populations also lack, such as iron, iodine, zinc and folic acid.

Without also providing these micronutrients, the broader problem of malnutrition will not be addressed. Currently, it is unlikely that cereal crops can be implanted with more than a single nutrient through genetic modification.

Given that it has taken almost 30 years and tens of millions of dollars (Dawe & Unnevehr, 2007) to achieve progress on a single nutrient, with still many lingering doubts about whether it will be accepted by governments, farmers and consumers, we do not believe the opportunity cost of GE nutrient fortification is justified.

Broad-based interventions aimed at improving access to multiple nutrients (like improving access to irrigation so that nutrient-rich vegetables can be grown year-round, or providing food supplements that are consistent with existing dietary practices) are likely to have greater impact on the nutritional wellbeing of populations.



NANOTECHNOLOGY AND NANOMATERIALS

Nanotechnology and nanomaterials have the potential to make important contributions to human development efforts in several sectors. Nanomaterials can improve water security, by removing diverse contaminants such as salt and arsenic from polluted water. They are also contributing to increased access to energy, through their use in photovoltaic collection and electrochemical storage of electricity. They also have diverse emerging applications in global health and resilience to global change. However, concerns have been expressed about potential toxicity of some nanomaterials to humans and ecosystems, which may present greater risks as the scale-up extent grows. Overall, early generations of nanomaterials are already being used in the water and energy sectors, and making limited contributions to 2030 SDGs. Rapid advances in nanotechnology suggests that new generations of materials will make larger contributions in the longer term.

CORE FACTS AND ANALYSIS

Nanotechnology is the manipulation of matter on the atomic or molecular scale. A commonly used definition of nanotechnology is the manipulation of matter with at least one dimension sized from 1 to 100 nanometers (**Exhibit 9**).

One nanometer (nm) is one billionth, or 10^{-9}, of a meter. At this scale, quantum mechanical effects are important and result in novel material properties.

Examples of recently developed nanomaterials include graphene, fullerene, carbon nanotubes, thin films and metal-organic frameworks (MOFs). Nanomaterials can be designed and manufactured for specific properties, such as strength, adsorption, conductivity and transparency, among others.

Nanotechnology is a very broad field and encompasses such disciplines as organic chemistry, molecular biology, semiconductor physics, surface science, microfabrication, molecular engineering and others.

The possibility of synthesis via direct manipulation of atoms was first described in detail by the physicist Richard Feynman (1960). The concepted were further popularized by Eric Drexel in his book Nanosystems: Molecular Machinery, Manufacturing and Computation (Drexel, 1992).

The 2016 Nobel Prize in Chemistry was awarded to Sauvage, Stoddart and Feringa for their work on molecular machines, which are molecules with controllable movements, and a major step towards nanofabrication (Nobel Prize, 2016).

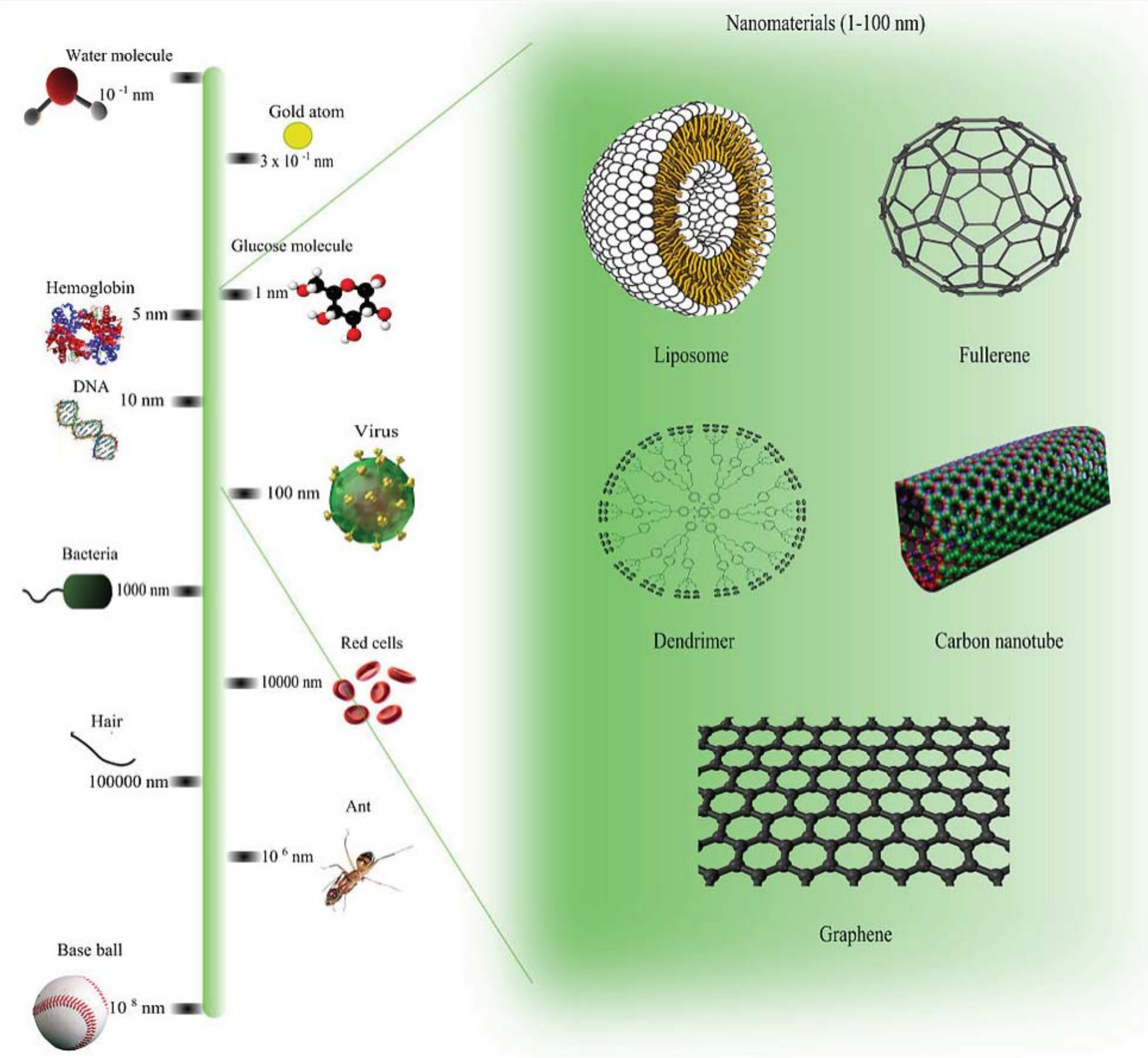


Exhibit 9: Nanomaterials are commonly defined as having at least one dimension sized from 1 to 100 nanometers. (Source: Wikimedia, 2018)

Accompanying these theoretical advances, the tools needed to conduct nanotechnology have become increasingly sophisticated and capable.

An important practical step was the invention of the scanning tunneling microscope in 1981, which provides unprecedented visualization of individual atoms and bonds.

A range of thin film deposition techniques have also been developed to create very thin layers of specific materials, which is useful in a range of applications including photovoltaic cells and electrochemical batteries.

One important thin film type is physical vapor deposition (PVD) methods such as evaporation, sputtering, laser ablation and arc-based emission (Rossnagel, 2003).

Another type is chemical vapor deposition (CVD) methods, such as thermal, plasma enhanced CVD, combustion CVD and atomic layer deposition (Hampden-Smith & Kodas, 1995).

A third important type is solution-based methods, such as spin coating, inkjet printing, spray pyrolysis, and gravure printing (Pasquarelli, et al., 2011).

KEY CHALLENGES

Recent advances in nanotechnology have raised a number of concerns, including potential issues about the toxicity and environmental impact of nanomaterials. Adverse effects of nanomaterials on human health depend on nanoparticle chemistry, size, shape, agglomeration state and electromagnetic properties, as well as exposure and individual factors such as genetics and existing diseases (Buzea, et al., 2007).

The introduction of nanomaterials such as silver and iron oxide into foods and food packaging has raised concerns among some researchers and regulators, though there is still substantial uncertainty regarding their risks (Bumbudsanpharoke & Ko, 2015; McClements & Xiao, 2017).

Also, while some nanotechnology applications are already established in the market, such as thin film photovoltaic collectors, it is unclear when other advances may become market ready.

While there are many potential applications for nanomaterials, for example in the water sector, it remains to be seen whether such products will become readily available and affordable, and whether laboratory advances will see widespread application within the SDG time frame of 2030 or beyond.

BREAKTHROUGH APPLICATIONS

Successful nanotechnology offers the ability to create many new materials and devices with a vast range of applications, such as in medicine, electronics, energy production and consumer products.

For example, there is potential for nanotechnology to provide new methods of combating cancer and other diseases (Bayford, et al., 2017).

Agriculture and food security may also be enhanced through the use of nanotechnology (Ditta, et al., 2012). Nanomaterials have potential to advance renewable energy technologies, for example photovoltaic collectors and electrochemical storage batteries (Hu, et al., 2015).

There is also potential for nanomaterials to enhance water security (Alvarez, et al., 2018), for example to remove arsenic from water (Wong, et al., 2017).

Graphene, for example, may play important roles in filtration and desalination of non-potable water (Aghigh, et al., 2015). By controlling properties such as material size, morphology and chemical structure, nanomaterials may be created with useful adsorptive, catalytic and optical properties that can facilitate water decontamination (Mauter, et al., 2018).

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