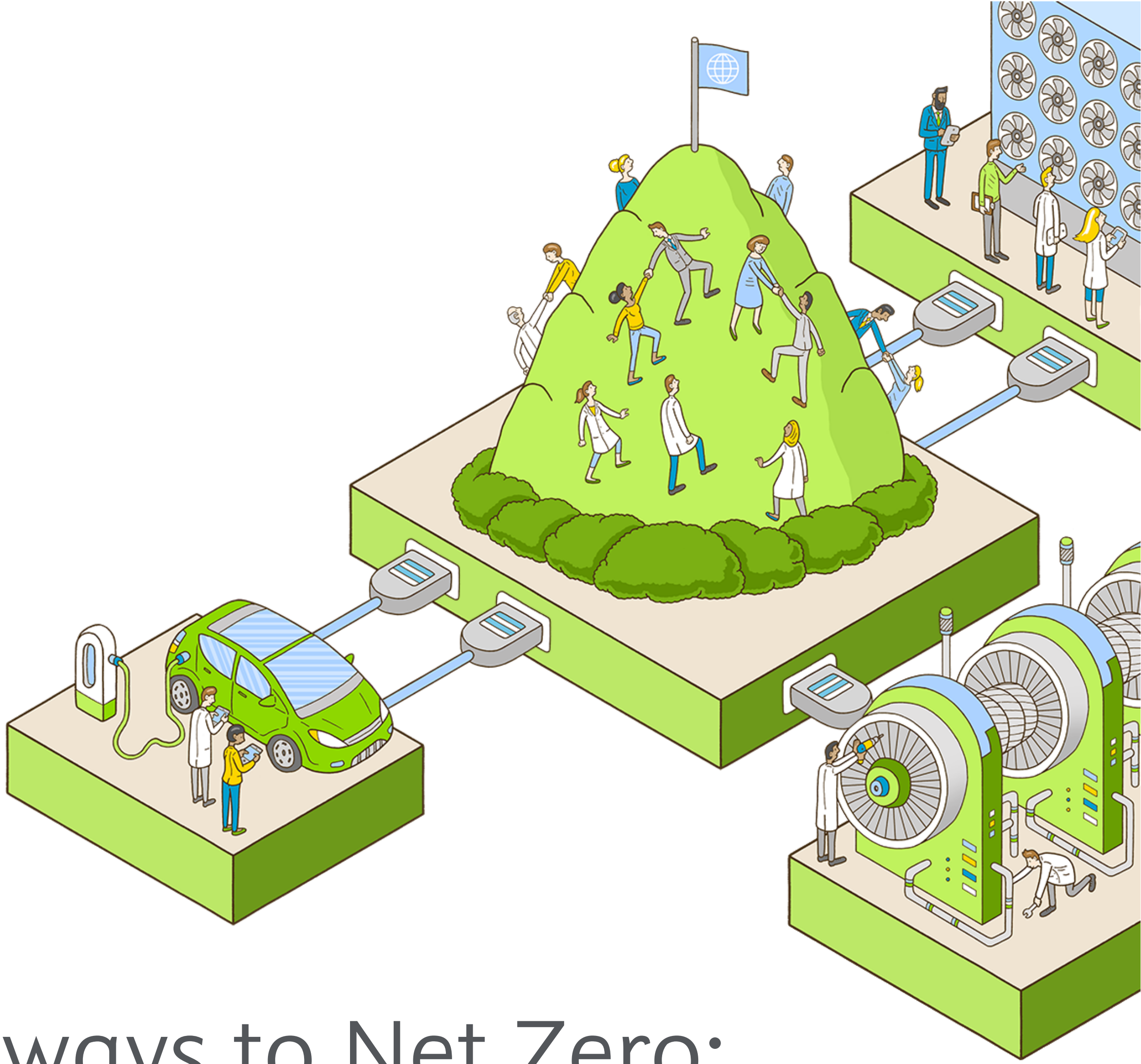


Pathways to Net Zero: The Impact of Clean Energy Research

Analytical Services

Executive summary

Achieving net zero greenhouse gas emissions by 2050 will require the rapid development and deployment of clean energy technologies. Research is essential to the success of this clean energy transition. This report examines the state of play in clean energy research over the last 20 years and provides expert insights into potential pathways forward.

The world is facing an unprecedented threat. Rising greenhouse gas (GHG) emissions from burning fossil fuels and deforestation are leading to global heating that is destabilizing the climate, putting lives, livelihoods and entire ecosystems at risk.[1] The landmark 2015 Paris Agreement[2] aims to avoid the most devastating effects of climate change and limit global temperature rise to no more than 2°C above pre-industrial levels. To achieve this goal, countries are aiming to reach *net zero* emissions by mid-century—a point representing the balance between unavoidable GHG emissions and their removal from the atmosphere, through reforestation or carbon capture and storage technologies. According to the International Energy Agency (IEA),[3] developing and deploying clean energy technologies is critical to achieving net zero by the agreed deadline of 2050. The IEA has stated that "as the major source of global emissions, the energy sector holds the key to responding to the world's climate challenge."[4] In practical terms, achieving net zero globally will require a two-pronged approach: curbing human-produced emissions and removing carbon from the atmosphere.

Many countries have already committed to reach some form of net zero by 2050, and as the world comes to terms with the effects of COVID-19, society's understanding of and response to the looming climate crisis will gain pace.

The development and deployment of clean energy entails far more than just technological advancement. The scope of the relevant research is enormous, encompassing solar, wind, bioenergy and other clean energy sources, the economics of electric power systems, infrastructure, energy storage, batteries for electric vehicles, smart home technologies, data security and privacy, to name but a few. All of these elements are critical to ensuring that clean energy plays its required role. In addition, a successful transition to net zero will require the engagement of corporates, governmental policies and intergovernmental agreements, and buy-in from the public.

This evidence-based report presents an analysis of a set of over 1.6 million research publications (identified from the Scopus database[5]) and 800,000 patents published between 2001 and 2020, with the aim of advancing our understanding

[1] IPCC. (2021). *Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Masson-Delmotte, V., et al. (eds.). Cambridge University Press. In Press. https://www.ipcc.ch/report/sixth-assessment-report-working-group-i/

[2] United Nations. (2015). *Paris Agreement.* Article 2, p. 3. https://unfccc.int/sites/default/files/english_paris_agreement.pdf

[3] IEA. (2021). *Net zero by 2050: A roadmap for the global energy sector.* https://www.iea.org/reports/net-zero-by-2050

[4] See https://www.iea.org/reports/net-zero-by-2050

[5] Scopus is Elsevier's abstract and citation database of peer-reviewed literature, covering 84 million documents published by some 7,000 publishers. For further details, see https://www.elsevier.com/solutions/scopus

of clean energy research and innovation and the pathways toward achieving a net zero future. Throughout this report, we refer to this publication set as “NØEnergy research”.

Our bibliometric analyses encompass global research output and funding, disciplinary diversity, international collaboration between the Global South and North, the role of corporates and their interaction with academia, as well as the evolution from basic to applied research and, ultimately, the transition from research to patents. We also examine, using altmetrics, how NØEnergy research is currently regarded by policymakers and the wider media.

In addition to our data-based quantitative analysis of NØEnergy research, this report includes in-depth interviews with a wide range of international experts. Their unique perspectives highlight some of the multifarious aspects of achieving net zero, both the obstacles and the opportunities presented by the transition to clean energy.

This report is aimed at global funders, policymakers, research funders and leaders, as well as researchers in fields related to clean energy. Readers can use the snapshot of the NØEnergy research and innovation landscape presented here to pinpoint their own position and identify emerging trends and potential opportunities. We hope this report will support readers’ decision-making processes regarding the future direction and focus of research and innovation efforts, with the aim of reaching net zero by 2050.

Key findings

Over the last 20 years, the share of publications in NØEnergy research among all research output has risen: NØEnergy publications contributed to 1% of the total global output in 2001, increasing to 5% in 2020. China’s research output has increased year on year since 2001, and the volume of its publications in NØEnergy overtook that of the United States in 2012. Although the United States is still a significant player in this area, its share of total research publications in the field has reduced somewhat over the last two decades.

NØEnergy research goes beyond traditional individual disciplines to encompass a much broader spread of data, expertise and knowledge, emphasizing the importance of a multidisciplinary approach.

“The climate crisis is as much a rural problem as an urban one, economic and human, domestic and international. This means transformation is required at every level of society: individuals, employers, institutions and international partners will need to work together to understand the trade-offs, agree compromises and seize opportunities. And just as scientists are pooling insights from diverse fields of expertise, policymakers will need to work in new ways, sharing ideas across disciplines to plot a clear path from here to net zero. This is a whole systems challenge.”

Patrick Vallance (UK Chief Scientific Adviser). (2021, August 9). The IPCC report is clear: nothing short of transforming society will avert catastrophe. *The Guardian*.

International collaboration in the field has increased from just over 30% in 2011 to 45% in 2020. This is a positive sign as energy challenges are global and international collaboration enables shared learning, producing research with a broader impact. However, our findings also indicate that levels of collaboration across scientific disciplines in the field are not above average. This is a concern because pooling diverse skills and perspectives from different disciplines is more likely to lead to research outcomes able to tackle grand societal challenges, such as climate change. If NØEnergy research continues to achieve average levels of cross-disciplinarity, the field may not have the necessary interdisciplinary reach to realize the large-scale technical and societal changes needed to achieve net zero.

The outlook and reach of NØEnergy research must be global, but our analysis finds that only a small proportion of research in the field is conducted in and for the Global South. These countries—defined as Upper-Middle-Income, Lower-Middle-Income and Low-Income Countries by the World Bank—are likely to be disproportionately affected by climate change and are potentially among the least able to deal with or mitigate against its worst effects. While there are positive indications from the growing number of Global South researchers in the field and their levels of collaboration with Global North and Chinese research powerhouses, these modest improvements to date may be insufficient to meet the challenges ahead. Clearly, there is still plenty of room to improve and increase Global North–South collaboration, which should be a priority for NØEnergy research policies in the future.

As might be expected from a field that needs to transition from basic research to technological innovation, publications in applied technology have increased substantially, by more than 20 percentage points over the past two decades. While Singapore, with its expertise in materials science and allied fields, produces proportionally the largest share of basic NØEnergy research among the top producers, South Korea and Japan are more focused on applied research and Denmark has the largest share of publications in applied technology.

“This report looks at what research is being done: is it enough, is it in the right places? Is it sufficiently collaborative? This is being done to guide funding and research strategy decisions, but also to guide the sorts of mechanisms that researchers deploy to enhance international and interdisciplinary collaborations; shining a light on the places where we need to do more to meet targets.”

Patricia Thornley, Director, Energy and Bioproducts Research Institute, Aston University[6]

The report also provides insight into the level of maturity of clean energy technologies and their evolution over time. Some subfields of NØEnergy research, such as electrical energy transport and distribution systems, are highly practical and center on applied technology. Other important areas such as batteries for electric vehicles and energy storage are still at the applied research stage.

The transition of research to the deployment of near- or mid-term technologies relies heavily on the corporate sector. The connections between academic and corporate research and the patenting landscape, which we evaluate in this report, give an insight into how well NØEnergy research is transitioning into deployable technologies. While

[6] Professor Patricia Thornley is the Director of the Energy and Bioproducts Research Institute at Aston University in the United Kingdom. An Advisory Group member for this report, she was not formally interviewed (see Section 2 for full interviews) but has provided commentary on the report.

collaboration between academia and industry has increased over the last 20 years, with Switzerland and the Netherlands leading the way in the share of co-publications, China is rapidly catching up. However, our analysis reveals that NØEnergy publications from corporates are declining and that few of the largest corporate emitters produce any significant research output in this field at all.

On a more positive note, we observe strong growth in patents connected to clean energy technologies, dominated by the United States, Japan and Germany, although our analysis may underrepresent China's efforts. By 2020, the total number of active patents in the field reached 800,000, with exponential growth over the last 10 years driven in large part by China, indicating that the transition from research to deployment is accelerating.

Addressing climate change is a matter of urgency, but our analysis finds that NØEnergy research receives only slightly more attention from policymakers and a wider online audience than other areas of research. Nevertheless, this research is finding its way into international policies and informs the work of organizations such as the World Bank, Intergovernmental Panel on Climate Change (IPCC) and Wuppertal Institut. But to effect the wide-ranging societal changes that will be needed to achieve net zero, the research community, funders, policymakers and other stakeholders may need to focus more heavily on topics with societal relevance and communicate the impact of research more clearly.

> *"Global warming is much more critical than we expected 30 years ago, so we need to accelerate our progress."*
>
> Hiroshi Komiyama, Chairman, Mitsubishi Research Institute, Inc.; President, Platinum Society Network; 28th President, University of Tokyo

Conclusions

While the indicators are positive for NØEnergy research and the transition to a net zero future, more effort and urgency are needed globally if the mid-century deadline set out in the 2015 Paris Agreement is to be reached and the worst effects of climate change are to be avoided.

More targeted, coordinated research in key areas, together with more collaborative efforts between the Global North and South, as well as initiatives by and for the Global South, are required to ensure that all countries and regions have access to the expertise and technologies needed to build capabilities at the local level to tackle climate change and make progress toward net zero. The success of the clean energy transition depends on buy-in from the Global South because these countries have the potential, in their legitimate efforts toward social and economic development, to neutralize the benefits accrued from achieving net zero. As Leon Clarke, University of Maryland, points out in his interview in this report, addressing climate change requires everyone's involvement and one of the most consistent and significant challenges is ensuring that all countries have the capacity needed to make progress toward net zero.

This report also identifies signs of the growing emergence and significance of the digitalization of energy systems. Cyber security and data privacy issues will be crucial to the future of interconnected clean energy systems and will also create demand for new skills and expertise.

The transition to net zero and clean energy technologies holds the potential for enormous economic benefits too. The invention and development of innovative technologies could form the basis of a thriving, competitive economy and a vibrant, fair energy infrastructure. The transition could revitalize local manufacturing and economies globally, supported by a skilled clean energy workforce.

Innovation and development, through collaboration nationally, internationally, between the Global North and Global South, and between academia and industry, must accelerate. Better sharing of knowledge and technological know-how between the Global North and South will enable decision-makers to select the clean energy technologies best suited to their needs. The push to adopt net zero approaches and clean energy technologies must be driven by policymakers and governments globally, as well as society more broadly. More research is needed to know which policies and investments are most effective and why, learning from successful examples around the globe. This research could also help us understand how to deploy what Chukwuka Monyei, University of Sussex, refers to in his interview as a "human-centered approach to driving clean energy technology … [with] coherence between governments and people". Achieving net zero will, crucially, necessitate buy-in from society as a whole.

Preface

Kumsal Bayazit

CEO, Elsevier

Although much progress has been made over the decades, our world still faces multiple societal, economic and environmental challenges. At Elsevier, our mission is to help researchers and health professionals advance science and improve healthcare outcomes through quality information and analytics. We are committed to support the communities we serve in tackling the greatest challenges they face. Few, if any, are more significant than the climate crisis. We have all seen the escalating effects of climate change in recent years, including changes in seasonal temperatures, rain and snow patterns, and intensity of events such as floods and wildfires in many geographies. As we approach the 26th UN Climate Change Conference of the Parties, or COP26, the need to tackle the environmental emergency is in sharp focus.

Elsevier is a proud signatory of the Climate Pledge. We hold ourselves accountable to achieve net-zero carbon emissions by 2040. We support a range of initiatives and work in partnership with the communities that we serve toward achieving our climate goals. To guide our efforts, we use data, combined with content and subject-matter expertise, to gain unique insights into how research can accelerate innovation in clean energy and mitigate climate change.

This study, analyzing more than 1.6 million research papers from our Scopus database, is one such contribution. It is designed to support evidence-led policy decisions and action by creating a picture of the clean energy research that advances our understanding and provides pathways to achieve net zero (NØEnergy research).

Strong agreements and action are pivotal to curbing climate change. However, it's not only world leaders who have a crucial role in reaching net zero. A global community of researchers is focused on developing new technologies, techniques and understandings to help us fight climate change.

The data-led insights provided in this report give an encouraging picture of the progress clean energy researchers are making in providing the tools to reach net zero. It shows growth in funding, collaboration, output, ambition and maturity of research that should make us all proud.

Publications in NØEnergy research have grown from 1% of all research undertaken in 2001 to 5% in 2020. That's a move from 16,000 to 170,000 research papers per annum over this period. That research has also shifted from being predominantly fundamental analysis to having a greater emphasis on the application of the knowledge. As a result, research published on applied technologies has grown by 20 percentage points over the past two decades. Over 100,000 patents focused on NØEnergy have been registered over the last three years, as businesses and research facilities alike look to create clean energy technologies. This is encouraging news when policymakers and organizations are looking for solutions to climate change that can make an impact now.

However, there is one area in particular where we, as a research community, can do more. While countries worldwide have stepped up research into NØEnergy, and in particular China has grown to become the largest contributor to NØEnergy research in terms of overall publications and patents, the collaboration between the Global North and the developing countries of the Global South, which will be most affected by climate change, has not grown at the same pace. Global South countries collectively contributed to just 21% of NØEnergy publications from 2001 to 2020. Despite being perceived as the best way of tackling science-based development challenges, North–South collaborations account for just 6% of NØEnergy research publications. Strengthening North–South collaborations is one way to ensure the Global South benefits from global research on NØEnergy.

Ultimately, this study provides a snapshot of the development of NØEnergy research over the last 20 years, providing insight into where we can improve and where the opportunities are. We need to do more given the urgency and scale of the challenge; corporations and world leaders can do more to boost vital research and funding; we need to ensure the Global South is a larger part of the research efforts. At Elsevier, we are committed to play our part with initiatives such as The Elsevier Foundation Chemistry for Climate Action Challenge, RELX Environmental Challenge, the Climate Advisory Board, our NetZero by 2040 commitment and the International Publishers Association's commitment to tackle climate change.

We hope this report offers actionable insights to help us navigate the most significant challenge our planet faces. It suggests that there is far more to come and that the science of net zero is progressing with the commitment of research communities, but we need to move faster to ensure that scientific innovation is converted into real-world application to limit global warming.

Foreword

Ban Ki-moon

Co-chair of the Ban Ki-moon Centre for Global Citizens, 8th Secretary-General of the United Nations

Image: © Caio Kauffmann

The latest UNFCCC NDC Synthesis report[7] shows the implementation of the Paris Agreement is progressing, with 70 signatory Parties set to reduce greenhouse gas emissions by an average of 26% by 2030. While we are not ahead in the race, we do show promise. Elsevier's report *Pathways to Net Zero: The Impact of Clean Energy Research* is launched just in time for COP26 and offers trends, opportunities and best practices in clean energy-related research and its subsequent contribution to the unanimous goal, set in Paris, of achieving net zero greenhouse gas emissions by 2050.

Elsevier's report, the first in a series, emphasizes the importance of cross-sectoral and inclusive partnerships when it comes to providing access to affordable, reliable, sustainable and modern energy for all by 2030—in line with the Paris Agreement. It presents data that will enable informed decisions when drawing up roadmaps and joint action among all stakeholders around the world to influence the path forward for clean energy in terms of funding, diversity, innovation and policymaking. By now, we all know that we need a paradigm shift to heal our relationship with planet Earth and for leaders in government, the private sector, financial institutions, civil society and philanthropies to drive faster action before it's too late.

In this regard, I must commend China, the European Union, Japan, South Korea, the United Kingdom and the United States for being the major contributors to clean energy research publications. Yet we must give the stage to those who are most affected by climate change and its impacts. Therefore, future research efforts and publications must include significantly more insight and data from the Global South.

To successfully adapt to the transition ahead it is important to evaluate every country's carbon emission reduction effort to accomplish our universal net zero goal in time. The international community as a whole needs to implement unwavering measures to transform our fossil fuel-based energy systems into sustainable systems based on renewable energy. Even though the pandemic exacerbated existing challenges, we have more opportunities than ever for a green recovery: we have the chance to make greater progress toward the implementation of the Paris Agreement than we did before.

Transition toward renewable energy sources should not be perceived as a challenge. On the contrary, this transformation will provide new opportunities to modernize our energy systems, diversify economies, create green jobs,

[7] See https://unfccc.int/process-and-meetings/the-paris-agreement/nationally-determined-contributions-ndcs/nationally-determined-contributions-ndcs/ndc-synthesis-report

increase productivity levels and evidently reduce poverty. I hope the insights provided in this detailed report will nourish new discussions and empower united actions that embrace both future industries and future generations to achieve the Paris Agreement's net zero goal by 2050.

To achieve the global goal of net zero emissions, the outcomes of clean energy-related research should be accepted as one of the global common goods. The international community should embark on discussing specific mechanisms to make them available in developing countries without barriers. A small step in this direction is the availability of the report's data set through the International Center for the Study of Research,[8] specifically for use by researchers.

In this regard, this report carries added importance.

[8] See https://icsr.net

Contents

Introduction

This report presents an analysis of clean energy research, using bibliometrics and altmetrics to reveal the research and innovation landscape, level of global collaboration and scope of technological development, and the field's prominence in policymaking and the media.

There are many pathways to reach net zero. Here, in the first of a planned series of reports, we provide a broad introduction to the impact of clean energy research on achieving net zero. Subsequent reports will delve more deeply into a selection of specific research questions and technologies identified in this analysis.

Using bibliometric and altmetric approaches, this report analyzes clean energy research output and trends, research funding, disciplinary diversity, international collaboration, the participation of the Global South and North, and the role of corporations and their collaboration with academia. The pathways from basic to applied research, from research to patents, and from research to policy are also examined. The report concludes with some further questions arising from our investigations.

> *"Data are the foundation of good strategy. If you don't know where you are and what's going on, you can't develop a good strategy."*
>
> Leon Clarke, Acting Director and Research Director, Center for Global Sustainability, University of Maryland at College Park

IPCC definition of net zero

The IPCC Glossary distinguishes between the terms *carbon neutrality*, *net zero* and *climate neutrality*.

In brief, carbon neutrality entails balancing emissions of anthropogenic CO_2 with their intentional removal from the atmosphere. This is also referred to as *net zero* CO_2 *emissions*.

Net zero represents the same concept but applied to all GHG emissions, not just CO_2.

Climate neutrality is the state whereby anthropogenic activities have no net effect on the climate system as a whole. The IPCC Glossary notes, "Achieving such a state would require balancing of residual emissions with emission (carbon dioxide) removal as well as accounting for regional or local biogeophysical effects of human activities that, for example, affect surface albedo or local climate."

For the full definitions and others, see the IPCC Glossary: https://www.ipcc.ch/sr15/chapter/glossary/

By analyzing the contribution of research and innovation to the development and implementation of clean energy technologies, this evidence-based report aims to drive forward knowledge and debate on this urgent global and socially significant challenge.

Building the publication set

Achieving net zero requires a very broad base of research, which brings a challenge in defining the scope of analysis. Before explaining the path we chose to follow in this report, we would like to acknowledge that our approach and scope is not necessarily perfect nor definitive.

The analyses in this report are based on publication and citation data from peer-reviewed research literature, policy-related documents, funding acknowledgments and patent information from Elsevier's Scopus database, SciVal and PlumX, LexisNexis' PatentSight, and Overton's policy database.

Capturing clean energy research related to net zero required the use of a diverse set of publications indexed in the Scopus database.[9] These publications focus on different methods and technologies for reducing emissions and removing carbon from the atmosphere. The analyses conducted here required the creation of a publication set that could capture all facets of this broad research field.

In Scopus, the search query "net zero" returns just over 1,000 documents, while just under 10,000 documents are identified when additional terms such as "decarbonization", "carbon neutral" or "zero carbon" are employed as well. However, as noted above, research on clean energy related to net zero is very broad and our analysis necessitated an approach that captures all relevant work beyond these specific terms. For this reason, we based our publication set on two existing Scopus publication sets relating to the United Nations' Sustainable Development Goals (SDGs), one on Affordable and Clean Energy (SDG 7) and the other on Climate Action (SDG 13).

SDG 7 and SDG 13 are the most relevant to clean energy research as a pathway to net zero. While the SDG 7 publication set captures most research related to curbing emissions, an important body of work associated with carbon removal, particularly carbon capture and storage, is encompassed by the SDG 13 set. Our overall publication set therefore encompasses all the publications related to SDG 7, as well as those from SDG 13 relevant to clean energy.

In the report, we refer to the resulting publication set as "NØEnergy", a term which will be used from here onwards.

Our analyses focus on the period 2001–2020, from the emergence of the term *net zero* to the last complete year of data in Scopus at the time of data extraction.

The Sustainable Development Goals

The Sustainable Development Goals (SDGs), launched by the United Nations in 2015, are defined as "the blueprint to achieve a better and more sustainable future for all", by addressing the global challenges we face.

Since their launch, Elsevier has worked with the research community to map the landscape of sustainability science, starting with the *Sustainability Science in the Global Research Landscape* report (2015), developed with SciDev.net. Since then, we have mapped publications in Scopus to 16 of the 17 SDGs, combining expert-led search queries with machine learning models.

The methods and queries for the SDG publication sets are available here: https://elsevier.digitalcommonsdata.com/datasets/9sxdykm8s4/1

Understanding research areas using SciVal topic clusters

The NØEnergy publication set based on our specific search queries generated a single but very large data set. We used SciVal topic clusters to analyze the broader area of NØEnergy in a more granular way.[10] Most of the report focuses on the

[9] See https://www.elsevier.com/solutions/scopus

[10] See https://www.elsevier.com/solutions/scival/features/topic-prominence-in-science

largest topic clusters within the NØEnergy publication set in terms of scholarly output; however, given the importance of some areas, such as carbon capture and storage, to achieving net zero, we also include such relevant and related topic clusters, which might not appear among the most published.

Publications in Scopus are categorized into more than 97,000 topics using an algorithm that considers the citation linkages between publications. Since topics are based on citation patterns and not journal categories, they are multidisciplinary. Topics are aggregated into over 1,500 topic clusters using the same algorithm. Both topics and topic clusters are mutually exclusive: a publication belongs to only one topic and only one topic cluster. Using topic clusters gives us the advantage of viewing the NØEnergy research landscape from the bottom up. Topic clusters are named by the three most relevant key phrases within the cluster—for example, *Wind Power / Electric Power Transmission Networks / Electric Power Distribution* or *Deforestation / Forest / Conservation*. Distinct key phrases are extracted using the Elsevier Fingerprint Engine, a text-mining software system.[11]

Further technical details of the methodologies, tools and analyses used here are provided in the Appendices.

The report is officially launched at the Times Higher Education Climate Impact Forum on 28 October 2021, ahead of the UN Climate Change Conference (COP 26) in November 2021. Electronic copies can be downloaded at: https://www.elsevier.com/connect/net-zero-report

The data set used in this report is available to subscribers of SciVal and for free to researchers via the ICSR Lab: https://icsr.net/icsrlab/

To commission a customized derivative report, please visit: https://www.elsevier.com/research-intelligence/request-a-consultation

"When we think about net zero, the scope of what's relevant from a research perspective is enormous. It encompasses so much of society that it really makes it hard to think about how to scope that down, because everything that you've got, you have to get down to zero.

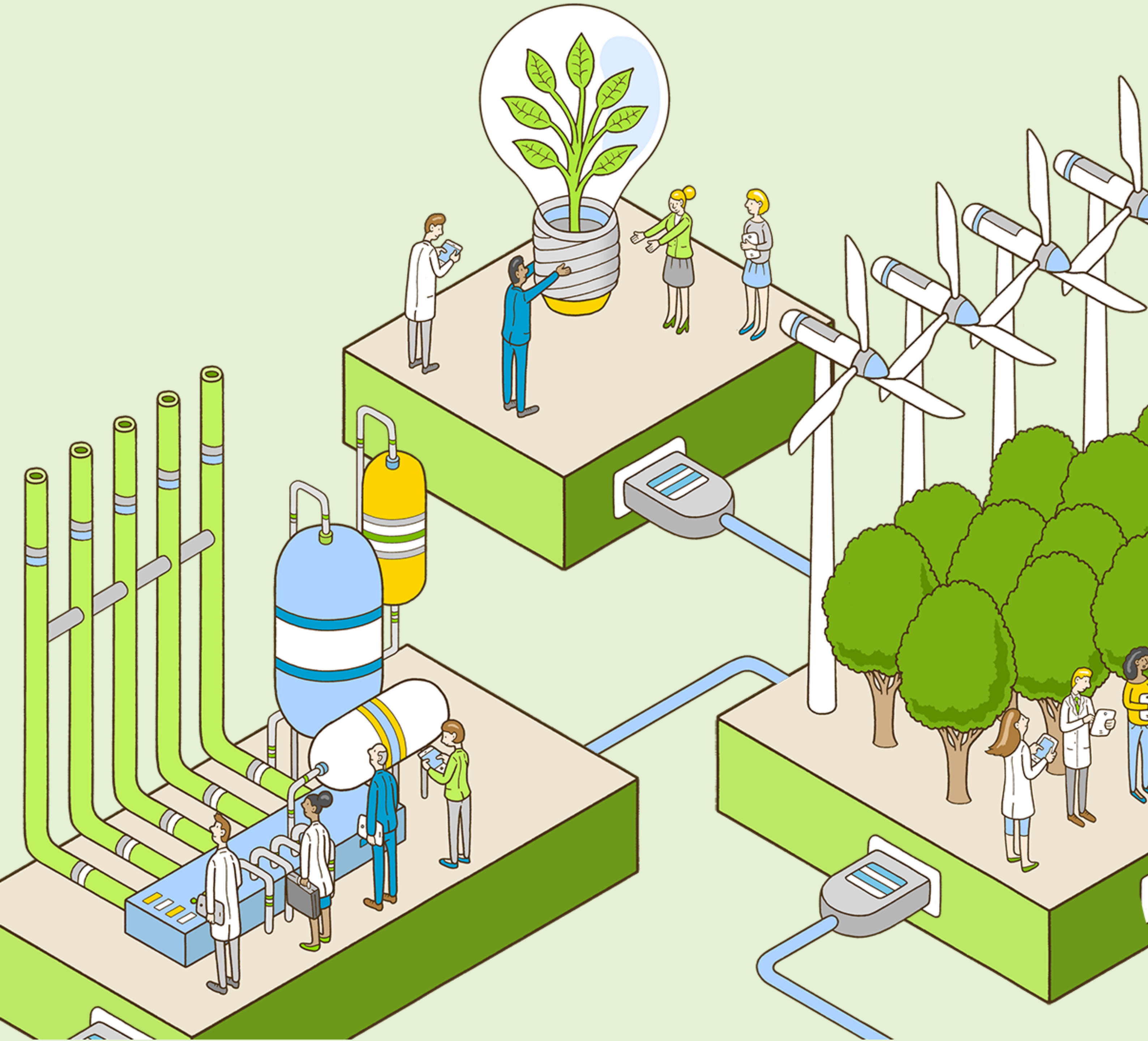
"That means that nothing gets left on the table. It calls for a very broad perspective on what your research is, and it was interesting to see this report grapple with that and try to pull something together that's trying to represent the scope of what's really needed."

Leon Clarke, Acting Director and Research Director, Center for Global Sustainability, University of Maryland at College Park

[11] See https://www.elsevier.com/solutions/elsevier-fingerprint-engine

Section 1

Bibliometrics: large-scale trends in NØEnergy research



1.1 How has NØEnergy research grown since 2001?

In the last two decades, NØEnergy research output has grown rapidly, from a share of just 1% of all global publications in 2001 to 5% in 2020. During this period, the total number of publications in NØEnergy reached over 1.6 million.

The term *net zero* in the context of clean energy began appearing in scholarly output in the early 2000s (Figure 1), as described in the history of the concept by the Energy & Climate Intelligence Unit.[12]

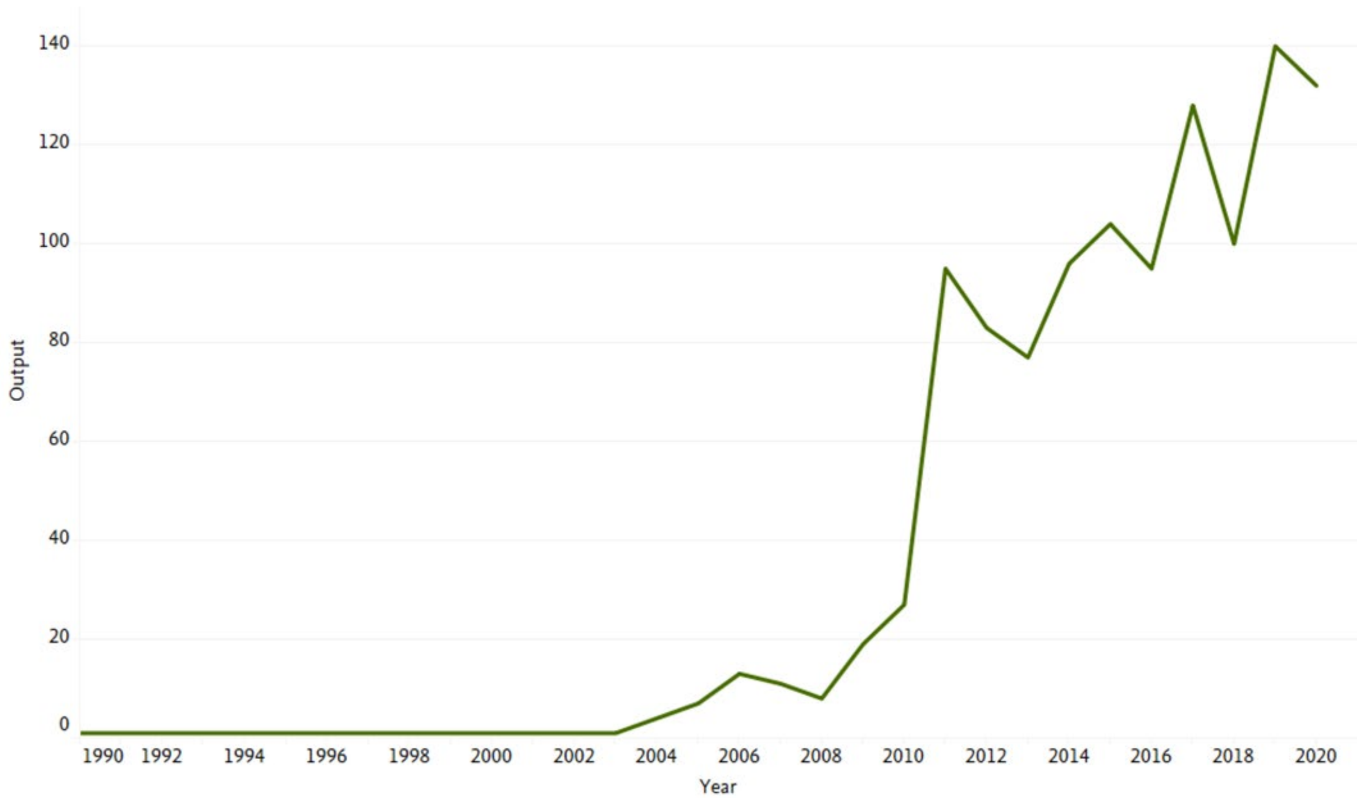


Figure 1
Results of the Scopus search query TITLE-ABS-KEY ({net zero} AND energy)
Source: Scopus

[12] See https://eciu.net/analysis/infographics/net-zero-history

Over the analysis period of 2001–2020, the annual number of NØEnergy publications increased continually, from just over 16,000 publications in 2001 to over 170,000 in 2020 (Figure 2), totaling more than 1.6 million publications over the study period. At the beginning of our analysis period, NØEnergy publications contributed to only 1% of the total, but by 2020 this proportion had risen to 5%, demonstrating the growing significance of the field. Overall, the number of NØEnergy publications showed a compound annual growth rate (CAGR) of 13.2% between 2001 and 2020, significantly greater than the overall global output for the same period (4.9%).

However, the growth rate of NØEnergy output has varied over the last two decades. Initially, global output grew by nearly 17.2% between 2001 and 2010, but it slowed to 8.2% over the last decade. The growth in overall global research output demonstrated a similar but less marked trend over the two periods, with growth slowing from 6.4% to 3.4% in the last decade. Indonesia, Saudi Arabia, Egypt and Russia, however, all bucked the trend, with higher growth in NØEnergy research output between 2011 and 2020, each country producing more than 10,000 NØEnergy publications.

Over the same period, the scholarly impact of NØEnergy research output, as measured by the field-weighted citation impact (FWCI), remained relatively stable at around 1.4 to 1.5 (Figure 3), indicating that this area ranked 40%–50% above the global average of 1.0.

Compound annual growth rate

The compound annual growth rate (CAGR) is defined as the year-over-year constant growth rate over a specified period of time. Starting with the first value in any series and applying this rate for each of the time intervals yields the amount in the final value of the series.

Field-weighted citation impact

The field-weighted citation impact (FWCI) is an indicator of the citation impact of a publication. It is calculated by comparing the number of citations a publication receives with the number of citations expected for a publication of the same type, publication year and subject.

An FWCI of more than 1.00 indicates that a publication has been cited more than would be expected based on the global average for similar publications; for example, a score of 2.11 means that a publication has been cited 111% more than the world average.

An FWCI of less than 1.00 indicates that a publication has been cited less than would be expected based on the global average for similar publications; for example, an FWCI score of 0.87 means the publication has been cited 13% less than the world average.

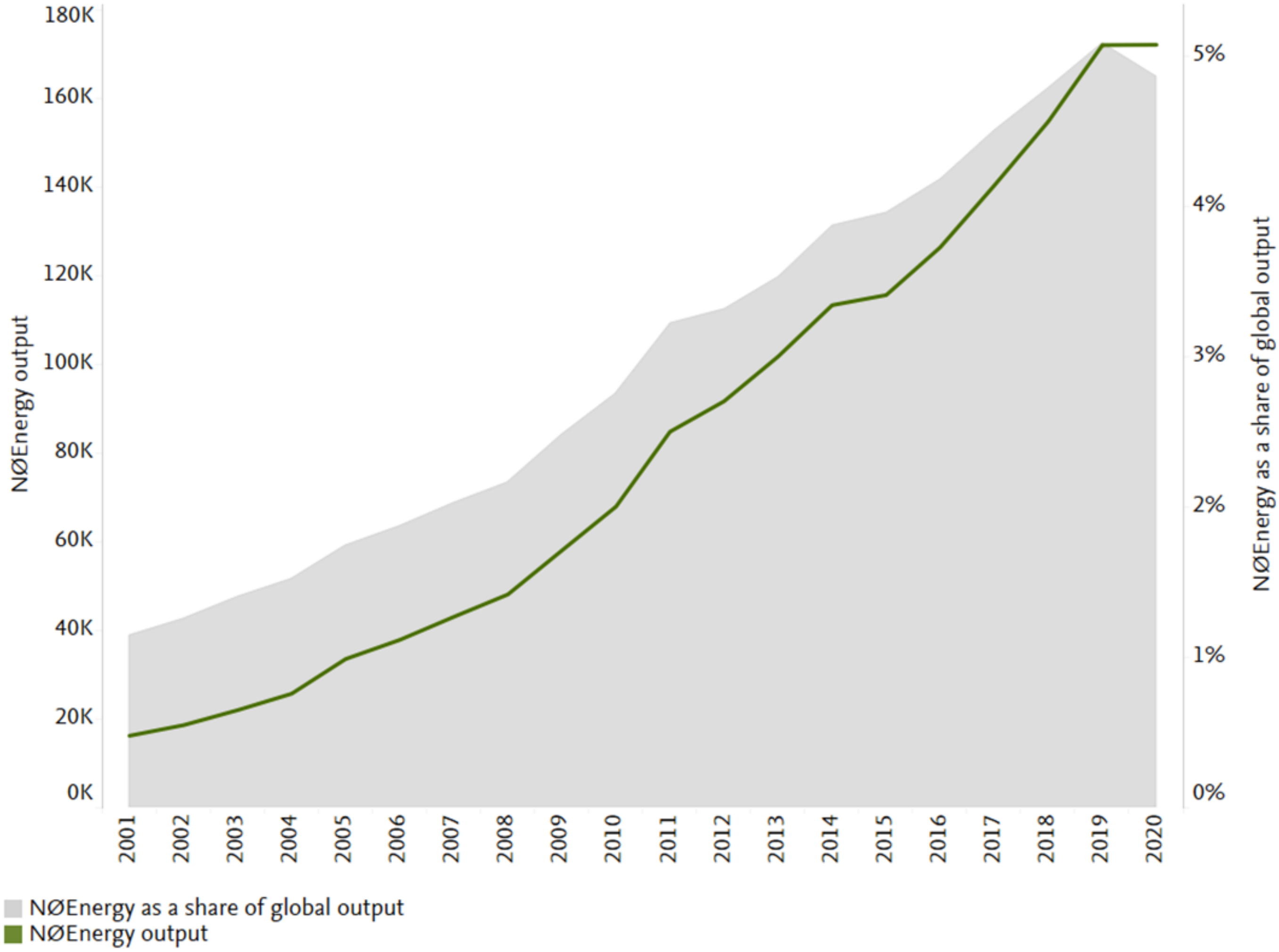


Figure 2
Number of publications in NØEnergy (green line, left-hand y-axis) and the share of NØEnergy publications within global research (gray shaded area, right-hand y-axis), 2001–2020.
Source: Scopus

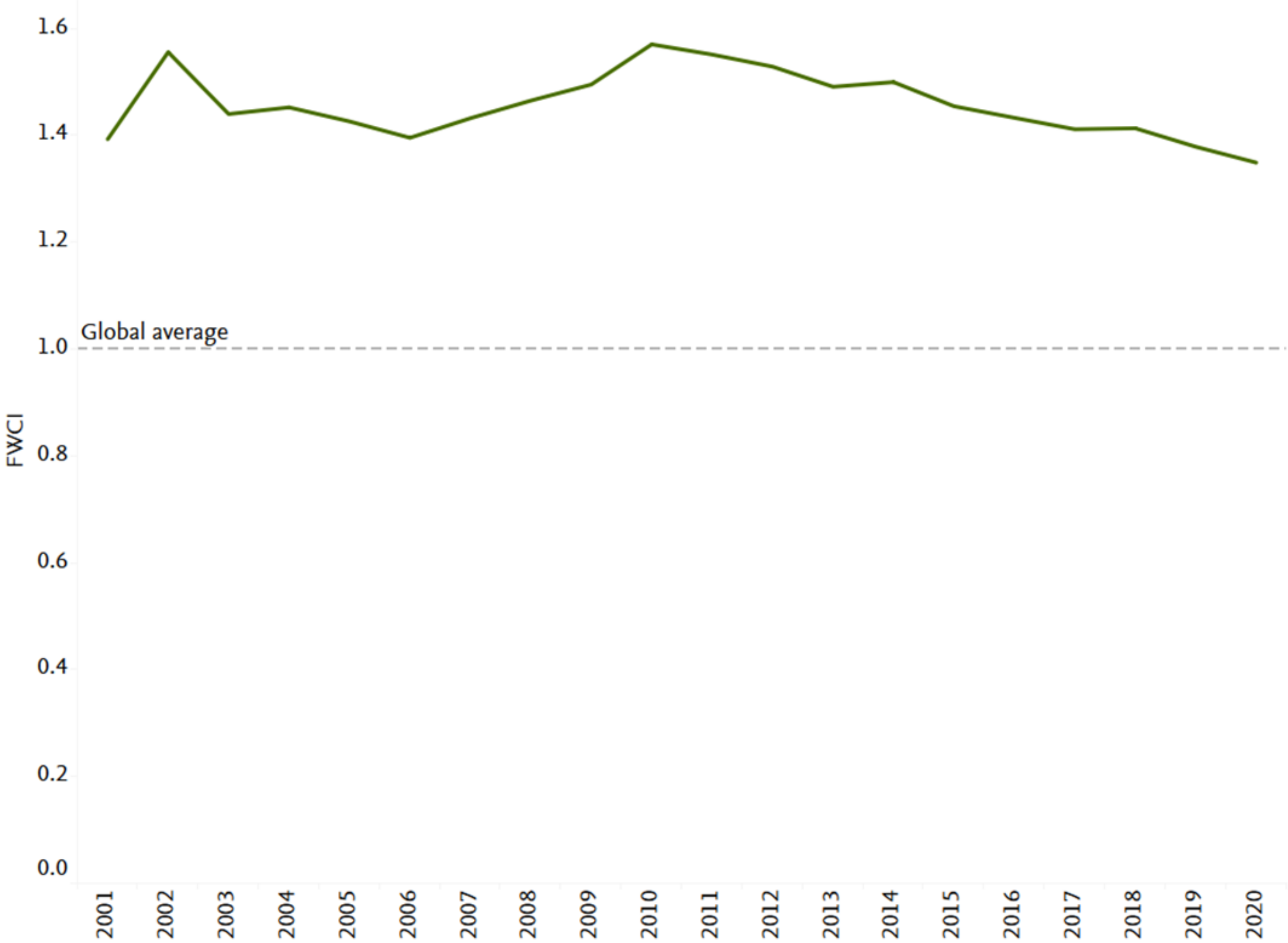


Figure 3
Field-weighted citation impact of NØEnergy publications, 2001–2020.
Source: Scopus

Assessing NØEnergy publications by topic cluster

Over the analysis period, more articles were published on lithium-ion batteries, power transmission and grids, solar energy and energy economics than on other topic clusters, as shown in Figure 4. Publications in *Lithium Alloys / Secondary Batteries / Electric Batteries* accounted for over 7% of the total, making it the single largest topic cluster (data not shown).

The prominence of topic clusters relating to computing, smart systems and data—such as the appearance of *Distributed Computer Systems / Cloud Computing / Clouds* or *Authentication / Cryptography / Data Privacy* in

Topic clusters

A topic cluster is a collection of publications with a common intellectual interest. Scopus publications are grouped into topic clusters using direct citation analysis. Publications are assigned to one—and one only—of 1,500+ topic clusters. Topic clusters are represented by their three most relevant key phrases, based on the abstract, title and author keywords of publications in that cluster.

Figure 6—may appear incongruous to NØEnergy research. However, these areas encompass vital issues relating to the implementation and integration of smart energy technologies, for example.

It is also worth mentioning *MIMO Systems | Orthogonal Frequency Division Multiplexing | Cognitive Radio* here, which contributed only 0.1% of publications in 2001 but increased significantly to make up 1.1% of all NØEnergy publications by 2020. This topic cluster addresses a broad range of related issues associated with digital communications and integration. Digitalization of energy systems—for example, through smart grids, the Internet of Things, cloud computing and wireless networks—will help improve the safety, productivity, accessibility and sustainability of energy systems.[13] But because these advances also raise new data security and privacy risks, topic clusters in this area are emerging as fertile areas of wide-ranging research.

The need to include such diverse topics underlines the broad impact that clean energy research is having and will continue to have in the future on consumers and society. Technologies and their practical use in the real world are an essential part of achieving net zero, highlighting the need for significant multidisciplinary and interdisciplinary research. Later sections will address these various aspects of knowledge transfer.

"Digitalization is not a core technology in itself, but it is an extremely important enabling technology that includes the deployment of sensors, communications systems, the use of artificial intelligence and the ability to manage large volumes of data through big data technologies."

Pablo Arboleya, Associate Professor and Holder of the Smart Cities Chair, Universidad de Oviedo

Energy efficiency, wind and solar, hydropower and nuclear, electrification and electric vehicles are highlighted as key steppingstones in the pathway to net zero in the IEA's report *Net Zero by 2050: A Roadmap for the Global Energy Sector*.[14] The largest topic clusters we observe within our analysis of NØEnergy are partially in line with these key areas, particularly energy efficiency, wind, solar and electric vehicles.

Other topic clusters are present, although not among the largest within the NØEnergy research publication set. Carbon capture and storage, for example, will be key to achieving and maintaining net zero, but it is not yet a mature and scalable technology. Of the three main topic clusters in this field, *Activated Carbon | Adsorption | Adsorbents* has shown continuous growth over the analysis period, whereas output from *Carbon Capture | Storage (Materials) | Shale* and *Carbon Dioxide | Amines | Flue Gases* has fluctuated considerably. In the broad field of bioenergy, the topic cluster *Bioenergy | Biomass | Biofuels* has remained relatively stable over the last decade, whereas the number of publications in *Microbial Fuel Cells | Anaerobic Digestion | Bioreactors* has more than doubled.

[13] IEA. (2017). *Digitalization and energy*. https://www.iea.org/reports/digitalisation-and-energy
[14] See https://www.iea.org/reports/net-zero-by-2050

Figure 4
Scholarly output for topic clusters accounting for at least 1% of all NØEnergy publications, 2001–2020. Circles indicate the field-weighted citation impact, and bars indicate the publication output of the topic cluster.
Source: Scopus

"Internet-enabled or Internet-related jobs are going to be critical for the future. We are looking for people versed in cryptology, in hacking, in the cyber security space, in different roles that we are not even aware of. This opens up another conflict, though: privacy and the ethics of the Internet of the future. How are we going to be able to balance issues of privacy, how much information should the government know? How can we encrypt this information? How can it be used, without giving governments too much access to such information, and what it can be used for and to what purposes...?"

Chukwuka Monyei, Research Fellow in Energy Justice and Transitions, University of Sussex

The distribution of topic clusters changed throughout the 2001–2020 period. Figure 5 shows all the topic clusters that contributed at least 1% of NØEnergy publications in five specific years: 2001, 2006, 2011, 2016 and 2020. *Lithium Alloys / Secondary Batteries / Electric Batteries* and *Electric Inverters / Electric Potential / DC-DC Converters* are the most published topic clusters, with the former increasing its share from 5% to over 11%, far outstripping the other areas.

At the start of the millennium, fusion research—with the aim of providing infinite clean energy—contributed the largest single share of publications in our data set, with the topic cluster *Magnetoplasma / Plasmas / Tokamak Devices* accounting for over 8% of all publications in NØEnergy. By 2020, however, this proportion dropped to just over 1%. While the output of most countries and regions in this field has fluctuated over our analysis period, China's has increased continuously. Its research efforts on fusion energy are focused on the Experimental Advanced Superconducting Tokamak (EAST)—nicknamed the "artificial sun"—which is designed to replicate the nuclear fusion process of the sun.

China's output in *Solar Cells / Conjugated Polymers / Organic Light Emitting Diodes (OLEDs)* also increased over the last decade, in contrast with the other countries that produced the largest volumes of publications. *Silicon Solar Cells / Solar Cells / Silicon* saw a sharp decline in output across the board.

Among the other topic clusters that account for notable shares of NØEnergy publications, *Wind Power / Electric Power Transmission Networks / Electric Power Distribution*, *Photocatalysts / Solar Cells / Photocatalysis*, *Wireless Sensor Networks / Routing Protocols / Sensor Nodes*, *Wind Power / Asynchronous Generators / Wind Turbines* and *Ventilation / Buildings / Air Conditioning* have become the largest.

"Looking at Figure 5, given there is so much focus at present in the media and elsewhere on hydrogen, it is perhaps surprising that it doesn't feature higher up in this chart.

"But the big elephant in the room here is that bioenergy with carbon capture and storage (BECCS) is being assumed to feature prominently in most IPCC and UK government pathways to 2050, and if that isn't being reflected in research, we might have quite a big problem in 5 to 10 years' time. Is BECCS a blind spot in global research activity given its prominence in global visions?"

Patricia Thornley, Director, Energy and Bioproducts Research Institute, Aston University

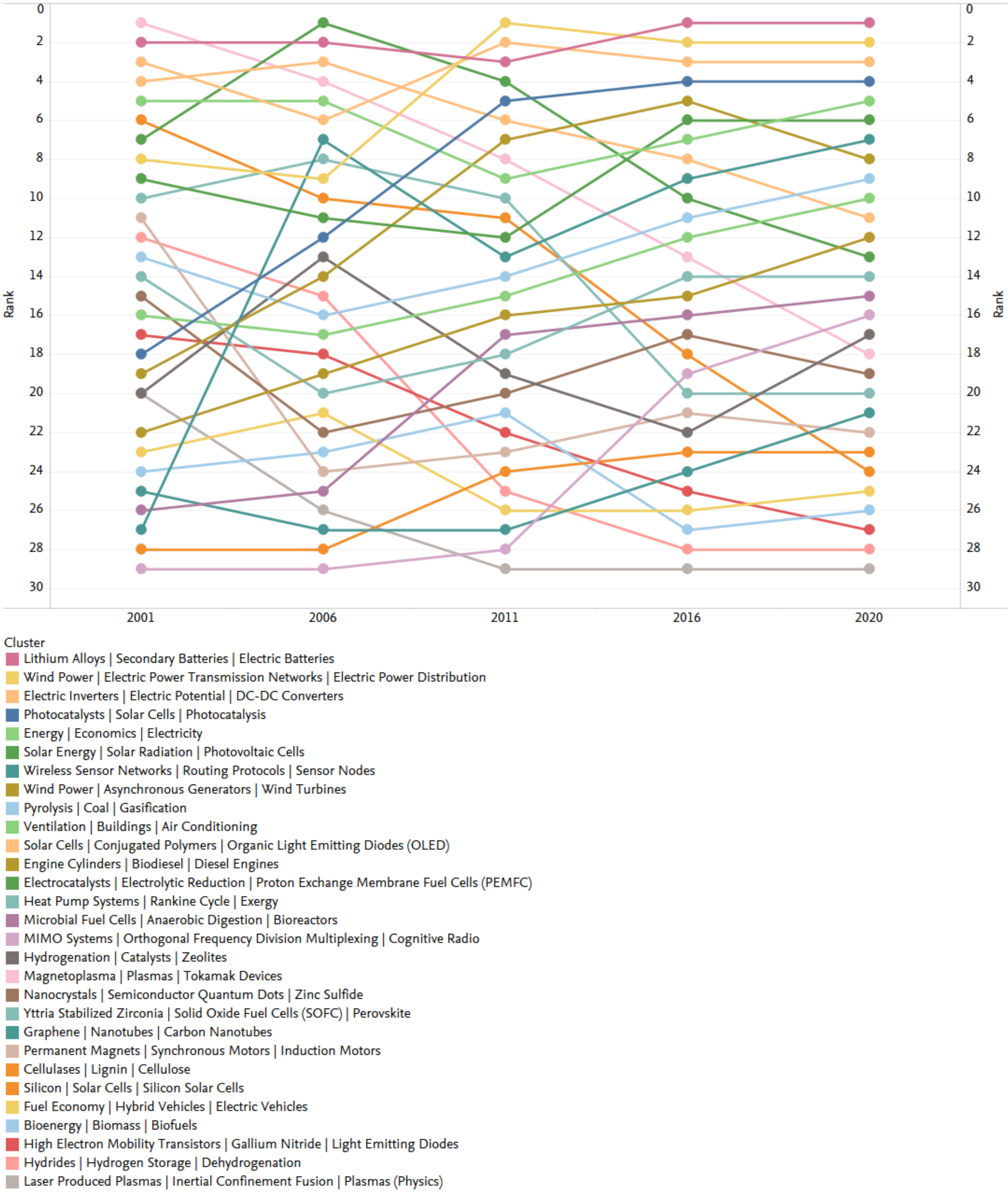


Figure 5
Topic clusters that contributed to at least 1% of all publications in 2001, 2006, 2011, 2016 and 2020 respectively.
Source: Scopus

Other topic clusters that contributed over 5,000 publications in 2011–2020 but accounted for less than 1% of publications overall are listed in Figure 6, in order of their output. Once again, the appearance here of topic clusters such as *Authentication | Cryptography | Data Privacy* indicates the growing importance of broader issues relating to the implementation and integration of smart energy systems. Further analysis on the multidisciplinarity and interdisciplinarity of NØEnergy research is presented in Section 1.4.

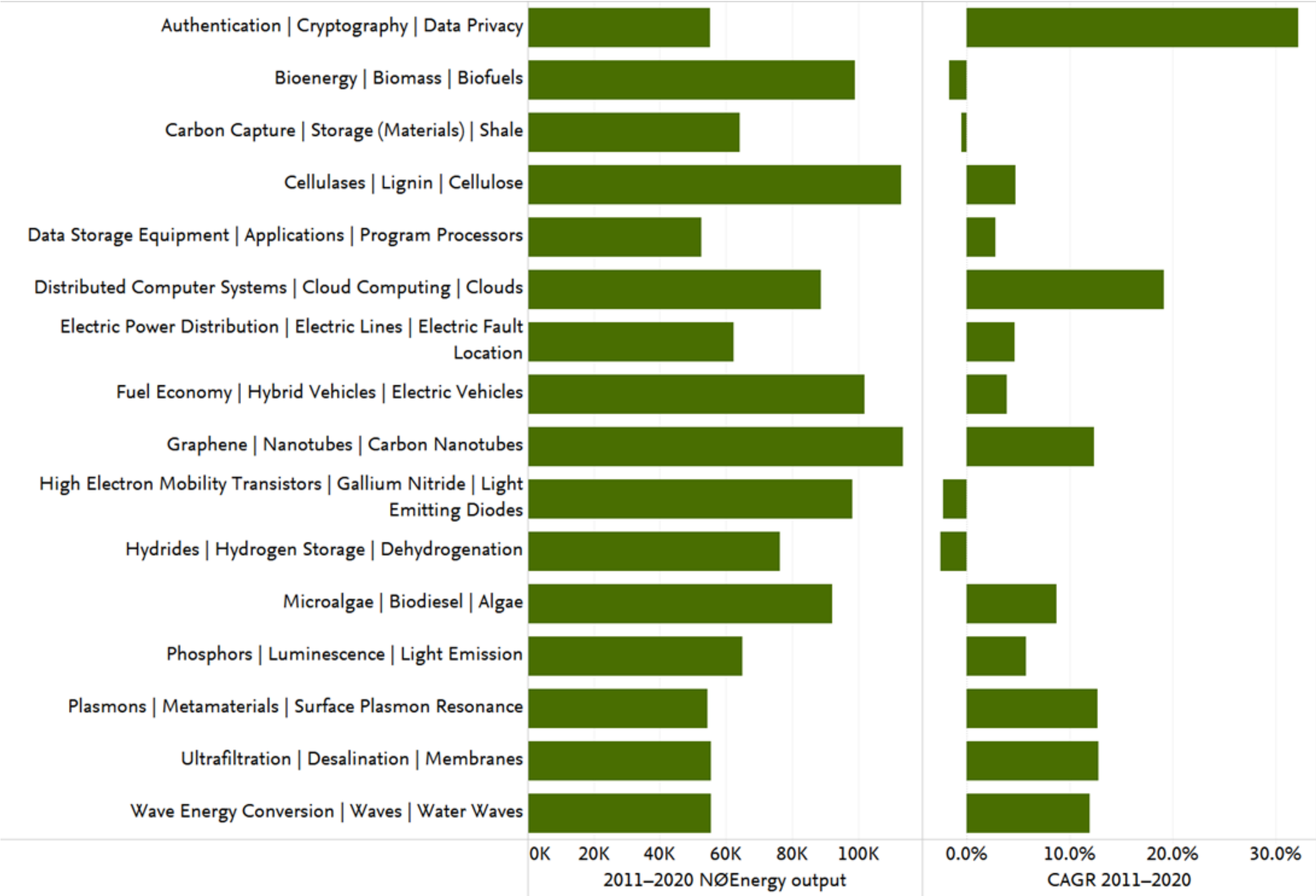


Figure 6
Compound annual growth rate for topic clusters that had more than 5,000 publications in NØEnergy for 2011–2020 but contributed less than 1% of all publications.
Source: Scopus

> *"The evolution of batteries, and of solar cells in particular, has been transformative. We wouldn't be considering the types of mitigation actions that countries are considering today, for over the next 10 years, if we hadn't seen those sorts of advances, to the point where photovoltaic cells are frequently competitive with or even cheaper than, say, coal generation."*
>
> Leon Clarke, Acting Director and Research Director, Center for Global Sustainability, University of Maryland at College Park

1.2 Who funds NØEnergy research?

Chinese funding agencies support the single largest share of NØEnergy publications by far. While Chinese-funded output increased between 2016 and 2020, publications acknowledging US funders have plateaued.

Research and development funding is urgently needed around the globe to support the development of new and improved technologies to achieve net zero. In this section, we present information on the funders acknowledged by NØEnergy research publications, to understand which are the most active, which topics receive the most support and where funding will be needed in the future.

Between 2016 and 2020, well over half of the 766,000 publications in NØEnergy acknowledged a funding source. Over the 2016–2020 period, the National Natural Science Foundation of China accounted for the largest proportion of these publications, contributing to nearly a quarter of the total and far outstripping other funding bodies (Figure 7). China's Fundamental Research Funds for the Central Universities ranked in second position, closely followed by the United States, with its major funding agencies being the National Science Foundation and Department of Energy. Outside China and the United States, the National Research Foundation of Korea, the United Kingdom's Engineering and Physical Sciences Research Council, the Japan Society for the Promotion of Science and the European Union's Horizon 2020 program are among the top 10 acknowledged funders. As would be expected, these agencies are from those countries that publish the most in NØEnergy.

"In China, the most highly relevant policy to the topic of net zero is the carbon-neutral policy proposed in 2020. China commits to scale up its Intended Nationally Determined Contributions by adopting more vigorous policies and measures. It aims to have CO_2 emissions peak before 2030 and to achieve carbon neutrality before 2060. To achieve carbon neutrality, China has developed detailed energy transition plans and provided substantial funding for research related to the energy transition."

Yutao Wang, Professor, Department of Environmental Science and Engineering, Fudan University

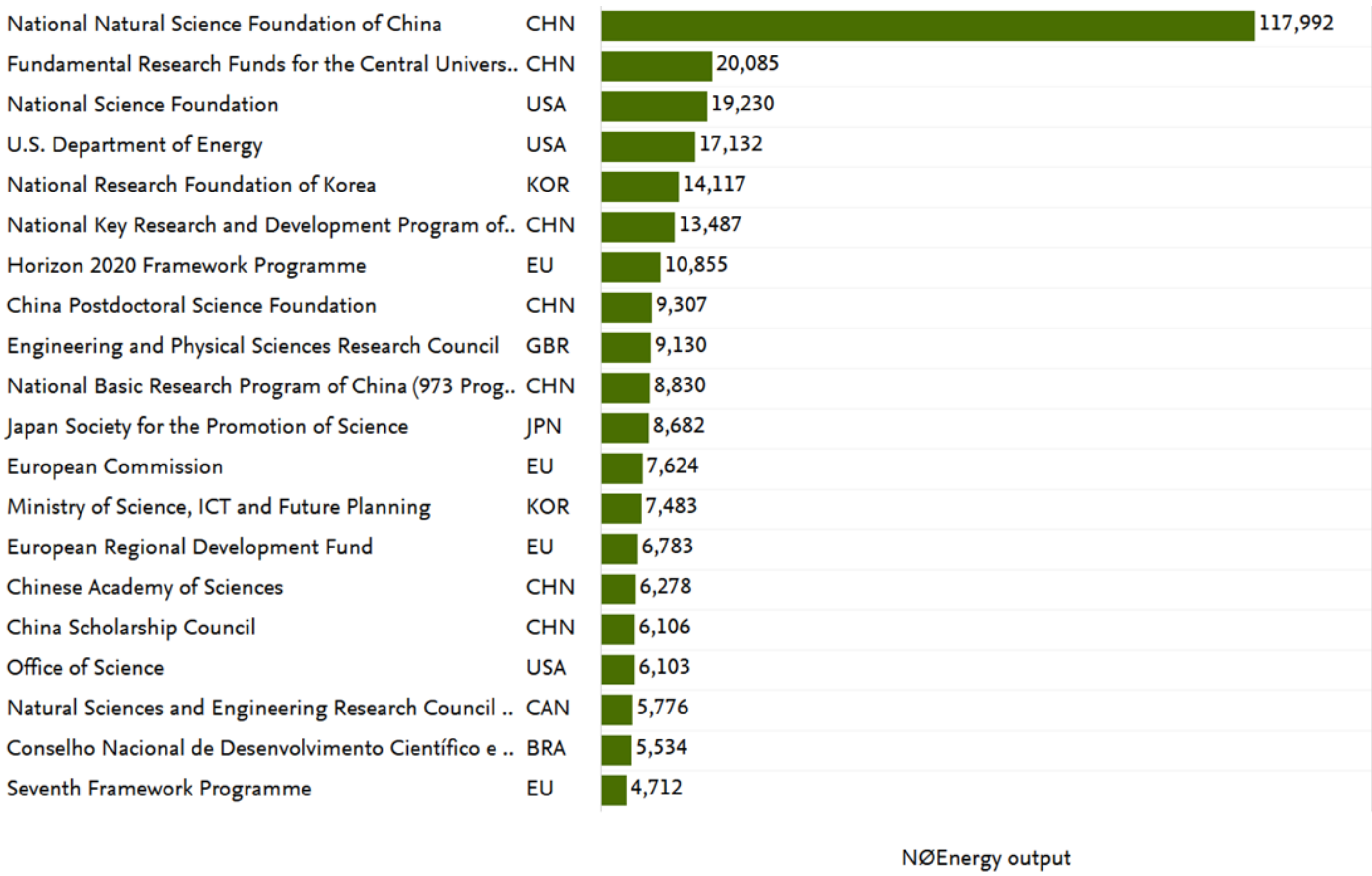


Figure 7
Top 20 funders in terms of funded publications in NØEnergy, 2016–2020.
Source: Scopus

These findings and those in the rest of this section are based upon funding acknowledgment data from Scopus. While they provide a useful overview, there are some limitations to the data. The first is the coverage of the database. Of the 28.8 million articles, reviews and conference proceedings published in Scopus after 2010, 11.2 million contain funding information.[15] Second, not all authors acknowledge funding sources clearly and therefore we are not able to measure the effect of attribution. Third, funding in some regions—for example, the European Union—is spread across multiple different funding programs. Finally, while data quality has continuously improved over the period of analysis, reference to a funding agency in a context not relevant to the funding of the research may be captured in error, resulting in a false positive.

We focused on the last five years because acknowledgment data have become more robust in this time, not only thanks to better coverage but also because more funders have mandated acknowledgment in publications. The findings presented in this section represent only those publications that can be attributed to a funder identified in Scopus. We refer to these as *funded publications*. Publications funded by an agency but not acknowledged by the author(s) are not included. It should also be noted that trends in the volume of funded publications (the output of funding) may differ from the volume of investment into research (the input of funding).

[15] See https://blog.scopus.com/posts/improvements-to-funding-data-in-scopus-now-165m-articles-with-funding-information-and-easier

The trends in output acknowledging the top 20 NØEnergy research funders reveal interesting patterns (Figure 8). The number of funded publications from the US National Science Foundation and Department of Energy plateaued or declined in the latter years of our analysis. Over the 2016–2020 period, output in funded publications from the largest Chinese funding agencies increased almost across the board. More generally, within the Asia-Pacific region, the number of funded publications from South Korean agencies (the National Research Foundation of Korea and Ministry of Science, ICT and Future Planning) increased, while that from the Japan Society for the Promotion of Science began to stall in recent years. The drop in output from some of these funders is to be expected, however. The European Commission's Seventh Framework Programme and Horizon 2020 are time-limited funding programs, for example. In other cases, such as the ongoing National Basic Research Program of China (Program 973), the decrease in attributed output might reflect changes in funding priorities.

These shifts in funding trends likely reflect changes in priorities at the national level as new policies are implemented, older programs are closed and changes in government occur. Understanding these shifts is vital when evaluating the importance of a topic on a regional or national level and how the field might be influenced in the coming years.

"The United States leads the world in research investments in clean energy and in the development of a number of future technologies that are likely to play a significant role in achieving deep decarbonization. However, the United States also currently struggles to leverage its leadership in clean energy R&I into leadership in clean energy markets and supply chains. If the United States can maintain its leadership in the discovery, invention and development of innovative clean energy technologies and leverage its strengths in innovation to create a vibrant clean energy infrastructure, then R&I will serve as a basis for a thriving economy."

Franklin Carrero-Martínez, Senior Director, Global Sustainability and Development & Science and Technology for Sustainability, National Academy of Sciences, Engineering, and Medicine

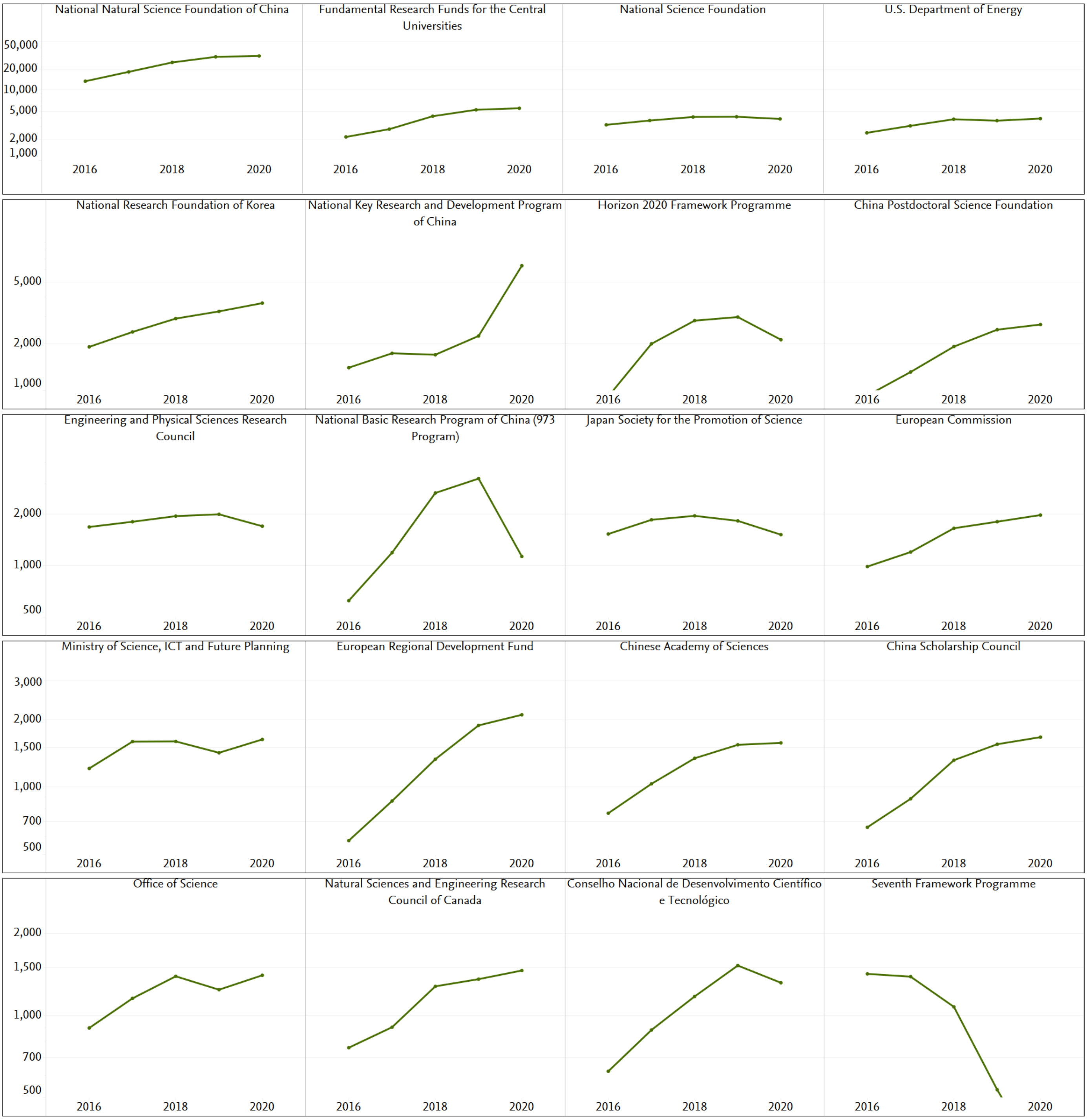


Figure 8
Annual output attributed to top 20 funders within NØEnergy, 2011–2020.
Source: Scopus

Assessing funded publications by topic

The topic clusters accounting for 1% or more of all NØEnergy publications from 2016 to 2020 are shown in Figure 9. As expected, some of the most prominent topic clusters, such as *Lithium Alloys / Secondary Batteries / Electric Batteries* or *Photocatalysts / Solar Cells / Photocatalysis*, also have some of the highest shares of funded publications. However, our analysis reveals that some of the topic clusters with the largest output, such as *Wind Power / Electric Power Transmission Networks / Electric Power Distribution* and *Electric Inverters / Electric Potential / DC-DC Converters* have less than 40% funded publications.

In the largest topic cluster, *Lithium Alloys / Secondary Batteries / Electric Batteries*, a number of organizations reported at least 100 funded publications, which represents at least 50% of each organization's total output. These organizations include Argonne National Laboratory, Vehicle Technologies Office, and Brookhaven National Laboratory in the United States; Shenzhen Technical Project, National Materials Genome Project, Tip-top Scientific and Technical Innovative Youth Talents of Guangdong Special Support Program, Central South University, Beijing University of Chemical Technology, Science and Technology Planning Project of Shenzhen Municipality, and Hunan Provincial Science and Technology Department in China; the University of Waterloo and Western University in Canada; Global Frontier Hybrid Interface Materials in South Korea; and BASF in Germany.

By contrast, the share of funded publications in the second largest topic cluster, *Photocatalysts / Solar Cells / Photocatalysis*, is split between fewer organizations. Of those with more than 100 funded publications, the Australian Centre for Advanced Photovoltaics has the largest share of funded publications (44%), followed by the Spanish group of institutions Generalitat Valenciana (38%).

The IEA's *Net Zero by 2050* report[16] raised the concern that "critical areas such as electrification, hydrogen, bioenergy and carbon capture, utilisation and storage (CCUS) today receive only around one-third of the level of public R&D funding of the more established low-carbon electricity generation and energy efficiency technologies." Our analysis supports this concern, revealing that while 54% of NØEnergy publications in the *Carbon Capture / Storage (Materials) / Shale* topic cluster include funding acknowledgments, the only agency with more than 100 publications and a considerable share of funded publications (27%) is the US National Energy Technology Laboratory. The next best, some way behind, is the United Kingdom's Natural Environment Research Council, with only 7% and 56 publications. In the topic cluster of *Bioenergy / Biomass / Biofuels*, only around 48% of publications acknowledge funding sources. The leading funders here, with more than 50 publications and over 10% of funded publications in the cluster, are the US National Institute of Food and Agriculture, US Department of Agriculture, Bioenergy Technologies Office (part of the US Department of Energy) and UK Biotechnology and Biological Sciences Research Council.

> *"Looking at these data, I'm not surprised by China's research volume. In a sense, they have what might be an advantage: they have to increase the country's power supply and electricity production, and renewables are the cheapest option."*
>
> Hiroshi Komiyama, Chairman, Mitsubishi Research Institute, Inc.; President, Platinum Society Network; 28th President, University of Tokyo

[16] See https://www.iea.org/reports/net-zero-by-2050

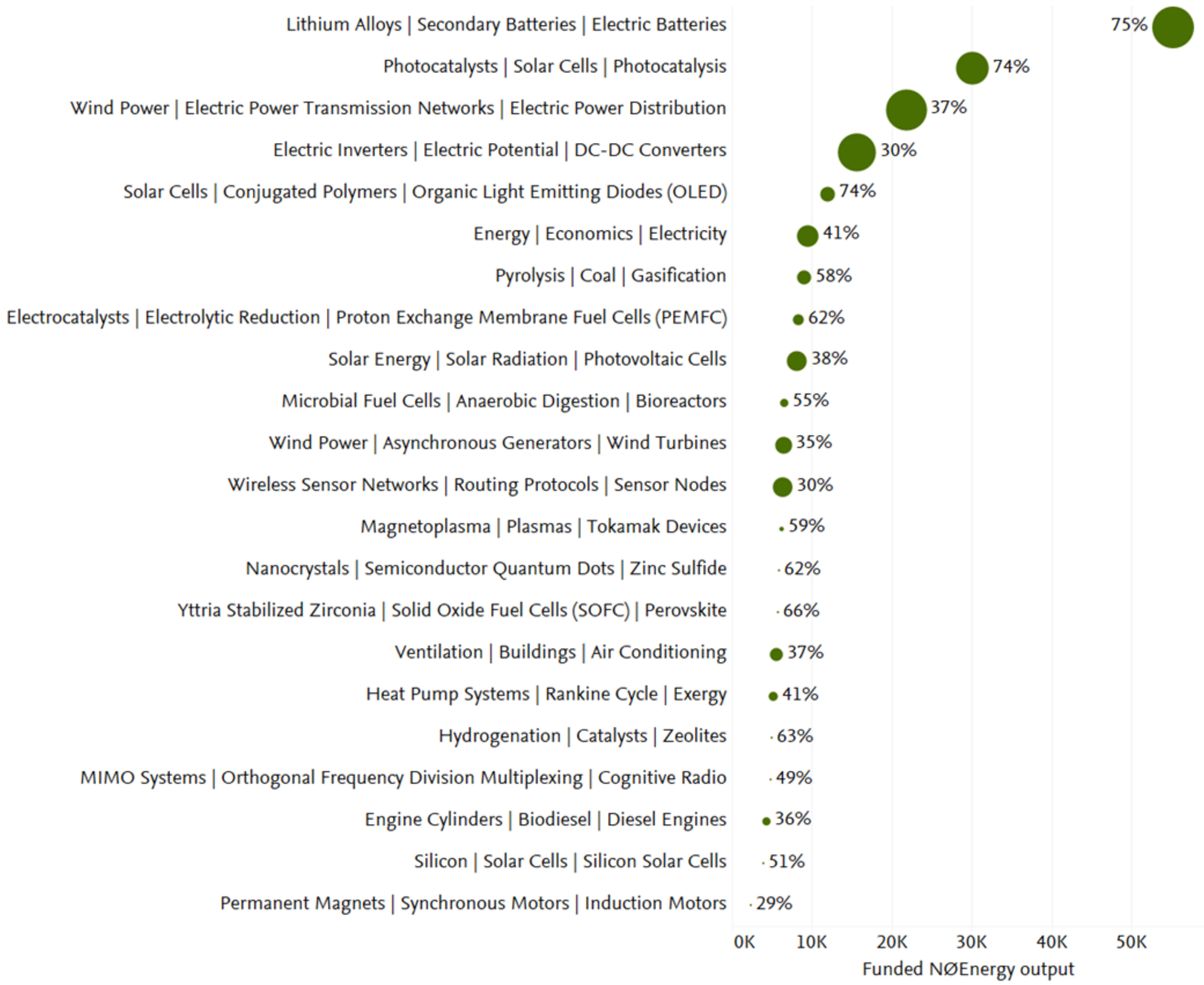


Figure 9
Number of NØEnergy publications with an acknowledged funding source by topic cluster for those clusters accounting for 1% or more publications in 2016–2020. The position of the bubble indicates the output of funded NØEnergy publications, the size of the bubble indicates the overall output and the percentages outside the bubble indicate the share of funded publications in that topic cluster.
Source: Scopus

Figure 10 shows the funded output of the top 20 funders and topic clusters where the share in that topic cluster accounted for 5% or more of the funded output of the agency. This shows that while most of these agencies were acknowledged highly for *Lithium Alloys / Secondary Batteries / Electric Batteries* and *Photocatalysts / Solar Cells / Photocatalysis* there are also differences across topic clusters. We see, for example, that the while European and US agencies were very prominent in *Magnetoplasma / Plasmas / Tokamak Devices*, Chinese agencies were not as present, despite the activity of output. On the contrary, we see that Asian funders are more visible for *Solar Cells / Conjugated Polymers / Organic Light Emitting Diodes (OLED)* as opposed to other agencies.

Agency	Cluster Keywords: Lithium Alloys | Secondary Batteries | Electric Batteries	Photocatalysts | Solar Cells | Photocatalysis	Wind Power | Electric Power Transmission Networks | Electric Power Distribution	Electric Inverters | Electric Potential | DC-DC Converters	Solar Cells | Conjugated Polymers | Organic Light Emitting Diodes (OLED)	Energy | Economics | Electricity	Electrocatalysts | Electrolytic Reduction | Proton Exchange Membrane Fuel Cells (PE..	Magnetoplasma | Plasmas | Tokamak Devices
National Natural Science Foundation of China	24%	11%	5%					
Fundamental Research Funds for the Central Universities	26%	13%						
National Science Foundation	13%	8%	6%					
U.S. Department of Energy	19%	7%						6%
National Research Foundation of Korea	21%	13%			7%			
National Key Research and Development Program of China	22%	11%	7%					
Horizon 2020 Framework Programme		6%	6%					14%
China Postdoctoral Science Foundation	29%	13%						
Engineering and Physical Sciences Research Council	8%	9%	7%					
National Basic Research Program of China (973 Program)	23%	11%	8%		5%			
Japan Society for the Promotion of Science	11%	13%			6%			
European Commission			7%			6%		
Ministry of Science, ICT and Future Planning	21%	14%			7%			
European Regional Development Fund	5%		8%	6%				
Chinese Academy of Sciences	27%	13%			12%			
China Scholarship Council	21%	10%						
Office of Science	26%	11%			10%			7%
Natural Sciences and Engineering Research Council of Canada	15%	5%	5%				6%	
Conselho Nacional de Desenvolvimento Científico e Tecnológico			7%	8%				
Natural Science Foundation of Jiangsu Province	26%	16%			7%			

Figure 10
Selected funded output share by topic cluster and funder for 2016–2020.
Source: Scopus

1.3 What are the national trends in NØEnergy research?

China leads the way with the largest number of publications in NØEnergy research, followed by the United States, but Saudi Arabia, India and Russia have shown the largest growth since 2011.

From a national perspective, China has a clear lead in NØEnergy publications, producing nearly 400,000 publications between 2001 and 2020, followed by the United States with 280,000. India, Germany and Japan complete the top five countries in terms of output. All the countries and regions that contributed to at least 1% of NØEnergy publications between 2001 and 2020 are shown in Figure 11.

Overall, 24 countries and regions contributed to at least 1% of the total global output in NØEnergy. This group of countries and regions is very similar to those that contributed to at least 1% of the total global output. The exceptions are Malaysia, Denmark and Singapore, each of which contributed to less than 1% of the total global output but more in NØEnergy. Malaysia contributed to only 0.7% of all publications during 2001–2020, but to 1.4% of NØEnergy publications over the same period. Similarly, while Singapore contributed to 0.6% of total global output, it contributed to 1% of NØEnergy publications. Other countries and regions not shown in the chart that published more than 5,000 NØEnergy publications and contributed to a higher proportion of publications in this area than overall include Hong Kong, Portugal, Saudi Arabia, Norway, Finland, Greece, Indonesia, Egypt, Thailand, Pakistan, Romania, Algeria, Morocco, Tunisia and the United Arab Emirates.

> *"To address climate change we need everyone involved, and one of the biggest issues that we face consistently is ensuring that all countries have the capacity they need to make progress: where is the research being produced, who's producing the research?"*
>
> Leon Clarke, Acting Director and Research Director, Center for Global Sustainability, University of Maryland at College Park

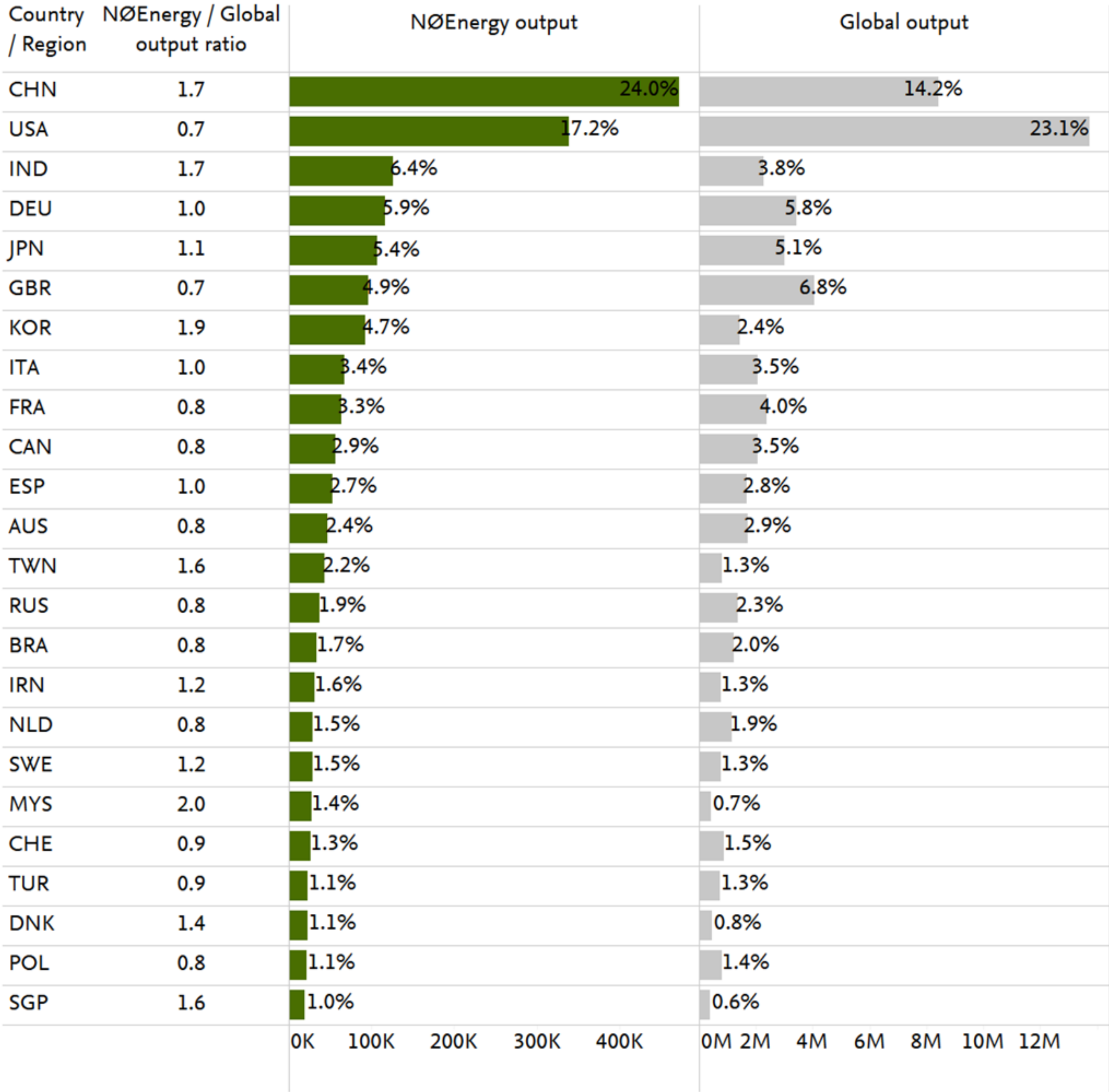


Figure 11
NØEnergy and overall global output by countries and regions that contributed to at least 1% of NØEnergy publications, 2001–2020. The number next to the country and region code indicates the ratio of NØEnergy share divided by overall share, where 1.0 indicates a higher share than the global average.
Source: Scopus

In the previous section, we showed that the number of publications acknowledging a Chinese funding agency has grown steadily, while the those citing a US agency have remained stable or declined. This observation is in line with the general trends in national NØEnergy output. China's NØEnergy output overtook that of the United States in 2012 (Figure 12) and has shown exponential growth. In contrast, output from the United States shows a more modest increase. China's strong growth in NØEnergy echoes overall research trends across all subjects, but it is worth noting that while China's total output overtook that of the United States in 2020[17] (Figure 13), this happened much earlier in NØEnergy.

During this period, India emerged ahead of other countries and regions, surpassing Germany in 2015 and achieving the third largest annual output by 2020. India has followed a similar trajectory to China: while its overall research output was the fourth largest as of 2019, its output in NØEnergy was the third largest as of 2015, four years earlier.

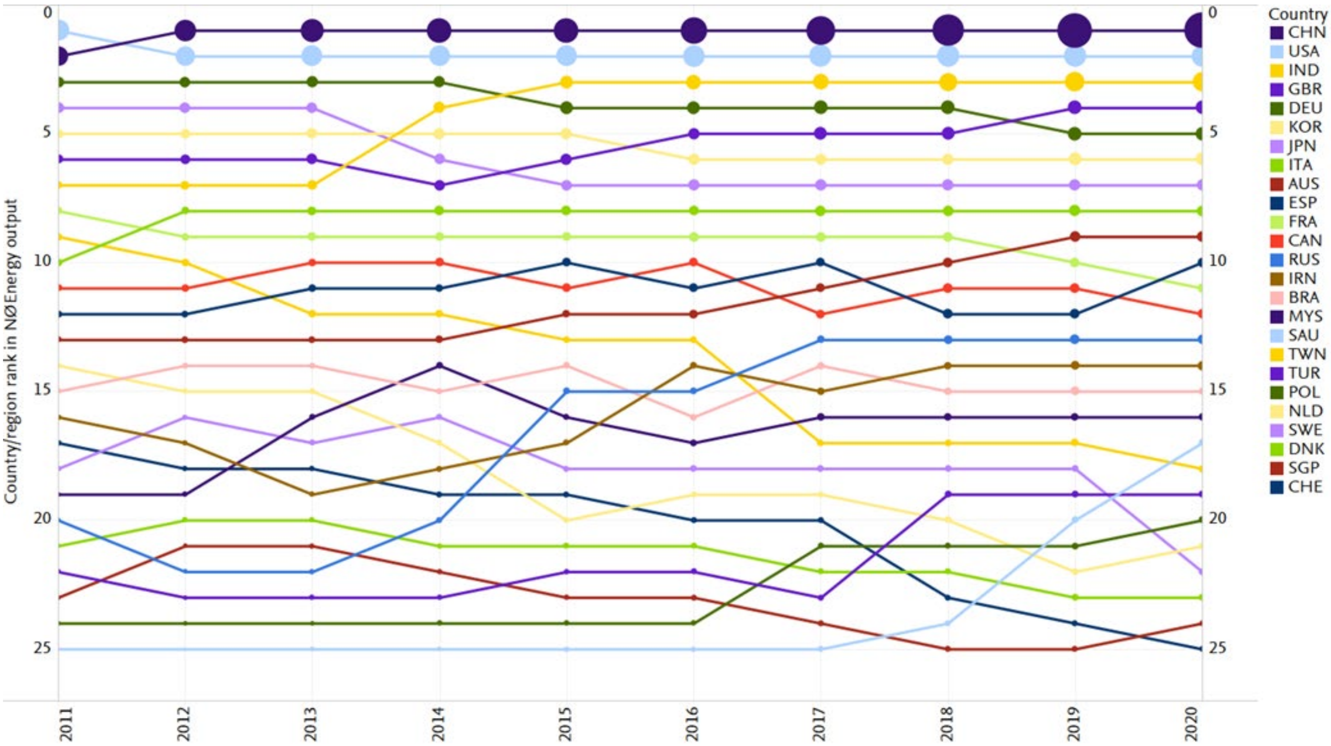


Figure 12
Scholarly output trends for countries and regions contributing to at least 1% of output in NØEnergy, 2011–2020. Countries and regions indicated with a colored line demonstrate a compound annual growth rate of over 10%, except Taiwan, which shows a negative growth rate. Y-axis is a logarithmic scale starting at 10 publications.
Source: Scopus

[17] Based on Scopus data.

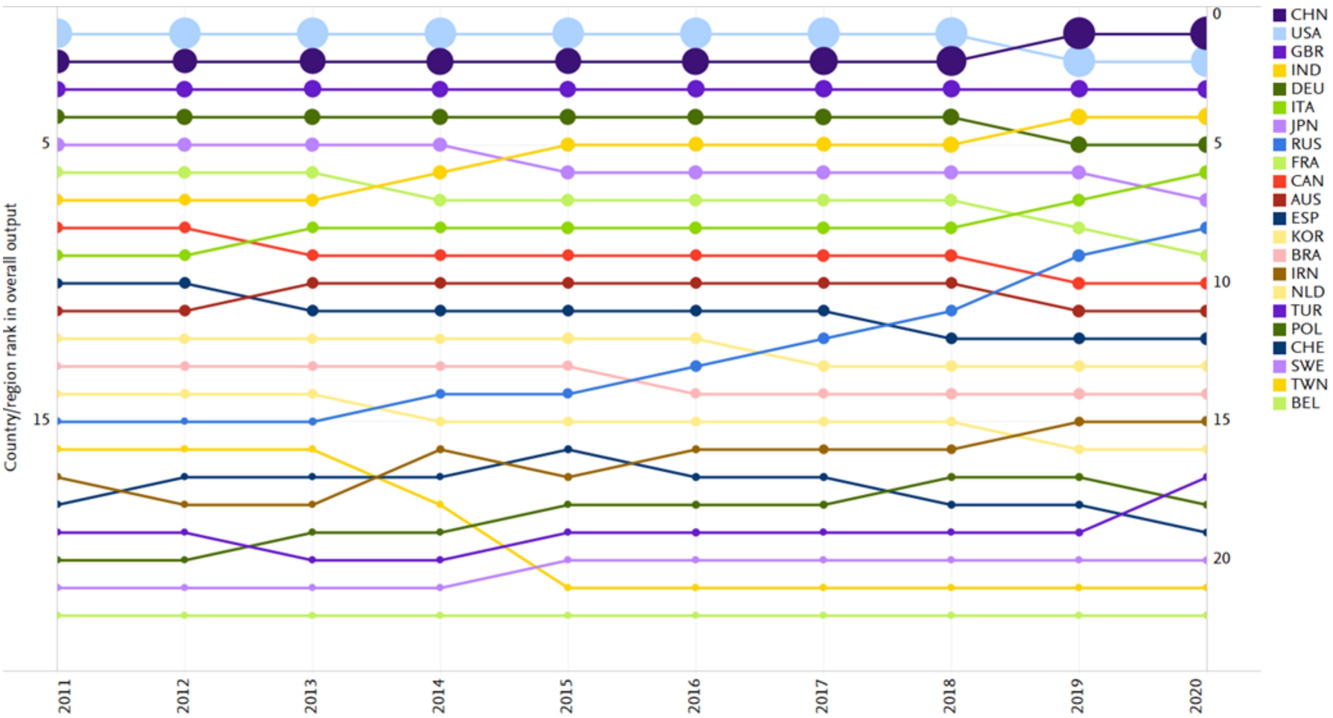


Figure 13
Overall scholarly output for countries and regions that contributed to at least 1% of overall output, 2011–2020.
Source: Scopus

Among those countries and regions contributing to at least 1% of the total global output in NØEnergy, Saudi Arabia (CAGR of 28.6%), India (20.7%) and Russia (18.8%) showed the highest growth during 2011–2020 (Figure 14). In addition, of those countries and regions that published a minimum of 10,000 publications between 2011 and 2020, Indonesia (36.2%), Egypt (28.6%), Iran (15.9%) and Hong Kong (15.1%) also demonstrated very high growth rates. Morocco, Nigeria, Pakistan and Vietnam are also worth noting for growth rates of over 20% and outputs that rose from a few hundred publications in 2001–2010 to a few thousand in 2011–2020.

> *"At present, many countries have committed to carbon neutrality plans, but the time frames for each country to reach carbon neutrality will differ. Therefore, the time costs and implementation effects of R&I for new technologies are the important factors for a country or region to consider in choosing this clean technology."*
>
> Yutao Wang, Professor, Department of Environmental Science and Engineering, Fudan University

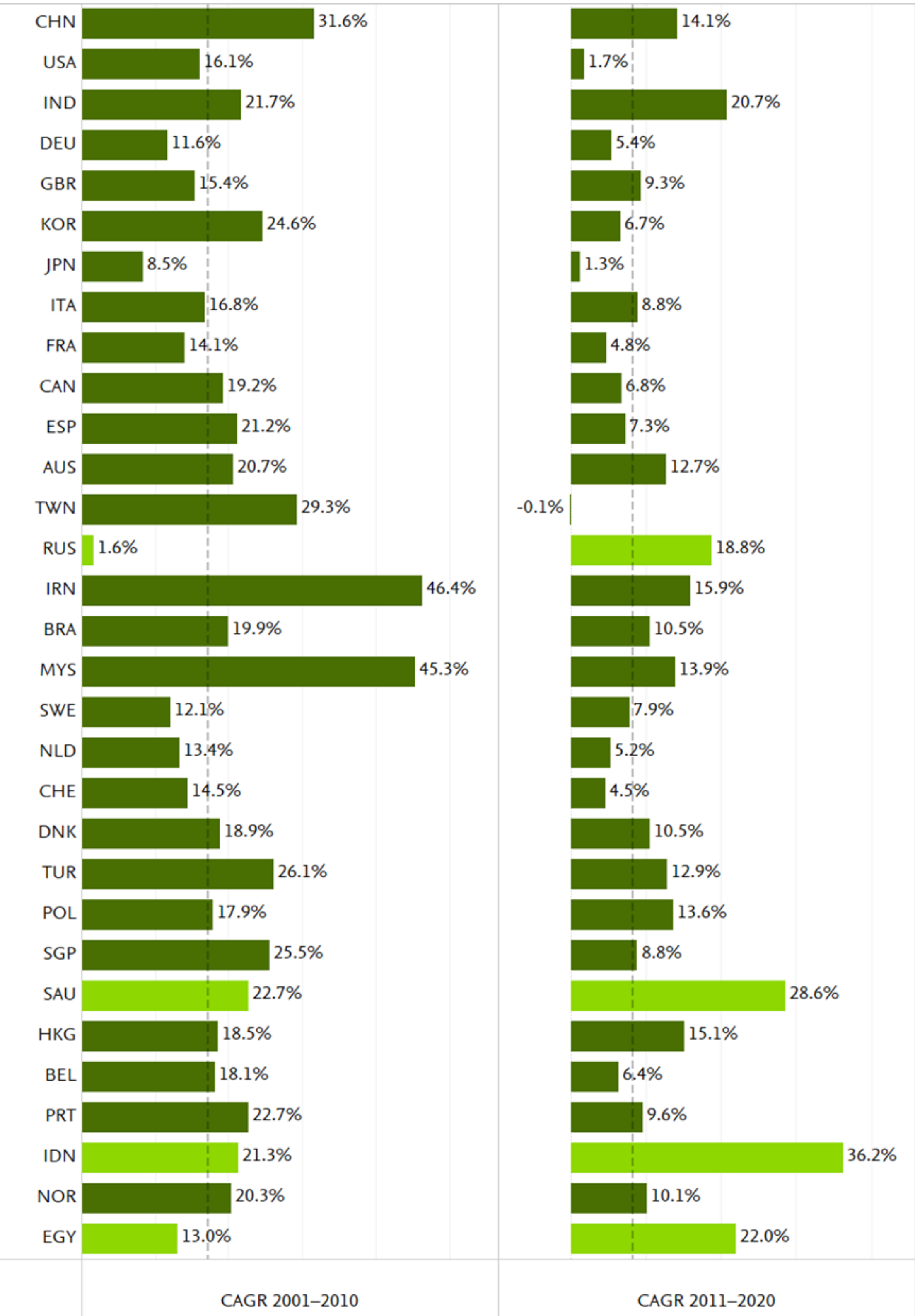


Figure 14
Compound annual growth rate in NØEnergy publications for countries and regions reporting at least 10,000 publications in 2011–2020. Countries and regions marked in light green had a higher growth rate over the latter period (2011–2020).
Source: Scopus

Specialization and scholarly impact of NØEnergy

Do countries and regions that are more specialized in NØEnergy also have higher scholarly impact in the field? Our analysis aims to capture scholarly impact through the FWCI (see the definition of this indicator in Section 1.1).

The level of specialization of a country or region in a certain area is indicated by the relative activity index (RAI). In this case, relative activity is calculated by comparing a country's or region's share of publications in NØEnergy with the global share of NØEnergy publications, which was over 4% for the period 2011–2020.

Figure 15 maps FWCI versus RAI for those countries and regions that contributed to least 1% of NØEnergy publications during 2011–2020.

Singapore, Denmark and Saudi Arabia show the highest levels of both specialization and scholarly impact, despite producing a relatively lower number of publications in the field. Switzerland, Australia, the United States, the United Kingdom, the Netherlands and Canada, meanwhile, display high scholarly impact despite having less specialization in NØEnergy. Asian countries and regions such as China, South Korea, India, Malaysia and Taiwan tend to be more specialized in general compared with their European and North American counterparts, but their scholarly impact is more limited. The relatively higher specialization of Asian countries and regions in NØEnergy may be driven by their focus in relevant areas such as materials science.

Of the remaining 71 countries and regions that published more than 1,000 NØEnergy publications but are smaller players in the field, 15 have a higher FWCI than the global average. Qatar leads this group with an FWCI of 2.1, arising from its publications in computing-related topic clusters such as *Wireless Sensor Networks / Routing Protocols / Sensor Nodes*, *Distributed Computer Systems / Cloud Computing / Clouds* and *Authentication / Cryptography / Data Privacy*.

Relative activity index

The relative activity index (RAI) is defined as the share of a country's or region's article output in a topic cluster relative to the global share of articles in the same topic cluster. A value of 1.0 indicates that a country's or region's research activity in a field corresponds exactly with the global activity in that field; a value higher than 1.0 implies a greater emphasis; and a value lower than 1.0 suggests a lesser focus.

Countries will tend to specialize in areas that are important to them, or where they already have the basis for expertise—for example, if they've got a university or research institution that has strengths and history in a particular area. This does underscore the need for international collaboration though, because otherwise gaps might not be addressed. It's not enough that each country will bring to the table what it's quite good at, or experienced in, or willing to fund. We have to take a broader view and see where the gaps are and how they can be filled.

Joan MacNaughton, CB HonFEI (Lady Jeffrey), Chair, Climate Group

Figure 15
Average field-weighted citation impact versus relative activity index per country or region, for those contributing to at least 1% of all NØEnergy publications, 2011–2020. Bubble size indicates the NØEnergy output of the country or region.
Source: Scopus

Figure 16 shows the RAI for countries and regions that contributed to at least 1% of all NØEnergy publications between 2011 and 2020 over two time periods: 2001–2010 and 2011–2020. China maintained and even slightly increased its level of specialization during these periods, while also increasing its output. India, Singapore and Saudi Arabia increased their specialization notably from the first period to the second, whereas South Korea, Japan and Taiwan saw their level of specialization decline. Among other countries and regions not shown in the chart but that produced more than 1,000 publications, Algeria, Morocco, Tunisia, the United Arab Emirates, Qatar, Pakistan, Bangladesh and Vietnam also increased their degree of specialization considerably compared with the global average.

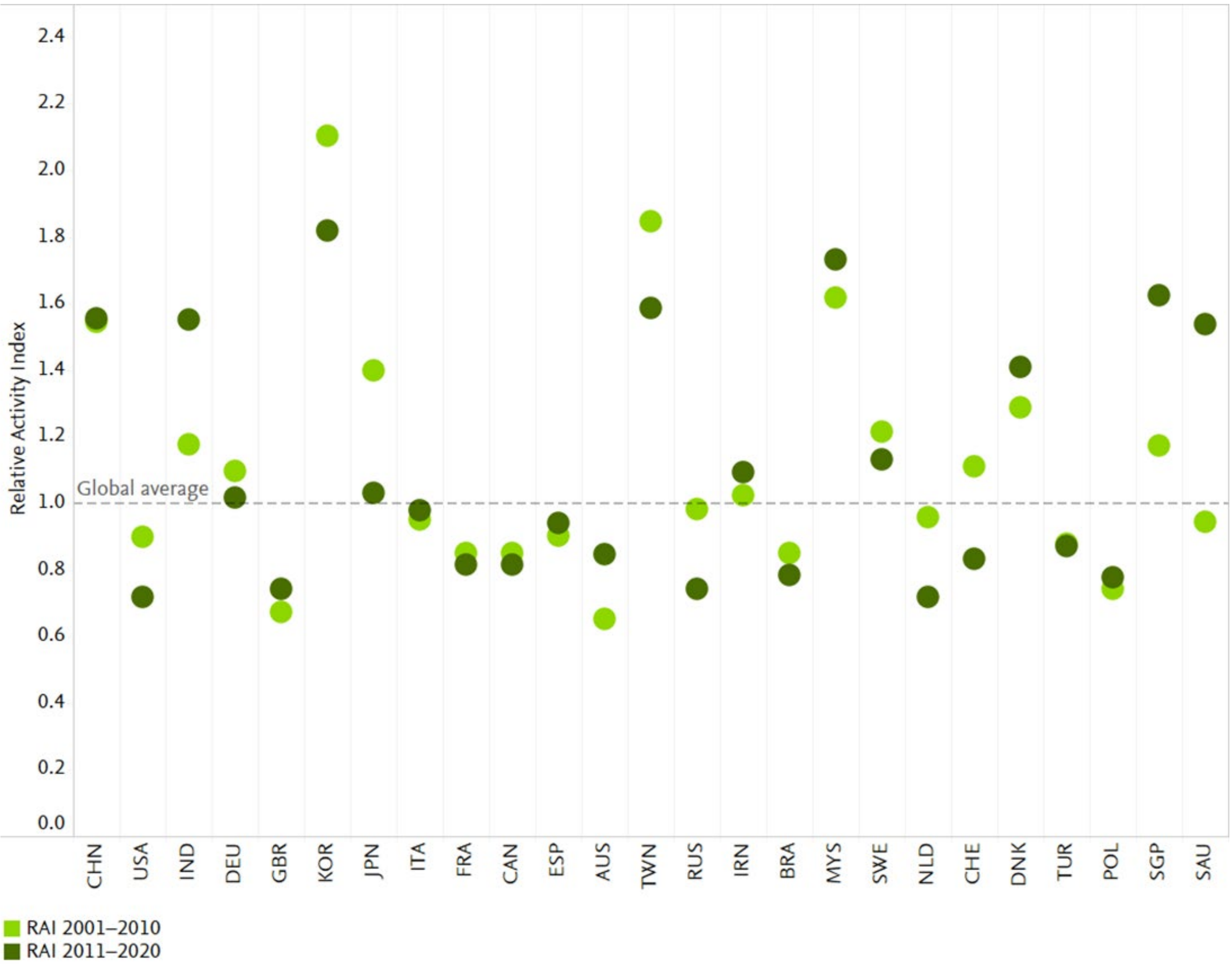


Figure 16
Relative activity index of countries and regions contributing to at least 1% of all NØEnergy publications, 2011–2020. Countries and regions are ranked by their output from left to right on the horizontal axis.
Source: Scopus

Different countries and regions, of course, tend to have different specializations for numerous reasons. As it is not possible to display the specializations of all countries and regions in this report, we focus on the three with the largest number of NØEnergy publications during 2011–2020 and the 20 most highly represented topic clusters. China, which produced the most NØEnergy publications, is most strongly represented in *Lithium Alloys | Secondary Batteries | Electric Batteries* and is three times more specialized in this area than the global average (Figure 17). In fact, in most of the topic clusters in which China is represented over this period, it had a higher degree of specialization than the global average, with the notable exception of *Engine Cylinders | Biodiesel | Diesel Engines*.

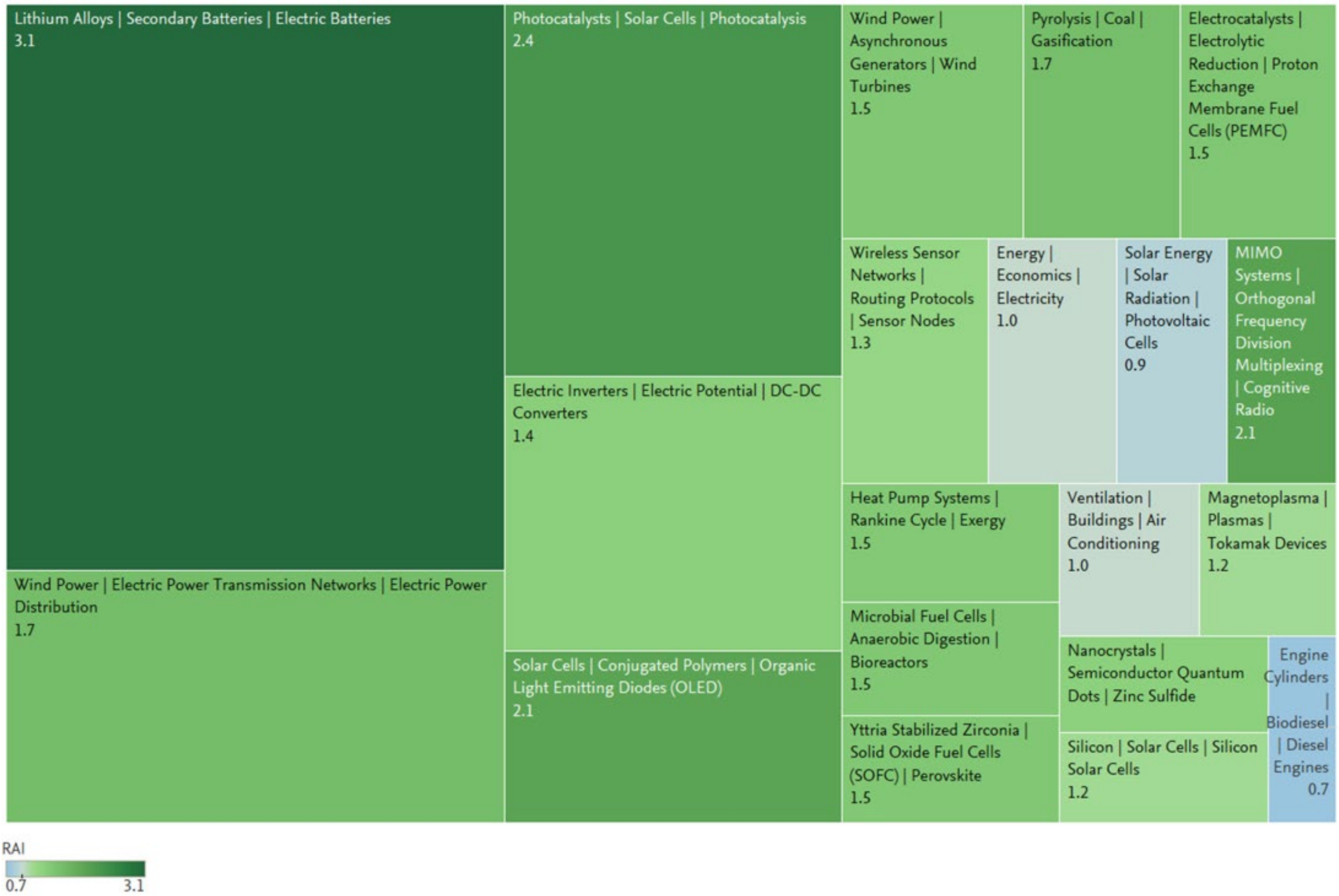


Figure 17
Top 20 topic clusters by output for China, 2011–2020. The relative activity index is indicated within the boxes.
Source: Scopus

Compared with China, the United States—which accounts for the second largest number of publications in NØEnergy—is relatively less specialized in most of the topic clusters in which it is most highly represented, with the exception of *Magnetoplasma | Plasmas | Tokamak Devices* (Figure 18).

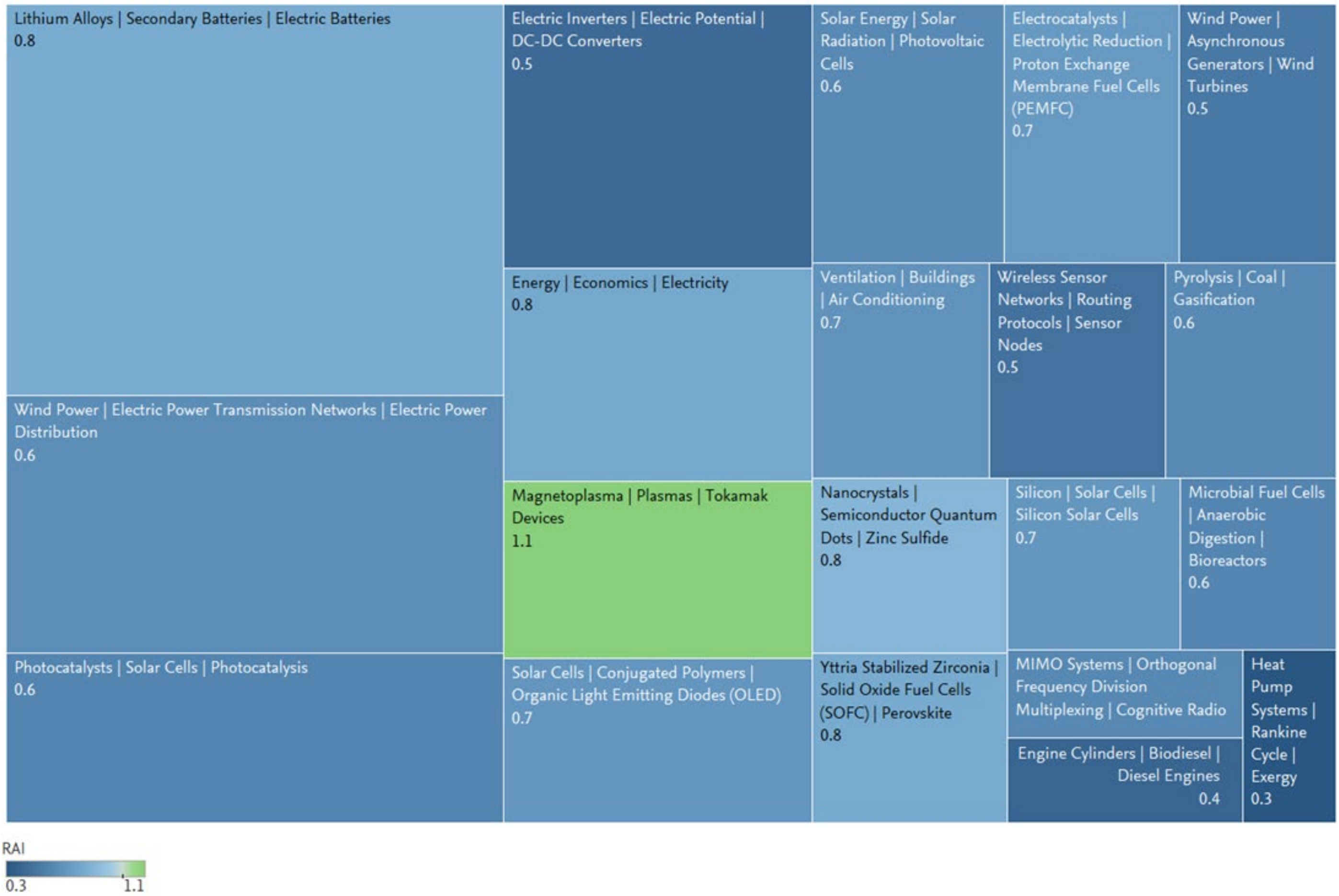


Figure 18
Top 20 topic clusters by output for the United States, 2011–2020. The relative activity index is indicated within the boxes.
Source: Scopus

India, which produced the third largest number of publications over this period, is most highly represented in the *Electric Inverters | Electric Potential | DC-DC Converters* topic cluster, in which it is also highly specialized. The country's other areas of specialization include *Engine Cylinders | Biodiesel | Diesel Engines* and *Wireless Sensor Networks | Routing Protocols | Sensor Nodes* (Figure 19).

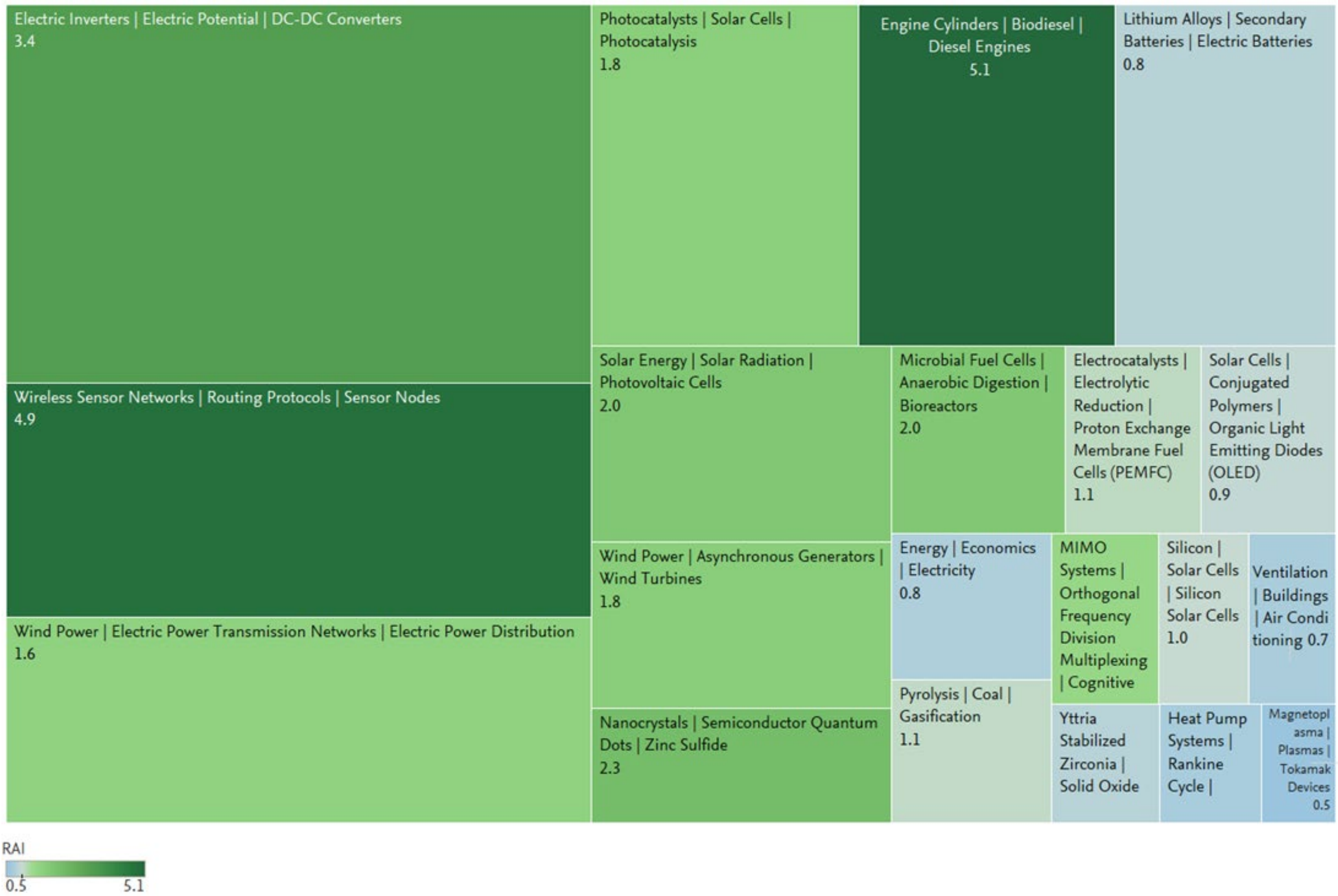


Figure 19
Top 20 topic clusters by output for India, 2011–2020. The relative activity index is indicated within the boxes.
Source: Scopus

Table 1 presents country/region–topic cluster pairs in terms of the highest FWCI for those that contributed to at least 1% of the total NØEnergy output for the period 2011–2020, because displaying the scholarly impact per topic cluster and FWCI is not possible.

Singapore and Switzerland show the highest FWCI values in several categories. Russia also achieved a very high overall FWCI value, primarily arising from 14 publications with exceptional scores of over 100 focused on the use of methanol in diesel engines. However, it should be noted that most of the citations appeared in other Russian publications, indicating a limited international reach.

Topic cluster	World FWCI	Top countries/regions by FWCI	FWCI of the top countries/regions
Lithium Alloys | Secondary Batteries | Electric Batteries	2.4	SGP	4.2
Photocatalysts | Solar Cells | Photocatalysis	2.3	CHE	6.1
MIMO Systems | Orthogonal Frequency Division Multiplexing | Cognitive Radio	1.9	SGP	6.3
Solar Cells | Conjugated Polymers | Organic Light Emitting Diodes (OLED)	1.8	DNK	3.7
Wireless Sensor Networks | Routing Protocols | Sensor Nodes	1.5	SGP	3.9
Engine Cylinders | Biodiesel | Diesel Engines	1.5	RUS	15.2
Pyrolysis | Coal | Gasification	1.5	SGP	2.9
Wind Power | Electric Power Transmission Networks | Electric Power Distribution	1.5	SGP, DNK	2.5
Nanocrystals | Semiconductor Quantum Dots | Zinc Sulfide	1.4	CAN	3.4
Electric Inverters | Electric Potential | DC-DC Converters	1.4	DNK	3
Hydrogenation | Catalysts | Zeolites	1.4	SGP	2.6
Energy | Economics | Electricity	1.4	TUR	2.4
Microbial Fuel Cells | Anaerobic Digestion | Bioreactors	1.3	SAU	2.2
Electrocatalysts | Electrolytic Reduction | Proton Exchange Membrane Fuel Cells (PEMFC)	1.3	SGP, CHE	1.9
Yttria Stabilized Zirconia | Solid Oxide Fuel Cells (SOFC) | Perovskite	1.2	SAU, AUS	2
Heat Pump Systems | Rankine Cycle | Exergy	1.2	IRN	2.2
Ventilation | Buildings | Air Conditioning	1.2	SGP, CHE	2.1
Solar Energy | Solar Radiation | Photovoltaic Cells	1.1	AUS	2
Wind Power | Asynchronous Generators | Wind Turbines	1.1	NLD	2
Permanent Magnets | Synchronous Motors | Induction Motors	1.1	ITA	2.2
Silicon | Solar Cells | Silicon Solar Cells	1	NLD	2
Magnetoplasma | Plasmas | Tokamak Devices	1	MYS	2.7

Table 1
Top countries/regions by field-weighted citation impact among those countries/regions and topic clusters that contributed to at least 1% of the total NØEnergy output, 2011–2020.
Source: Scopus

It is worth highlighting some other country/region–topic cluster pairs that had an average FWCI value of 2.0 or more. The United Kingdom, for example, had the highest impact in *Organometallics / Ligands / Crystal Structure* during 2011–2020, with an average FWCI value of 3.7, compared with the global average of 2.6. The United States and Germany also achieved FWCI values over 3.0, with China, Japan and France demonstrating scholarly impact above the global average in this topic cluster.

The United States had the highest scholarly impact in the topic cluster *Models / Algorithms / Computer Vision* over the same period, with an average FWCI value of 4.3, well above the global average value of 2.4. South Korea, the United Kingdom and Italy also ranked above the global average in this area.

The *Ruthenium / Ligands / Catalysts* topic cluster, which is associated with sustainable hydrogen production, was dominated by Canada with an average FWCI value of 4.5, well above the global average of 2.3. The Netherlands, the United States, France, Switzerland and China also demonstrated FWCI values above the global average in this field.

Saudi Arabia led the *Authentication / Cryptography / Data Privacy* topic cluster, with an average FWCI value of 3.2. The United States, Australia, Canada, Italy, Singapore, the United Kingdom, Taiwan and South Korea also displayed FWCI values above the global average of 2.1.

France, with an FWCI value of 4.2, led Italy, the United States and the United Kingdom, all of which had higher FWCI values than the global average (of 2.0), in the topic cluster *Internet / Technology / Radio Frequency Identification (RFID)*.

In the topic cluster *Intrusion Detection / Computer Crime / Network Security*, where the global average was 2.0, the United Kingdom had the highest FWCI value of 3.4, followed by the United States and India.

Finally, many countries and regions achieved higher than the global average FWCI values (2.0) in the topic cluster *Distributed Computer Systems / Cloud Computing / Clouds*. Hong Kong took the top spot with an average FWCI value of 7.1, followed by Australia, Canada, Finland, Singapore, the United States, the United Kingdom, Sweden, Italy, South Korea, Saudi Arabia, Brazil, France, Spain, Switzerland and Greece.

1.4 How interdisciplinary is NØEnergy research?

Achieving net zero will require the concerted efforts of many different scientific areas. But NØEnergy research tends to be focused on a few disciplines, which could limit its ability to produce the societal outcomes needed to combat climate change.

A key tenet of current research strategy is that approaches integrating ideas, practices and people from different disciplines are more likely than a monodisciplinary focus to lead to durable change in social, economic and policy practice. This is particularly the case for grand challenges such as climate change, where NØEnergy research must, to fulfill its innovation and development promise, tap into a broad range of diverse disciplines.[18]

Here we present an overview of cross-disciplinary practices and achievements in NØEnergy research in general and in specific topic clusters within the field. When we talk about the disciplinary diversity of research, we mean the diversity of influences on research rather than the discipline in which the research itself is categorized (see text box next page). The disciplinary nature of research can take many forms, but in this section we focus on two: conceptual diversity and collaborative diversity.[19]

Two key findings about the disciplinary makeup of NØEnergy research emerge from our analysis:

- The largest topic clusters in this field tend to be comparatively monodisciplinary or record an average level of disciplinary diversity, whereas smaller topic clusters in areas such as biofuels, carbon capture or energy economics are more diverse.
- Research related to Climate Action (SDG 13) is highly diverse, both conceptually and in terms of team composition, but makes up only a small proportion of the total number of NØEnergy publications. Research on Affordable and Clean Energy (SDG 7), by contrast, produces many more publications, but these are much more uniform in their disciplinarity.

[18] Schneider, F., Buser, T., Keller, R., Tribaldos, T., & Rist, S. (2019). Research funding programmes aiming for societal transformations: Ten key stages. *Science and Public Policy, 46*(3), 463–478. doi:10.1093/scipol/scy074; Van der Hel, S. (2016). New science for global sustainability? The institutionalisation of knowledge co-production in Future Earth. *Environmental Science and Policy, 61*, 165–175. doi.org/10.1016/j.envsci.2016.03.012; Belmont Forum. (2016). *The Belmont Challenge: a global, environmental research mission for sustainability* [White paper]. https://www.belmontforum.org/wp-content/uploads/2017/04/belmont-challenge-white-paper.pdf

[19] Pinheiro, H., Vignola-Gagné, E., & Campbell, D. (2021). A large-scale validation of the relationship between cross-disciplinary research and its uptake in policy-related documents, using the novel Overton altmetrics database. *Quantitative Science Studies*, 1–40. doi:10.1162/qss_a_00137

In general, NØEnergy research displays average levels of collaborative and conceptual diversity, with scores for 2011–2020 of 1.02 and 0.99 respectively, against a benchmark of 1.00 (data not shown). In the same period, the field also had an average level of publications with exceptionally high collaborative diversity (9.5%), which is close to the benchmark level of 10%, but the level of publications with exceptionally high conceptual diversity was below average (7.1%) (data not shown).

On balance, the field appears to be average or slightly more uniform in its disciplinary makeup compared with other areas of research. The field records many average scores in diversity measures, a performance that is arguably below expectations, given the push for cross-disciplinarity research to tackle the grand challenges presented by climate change and the achievement of net zero.

As Figure 20 shows, the SDG 7 component of NØEnergy publications underpins the disciplinary uniformity of the field. NØEnergy publications related to SDG 13, by contrast, record higher scores for both disciplinary indicators, but because these publications make up only 3.5% of the total number in NØEnergy, their influence is limited.

Conceptual diversity and collaborative diversity

Conceptual diversity or interdisciplinarity

This indicator relates to the diversity of the disciplines associated with the prior findings on which the research is based and that are cited within the publication (i.e., the thematic subfields associated with the references). The interdisciplinarity indicator captures the conceptual underpinnings of research. In this report, we also refer to this as "conceptual diversity".

Collaborative diversity or multidisciplinarity

This indicator relates to the diversity arising from collaboration between co-authors from different disciplines contributing to a research publication (i.e., the topics associated with the prior publications of the authors).

This multidisciplinarity indicator captures the collaborative underpinning and team composition of research. In this report, we also refer to this as "collaborative diversity".

Scores for these indicators are 1.00 at the global level (for a given subfield): a field will score above 1.00 if it is more diverse than the global average and less than 1.00 if it is below the global average.

It is also possible to measure the percentage share of a publication set that achieves exceptionally high levels of either interdisciplinarity or multidisciplinarity. In this report, we discuss publications that are within the top 10% most interdisciplinary or multidisciplinary within their field. For these indicators, a score of more than 10% is above average and a score of less than 10% is below.

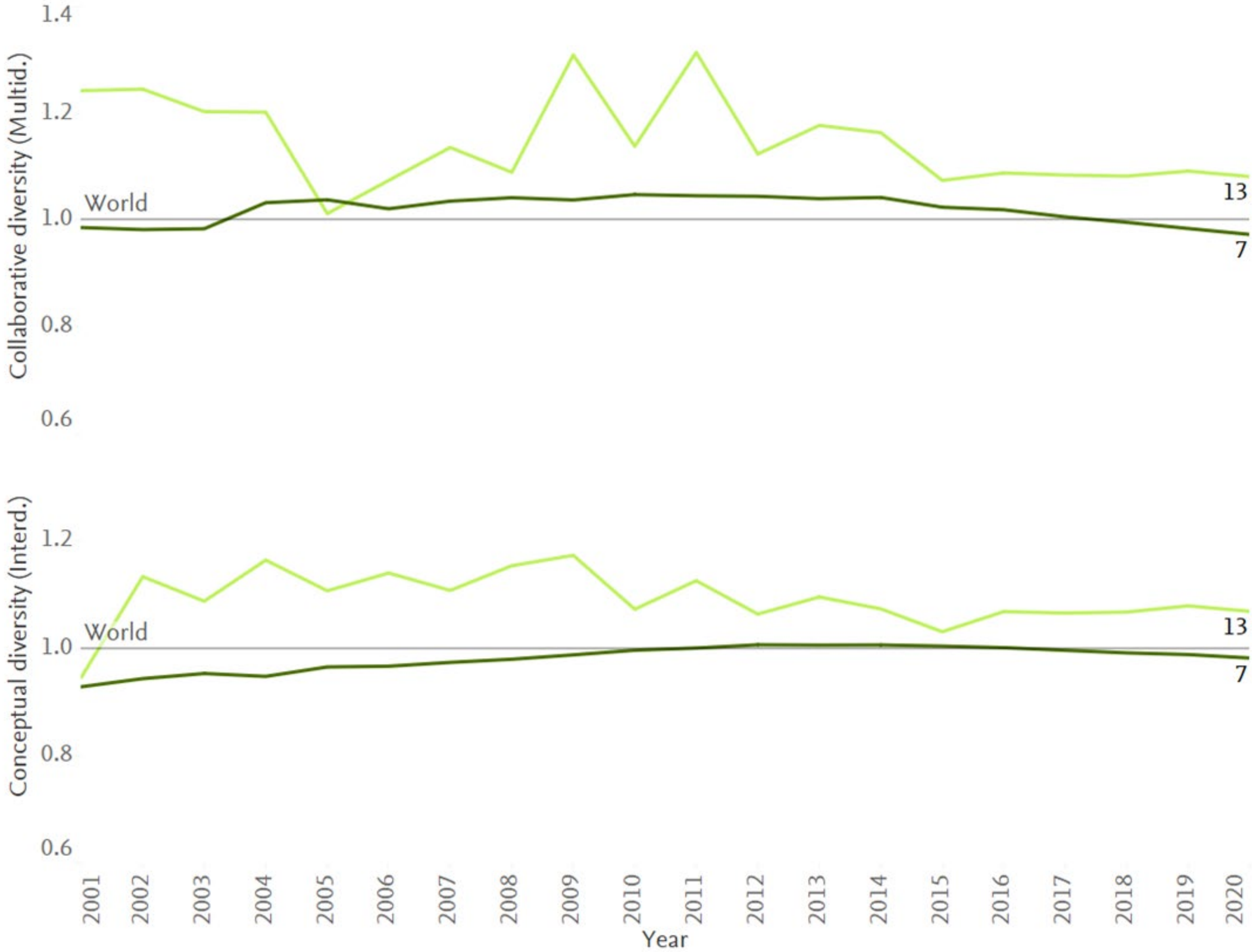


Figure 20
Trends in the disciplinarity diversity of NØEnergy publications, shown in relation to the data sets for Affordable and Clean Energy (SDG 7) and Climate Action (SDG 13), 2001–2020.
Source: Scopus

> *"Research on complex, multidisciplinary and transdisciplinary issues central to achieving the SDGs increasingly utilizes large data sets to accelerate the generation of knowledge. Understanding the implications of synergies and trade-offs among the goals would require continued monitoring and research to develop better data-driven tools and services for policymakers, institutional leaders and the research community."*
>
> Franklin Carrero-Martínez, Senior Director, Global Sustainability and Development & Science and Technology for Sustainability, National Academy of Sciences, Engineering, and Medicine

The degree of conceptual diversity (or interdisciplinarity) of the field is even more apparent in the chord diagrams presented in Figure 21 and Figure 22. These diagrams visually represent the strength of connections between different disciplines within a given topic. Stronger connections are represented by thicker lines, with blue/violet-colored links connecting intellectually distant disciplines and pink/orange-colored links between more similar subfields.

The first figure shows the strength of interdisciplinary connections within the *Lithium Alloys / Secondary Batteries / Electric Batteries* topic cluster, relative to average levels. In the chord diagram, interdisciplinary connections are quite sparse, but some very diverse subfields are connected. Connections between intellectually close subfields (such as Energy, Engineering, Physics and Chemistry) are more frequent and sustained. Most notably, this topic cluster has a strong connection between the Energy and Nanoscience & Nanotechnology subfields.

By contrast, the chord diagram for one the most interdisciplinary topic clusters in NØEnergy, *Energy / Economics / Electricity* (Figure 22), shows multiple connections between diverse subfields and these interdisciplinary connections are much stronger. The strongest links are between the fields of Energy and Economics, followed by Energy and Meteorology & Atmospheric Sciences. The diagram also reveals weaker but still diverse connections between Energy and Ecology, Energy and Business & Management, and Economics and Environmental Sciences. The strongest connection is between Energy and Environmental Sciences, although these subfields are more conceptually proximate.

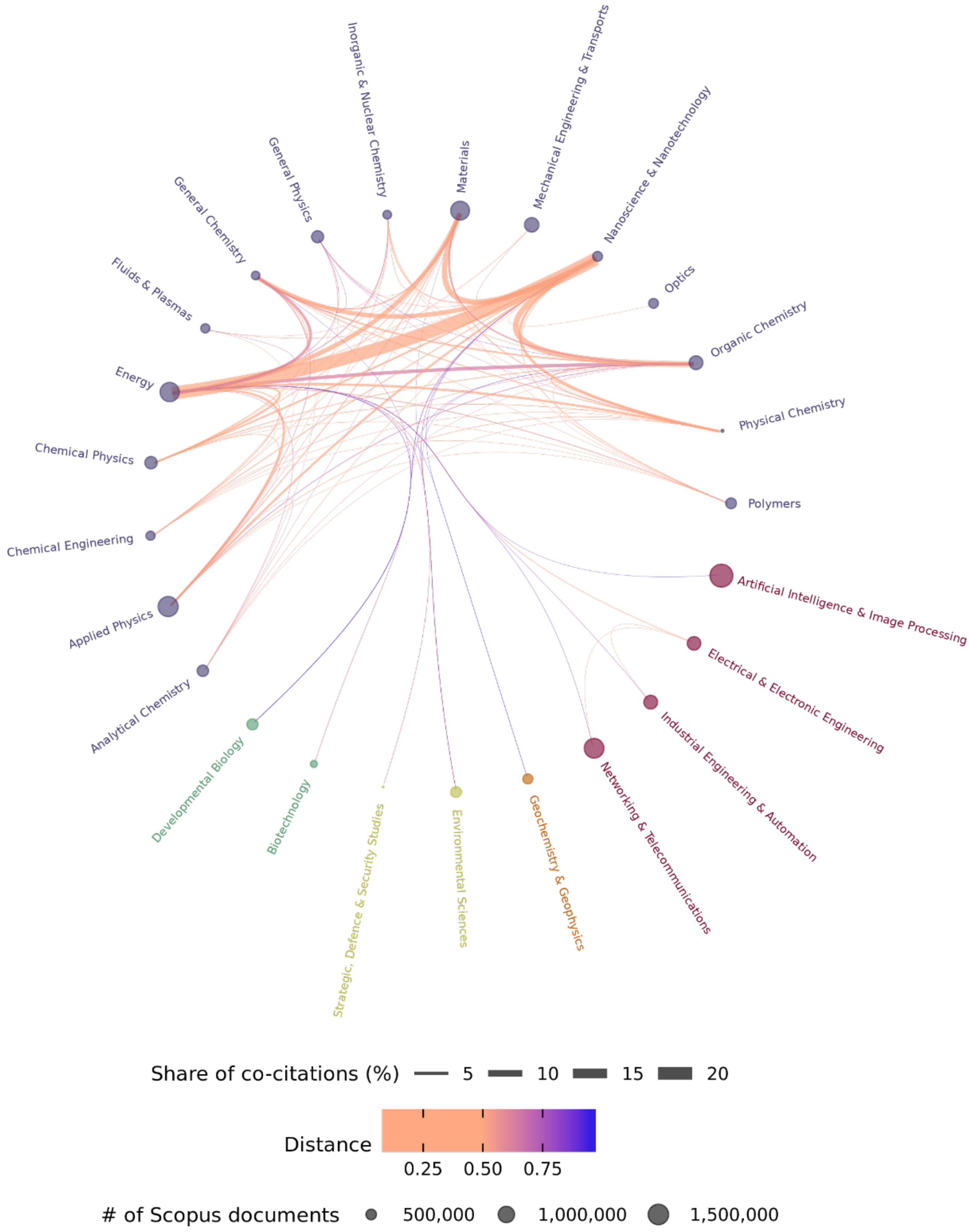


Figure 21
Mapping of interdisciplinary connections within NØEnergy research in the topic cluster *Lithium Alloys | Secondary Batteries | Electric Batteries*, 2011–2020.
Source: Scopus

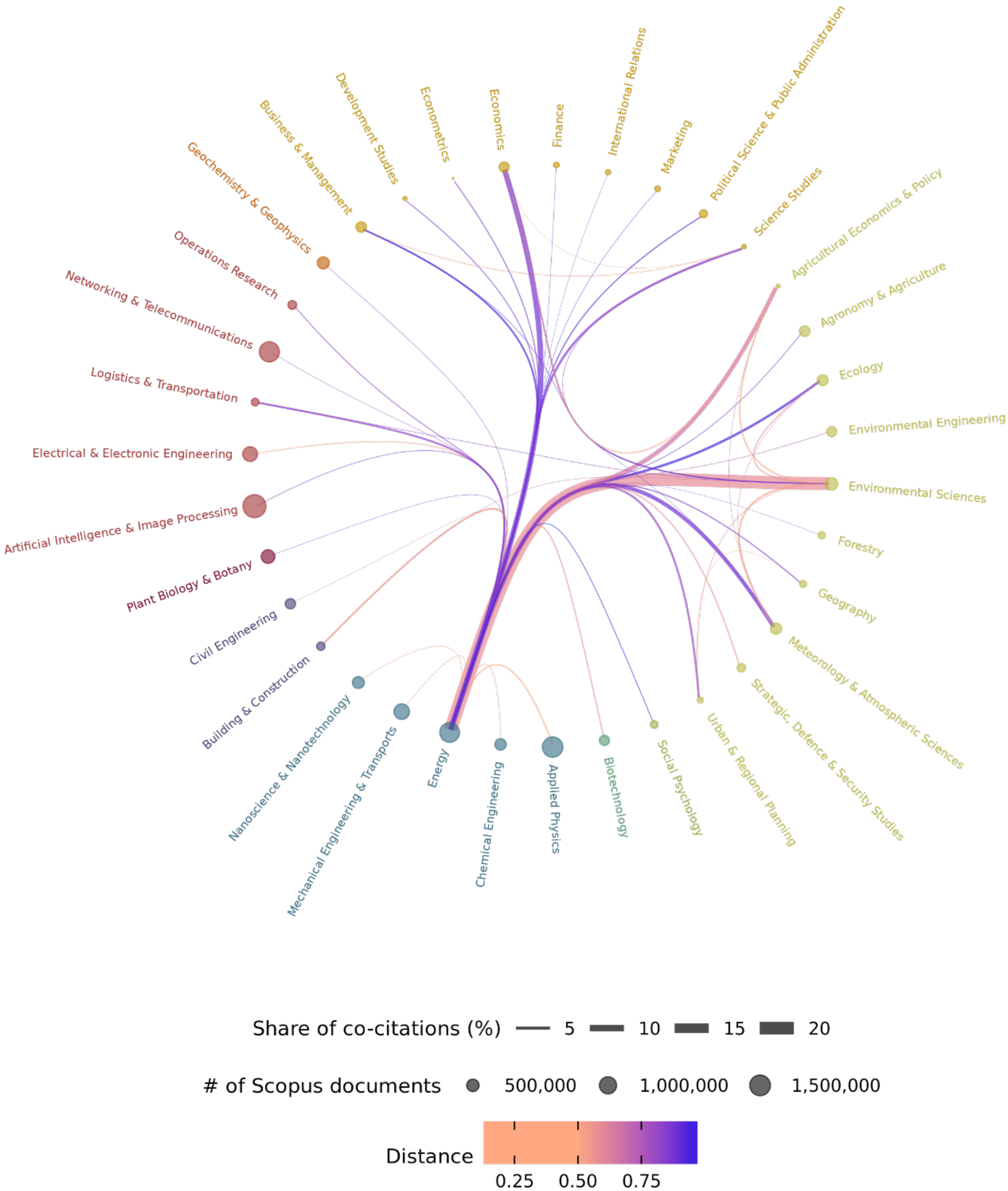


Figure 22
Mapping of interdisciplinary connections within NØEnergy research in the topic cluster *Energy / Economics / Electricity*, 2011–2020.
Source: Scopus

> *"We have to focus on humans because the big beneficiaries of the transition are definitely going to be humans! Figure 22 in the report shows that there isn't a very good connection between research in the core sciences and research in the humanities, in the arts and all those particular areas. That's already exposing a potential failure of the current trend, and if we continue with this current research trend, we're definitely going to have failure. There would be a lot of opposition to the outcomes because you won't have a lot of buy-in ... Our research must be human-centered."*
>
> Chukwuka Monyei, Research Fellow in Energy Justice and Transitions, University of Sussex

Some topic clusters and areas of research appear to either drive or limit the expansion of disciplinary diversity in NØEnergy research. Figure 23 shows the 10 largest topic clusters in NØEnergy by publication volume (each contains between 25,000 and 105,000 articles). These topic clusters reveal an interesting variety of profiles in disciplinary diversity, with the larger clusters tending to show average levels of disciplinarity diversity. Some clusters even tend toward disciplinary uniformity.

Three topic clusters—*Energy / Economics / Electricity*, *Wind Power / Asynchronous Generators / Wind Turbines* and *Photocatalysts / Solar Cells / Photocatalysis*—contain publications that display, on average, high or very high levels of both conceptual and collaborative diversity. Of these, *Energy / Economics / Electricity* is, by far, the most multidisciplinary topic analyzed here.

Our findings also illustrate how collaborative and conceptual diversity can be independent. For example, *Solar Energy / Solar Radiation / Photovoltaic Cells* displays a high degree of collaborative diversity but a low level of conceptual diversity. In other words, although the research teams may be diverse, the supporting literature cited in publications underpinning their strategy and methodology is likely to be more uniform, originating from just a few subfields.

The allied topic cluster of *Solar Cells / Conjugated Polymers / Organic Light Emitting Diodes (OLEDs),* however, is slightly above average in conceptual diversity or interdisciplinarity, with expected levels of collaborative diversity in team composition.

Electrocatalysts / Electrolytic Reduction / Proton Exchange Membrane Fuel Cells (PEMFCs) and *Wind Power / Electric Power Transmission Networks / Electric Power Distribution* are both average with respect to collaborative diversity but below average in conceptual diversity.

The remaining three topic clusters, *Lithium Alloys / Secondary Batteries / Electric Batteries*, *Electric Inverters / Electric Potential / DC-DC Converters* and *Wireless Sensor Networks / Routing Protocols / Nodes,* demonstrate average levels of both conceptual and collaborative diversity.

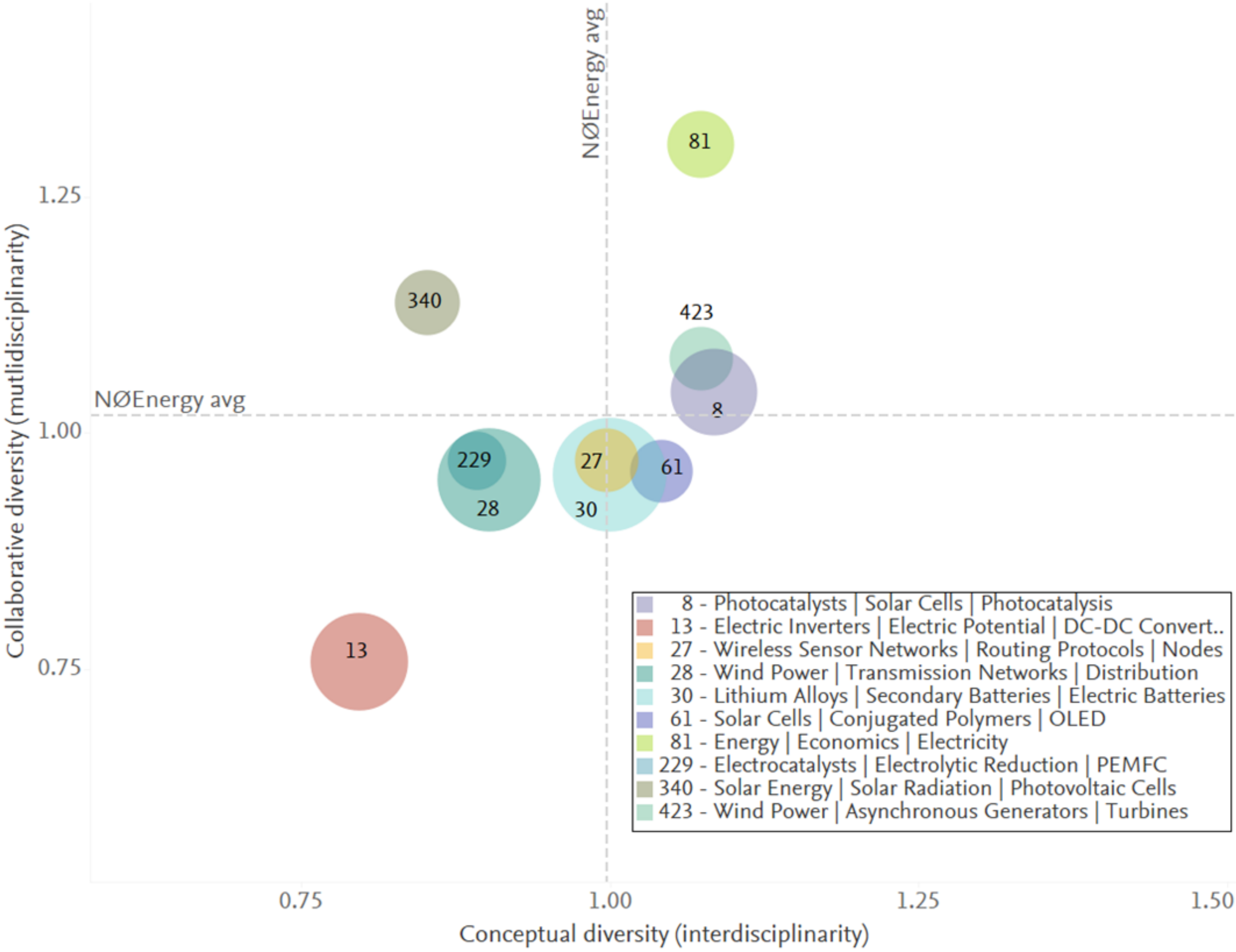


Figure 23
Conceptual and collaborative diversity in the 10 largest NØEnergy topic clusters, 2011–2020. Bubble size represents volume of publications in the topic cluster.
Source: Scopus

Our analysis of the most collaboratively diverse topic clusters (Figure 24)[20] highlights the NØEnergy research areas associated with clean energies, carbon capture or topics that intersect with other environmental concerns.

The most interdisciplinary topic cluster, *Energy | Economics | Electricity* (as shown in Figure 23), reappears in the ranking of the top 10 most multidisciplinary (or collaboratively diverse) topics but is now the least diverse of those we analyzed. Smaller topic clusters tend to demonstrate higher levels of multidisciplinarity. For example, the topic cluster *Air Pollution | Particulate Matter | Air Pollutants*, which focuses on the mitigation of air quality and health issues related to the use of biomass-based stoves in homes, achieved the highest score (of 1.63) for only 1,750 publications.

There are three topic clusters within the top 10 most multidisciplinary (or collaboratively diverse) shown in Figure 24 that are broadly associated with biofuels: *Microalgae | Biodiesel | Algae*, *Bioenergy | Biomass |*

[20] Operationalized as top scores on multidisciplinarity, for topics with at least 1,500 publications between 2011 and 2020.

Biofuels and *Soil / Biochar / Soil Organic Carbon*. In the field of carbon storage research, *Carbon capture / Storage materials / Shale* demonstrates relatively high multidisciplinarity and interdisciplinarity measures of 1.37 and 1.18, respectively, for over 6,000 publications.

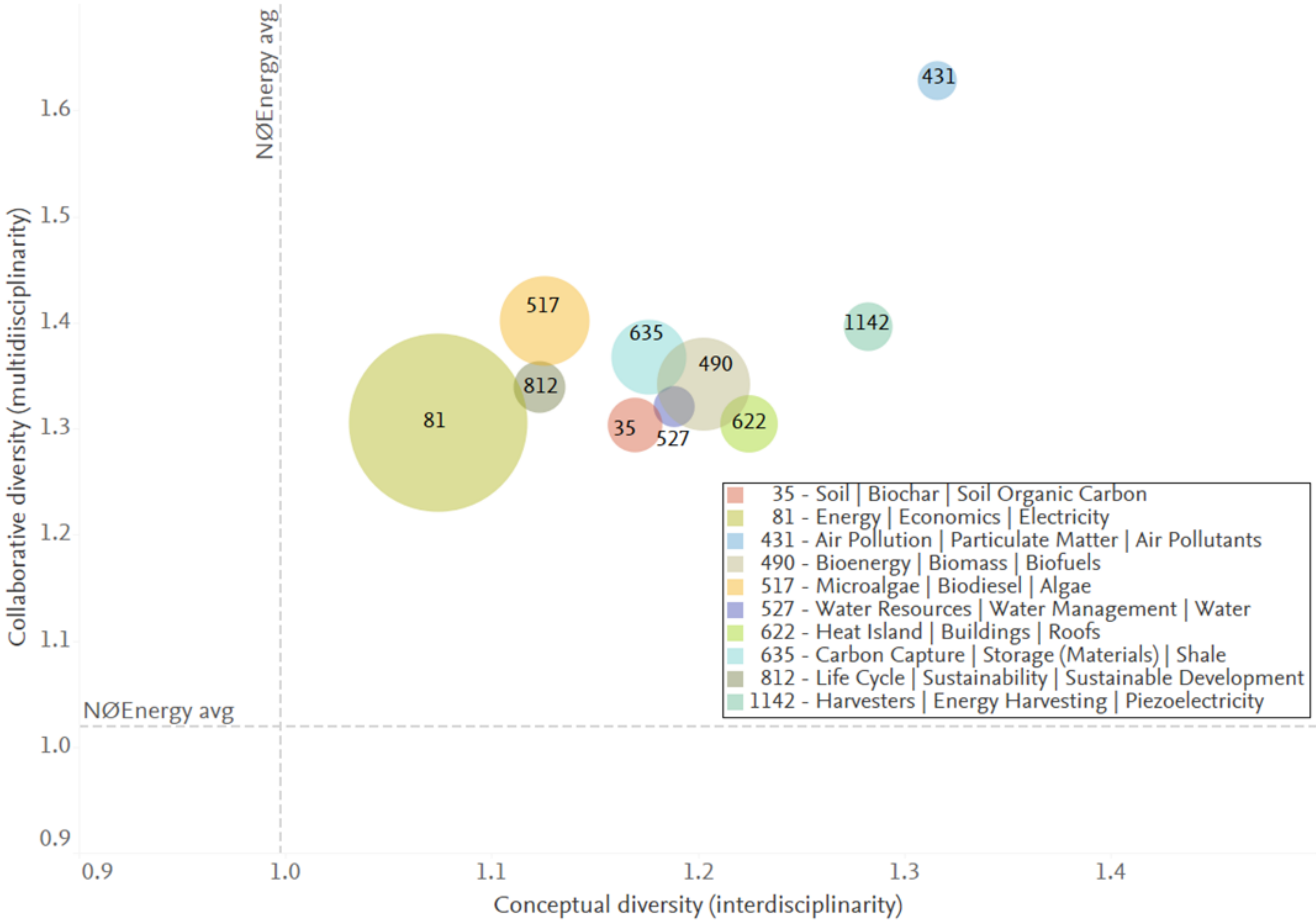


Figure 24
Conceptual and collaborative diversity in NØEnergy topic clusters with the highest collaborative diversity, 2011–2020.
Bubble size represents volume of publications in the topic cluster.
Source: Scopus

The topic clusters that score most highly for conceptual diversity[21] in NØEnergy are those associated with the development and design of consumer products, such as electric vehicles, and the challenges inherent in their use and deployment, including data privacy issues, for example (Figure 25). These interdisciplinary topics include *Models / Applications / Ubiquitous Computing*, *Authentication / Cryptography / Data Privacy* and *Intelligent Buildings / Internet / Bluetooth*. Other highly interdisciplinary and multidisciplinary areas include the largest topic cluster examined here, *Fuel Economy / Hybrid Vehicles / Electric Vehicles*, which has close to 10,000 publications and a score of 1.17 for multidisciplinarity, and *Steering / Vehicles / Tires*, which performs highly on conceptual diversity (1.28 for conceptual diversity, 1.21 for collaborative diversity).

[21] Operationalized as top scores on interdisciplinarity, for topics with at least 1,500 publications between 2011 and 2020.

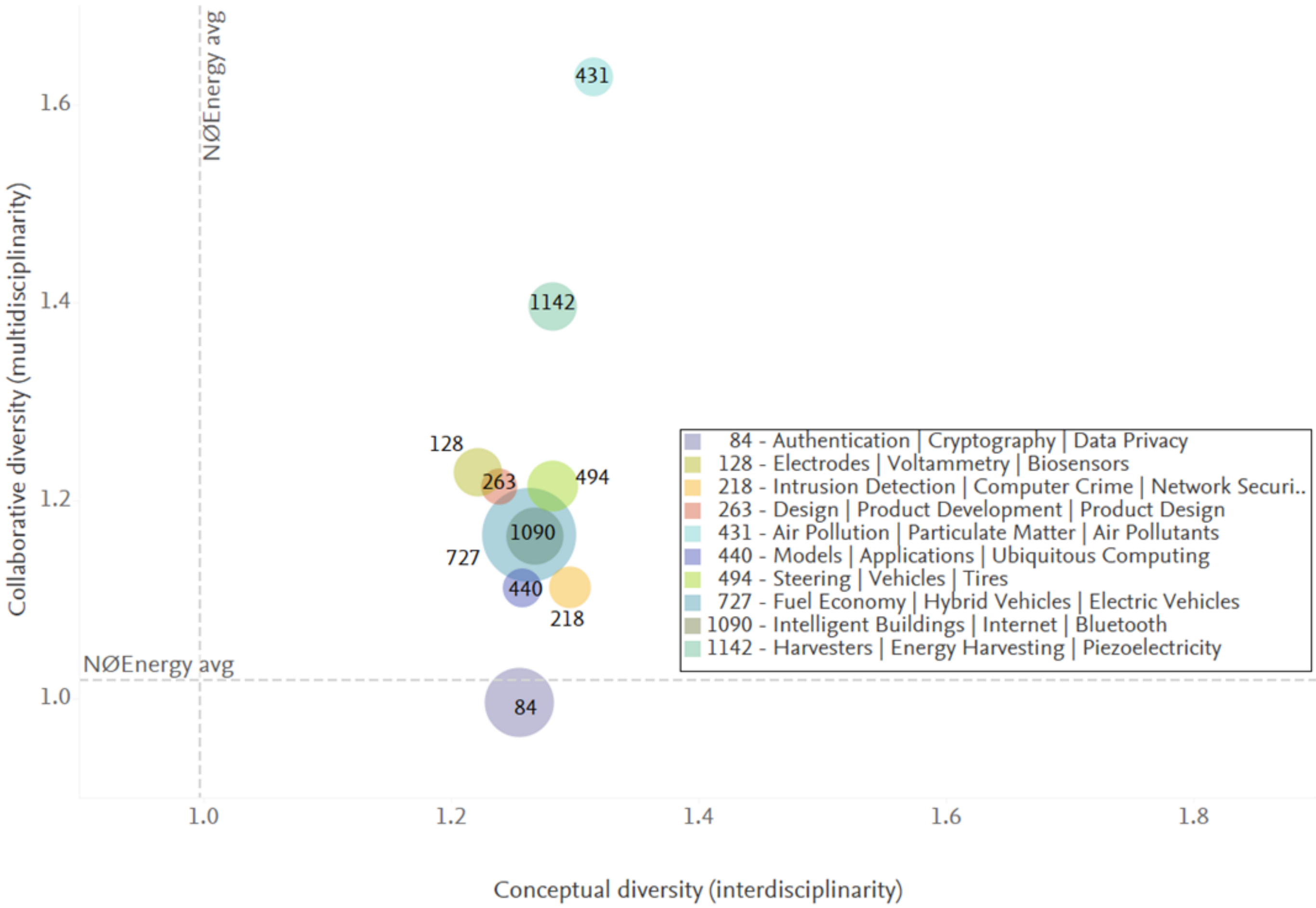


Figure 25
Conceptual and collaborative diversity in NØEnergy topic clusters with the highest conceptual diversity, 2011–2020.
Bubble size represents volume of publications in the topic cluster.
Source: Scopus

1.5 How internationally collaborative is NØEnergy research?

International collaboration in NØEnergy research has increased over the last decade. Saudi Arabia, Singapore, Switzerland and Canada demonstrate the highest levels of international collaboration.

Collaboration between research organizations and institutions both nationally and internationally is particularly essential in tackling wide-reaching societal challenges such as climate change. The IEA's *Net Zero by 2050* report highlights the need for greater international collaboration among countries, "to ensure that developing economies have the financing and technologies they need to reach net zero in time."[22] International collaboration also tends to produce higher-impact research. In this section and the next, we focus on international collaboration in general, as well as that between the Global North and South.

Our analysis indicates that the share of NØEnergy publications demonstrating international collaboration has increased, going from 31% in 2011 to 45% in 2020 and accelerating over the last decade (Figure 26).

Types of collaboration

Research collaboration is measured by counting publications resulting from the efforts of two or more authors. Such publications are referred to as co-publications throughout the report. Collaboration can be categorized into various types; in this report, we focus on the following three:

- *International collaboration*—where the affiliations listed by the authors of a publication include institutions from two or more countries or regions
- *South international collaboration*—where the affiliations listed by the authors of an international co-publication include at least one author from a Global South country; this category includes both North–South and South–South co-publications
- *Academic–corporate collaboration*—where the affiliations listed by the authors of a publication include institutions or organizations from both academia and the corporate sector; this is a type of intersectoral collaboration

[22] See https://www.iea.org/reports/net-zero-by-2050

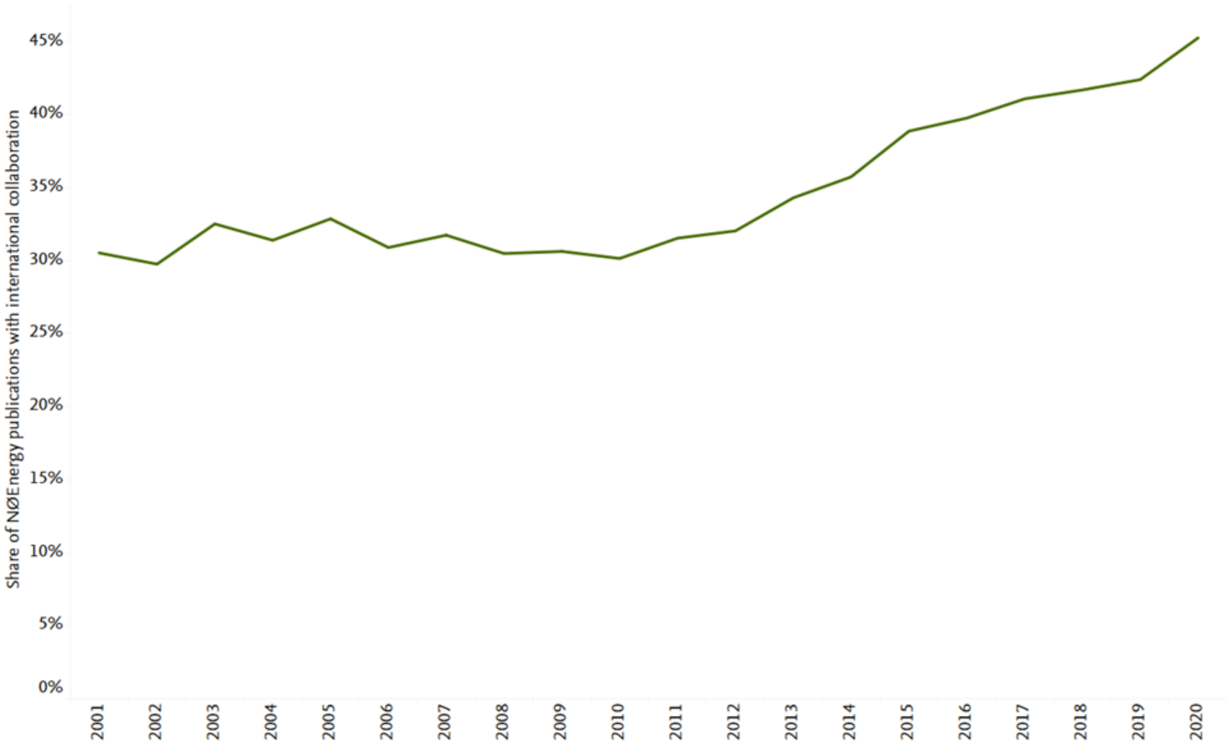


Figure 26
Share of NØEnergy publications with international collaboration (weighted calculation), 2011–2020.
Source: Scopus

What is the benchmark for international collaboration in research?

The global average share of research publications with international collaboration currently stands at 23%.

In other words, one paper out of four includes researchers from at least two different countries. But since most international collaborations involve multiple countries, the global international collaboration share, if computed in the same way for countries, can be misleading. This is because a single paper published by an international partnership will count only once at the global level but multiple times at the country level, once for each country involved. This means almost all countries achieve a share far above the average global level. To counteract this effect, we have computed the global level as a weighted average of the scores of all countries, which results in a score close to 40%, which is much more representative of the situation at the level of countries.

At over 75%, Saudi Arabia shows the highest share of publications with international collaboration among those countries and regions that contributed to at least 1% of all NØEnergy publications during 2011–2020 (Figure 27). Singapore, Switzerland and Canada follow with shares of 66%, 63% and 62%, respectively. These four countries not only had the highest shares of publications demonstrating international collaboration but also increased their shares from 2001–2010 to 2011–2020. Among the five countries with the most publications, the United Kingdom also increased its share of publications with international collaboration by more than 10%.

India, Russia and Poland, on the other hand, show declining shares of publications with international collaboration. Russia's share of international collaboration publications fell from 37% in 2011 to 28% in 2020. India had a larger share of publications with international collaboration than the global average in 2001–2010, but its share dropped below the global average over the last decade.

The United States, the United Kingdom, France, Australia, Iran and Turkey all show demonstrably higher levels of international collaboration in NØEnergy than overall. In contrast, Germany, Italy, Taiwan, Switzerland and Denmark have lower levels of international collaboration in NØEnergy compared with their overall share.

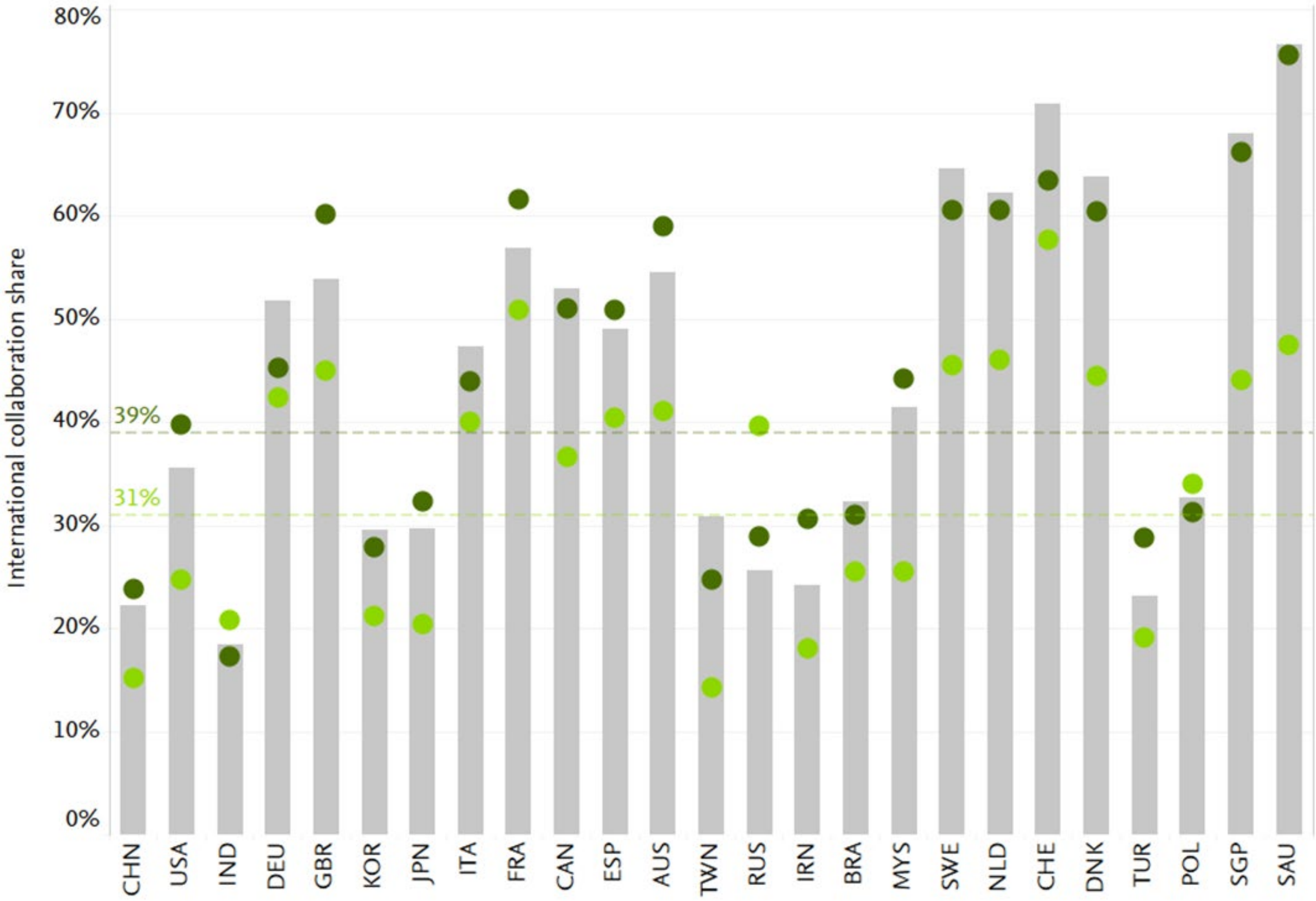


Figure 27
Share of NØEnergy publications with international collaboration for those countries and regions that contributed to at least 1% of NØEnergy publications in 2011–2020. The light green line indicates the global average share of publications with international collaboration for NØEnergy during 2001–2010, and the dark green line indicates the average for 2011–2020. The gray bar indicates the overall international collaboration share of that country or region in 2011–2020.
Source: Scopus

Figure 28 shows the share of publications demonstrating international collaboration for topic clusters that accounted for at least 1% of all NØEnergy publications in 2011–2020. The topic cluster *Magnetoplasma / Plasmas / Tokamak Devices* had the highest share of publications with international collaboration, as research in this area is generally focused on larger infrastructure projects that require investment and participation from multiple countries. The share of publications with international collaboration increased for all the topic clusters investigated except for *Permanent Magnets / Synchronous Motors / Induction Motors*, which saw a small decline. The topic cluster *Energy / Economics / Electricity* shows the largest increase in international collaboration, rising from 8% of publications in 2001–2010 to 23% in 2011–2020. An increase in international collaboration of over 10% is also seen in the topic clusters *Pyrolysis / Coal / Gasification*, *Microbial Fuel Cells / Anaerobic Digestion / Bioreactors*, *Yttria Stabilized Zirconia / Solid Oxide Fuel Cells (SOFC) / Perovskite* and *MIMO Systems / Orthogonal Frequency Division Multiplexing / Cognitive Radio*.

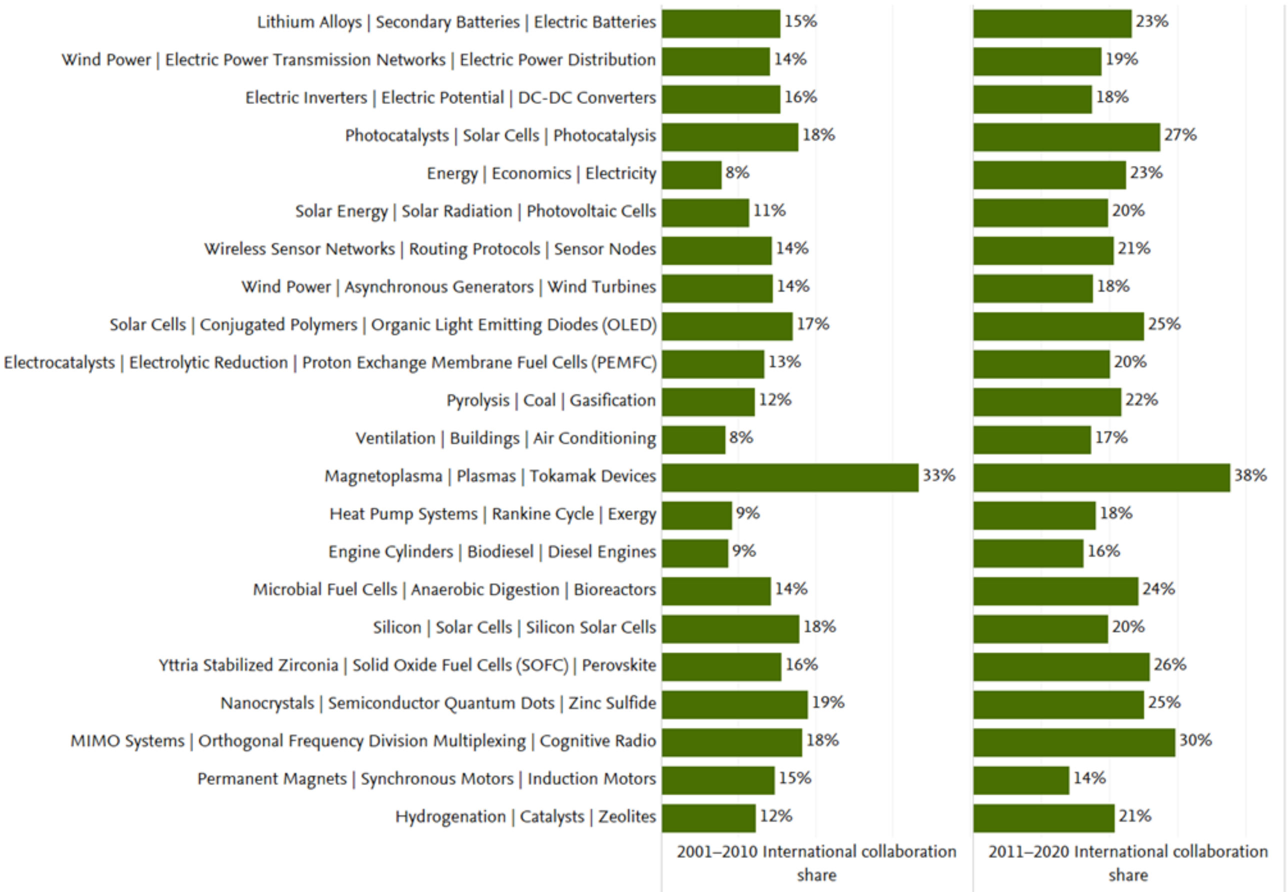


Figure 28
Share of publications with international collaboration for topic clusters accounting for at least 1% of all NØEnergy publications during 2011–2020.
Source: Scopus

1.6 How does the Global South participate in NØEnergy research?*

Only a small proportion of NØEnergy research is conducted by or in the Global South, which could make practical implementation problematic in the future.

The IEA's *Net Zero by 2050* report highlights the need for greater international collaboration among countries,[23] and in the 2030 Agenda, the United Nations called for countries to "[p]romote the development, transfer, dissemination and diffusion of environmentally sound technologies to developing countries on favourable terms".[24] Moreover, the launch of initiatives such as the Least Developed Countries 2050 Vision for a Climate-Resilient Future highlights a global will to develop local capacities through research and, notably, international collaborations.[25] The concept of capacity-building,[26] where a country develops its local skills, abilities, processes, organizations, communities and resources to adapt and thrive, is particularly key in energy systems. Research and innovation are essential to capacity-building, which can be needed in niche areas necessary to support energy infrastructure development such as cyber security or IT networks.

The need to support cooperation between the Global South and Global North (defined below) also ties into some commentators' concept of a "just transition to net zero" and

> *"Researchers are more willing to follow hot issues and hot areas because of easier access to data, more financial support, greater ease in collaborating and easier field surveys. This [work on the Global South] reminds us that we need to give more visibility to research on 'South international publications' and 'South focus' topics and call on all researchers to pay more attention to the Global South's research."*
>
> Yutao Wang, Professor, Department of Environmental Science and Engineering, Fudan University

[23] See https://www.iea.org/reports/net-zero-by-2050
[24] UN General Assembly. (2015). Transforming our world: the 2030 Agenda for Sustainable Development. *A/RES/70/1*.
[25] Least Developed Countries Initiative for Effective Adaptation and Resilience (LIFE-AR). (2019). *LDC 2050 Vision: towards a climate-resilient future.* http://www.ldc-climate.org/wp-content/uploads/2017/12/LDC-Group-Vision.pdf
[26] See https://www.un.org/en/academic-impact/capacity-building
*This chapter was amended on 8 November 2022 with an updated definition of the Global South country group.

recognizes that a major portion of global investment earmarked for achieving net zero should target middle- and low-income countries.[27]

In this section, we focus on the participation of Global South countries in NØEnergy research and explore whether collaboration with developing countries is underway and in which areas.

It is important to note that there are no internationally accepted metrics for the levels of scientific infrastructure development, nor are policy targets or roadmaps of desirable research performances for Global South countries available. This section is in no way able to assess performances of Global South countries, which face a unique set of challenges in building up NØEnergy research systems. Nevertheless, some basic measurements of participation levels of Global South countries in NØEnergy research are useful, if only to guide evidence-based policies. Here we endeavor, in addition to providing basic measurements, to assess how countries within the Global North fare in relation to one another in supporting North–South collaboration and other forms of international development through research and innovation. Global North–South collaboration, in turn, should also be deployed as steppingstones toward reinforced local capacity and increased South–South collaboration.

Collectively, Global South countries contributed to 21% of NØEnergy publications from 2001 to 2020. This is just below the share of publications of the 27 Member States of the European Union (EU-27) (23%) and China (24%). If countries are considered by their relative level of economic development (or income level), Low-Income Countries (LICs) contributed to only 0.2% of NØEnergy publications and Lower-Middle-Income Countries (LMICS) only 10%. The latter decade of the study saw a slight shift in these shares, but only for some entities. Global South countries increased their share to 24% for 2011–2020, whereas the US share dropped to 16%. China increased its share to 27%, and the LMIC share increased to 12% (Figure 29). In all periods, Global South countries are clearly overshadowed by the Global North in terms of the volume of publications produced, as evident in Figure 29.

Defining the Global South

The Global South refers to three groups of countries, in line with World Bank definitions:

- Upper-Middle-Income Countries (UMICs)
- Lower-Middle-Income Countries (LMICs)
- Low-Income Countries (LICs)

In this report, the Global South excludes China, which is normally considered a UMIC country. This is because although China is a recipient of some development aid, it is also a scientific powerhouse. China collaborates routinely because of its high academic status rather than as a result of development-oriented scientific collaboration.

Global North countries are divided into four categories:

- China
- EU-27 countries (including Bulgaria)
- The United States
- High-Income Countries (HICs), including Australia, Canada, Israel, Japan, Saudi Arabia, South Korea, Switzerland and the United Kingdom.

For further details on the World Bank classification, see https://datahelpdesk.worldbank.org/knowledgebase/articles/906519

Although the share of NØEnergy publications with at least one researcher from the Global South doubled in the 2001–2020 period, ultimately researchers from Global South countries accounted for only a fifth of all authors (Figure 30). Furthermore, North–South and South–South collaborations drive collaborative

[27] Robins, N. (2021, June 9). *No one should get left behind.* Grantham Research Institute on Climate Change and the Environment. https://www.lse.ac.uk/granthaminstitute/news/no-one-should-get-left-behind/

diversity and South-focused applied research, but only a very small proportion of research in the period included a fieldwork component in Global South locations, limiting opportunities for related development work (Figure 31).

Overall, while the trends are encouraging, our findings emphasize the need for greater inclusion of the Global South in NØEnergy research. Increasing the frequency of North–South and South–South collaborations should be a priority for future NØEnergy research policies. Moreover, our analysis of public–private collaborations and levels of multidisciplinarity indicate clear priorities for improvement. While some areas within NØEnergy research have a strong South focus, these tend to show lower impact in citations (citation impact data not shown). Research leaders and science policymakers might want to consider taking a more active stance in supporting and promoting these areas of research. The current trajectory of NØEnergy research is positive, but it may be too modest to address the major development challenges ahead, particularly for the Global South.

Measuring the contribution of the Global South

Some indicators computed for this report focus on the intensity of Global South participation in NØEnergy research. This includes shares of publications with at least one author from the Global South.

"South international co-publications" include at least one author from a Global South country. This category therefore includes both North–South and South–South co-publications.

"South focus" refers to publications with mentions of Global South locations (cities, countries or regions) in titles, abstracts or keywords, which are likely to be associated with fieldwork, local prototyping, or research associated with regional issues.

> *"The global commitment to net zero emissions by 2050 is growing, across governments, businesses, investors, cities, regions and civil society. However, COVID-19 is forcing many governments and businesses in the African region to focus on immediate survival. In addition, with limited resource and budget allocations, the majority of African countries are focused on improving productivity and accelerating economic growth, further delaying the net zero transition."*
>
> Kariuki Ngari, Managing Director & CEO, Standard Chartered Bank Kenya

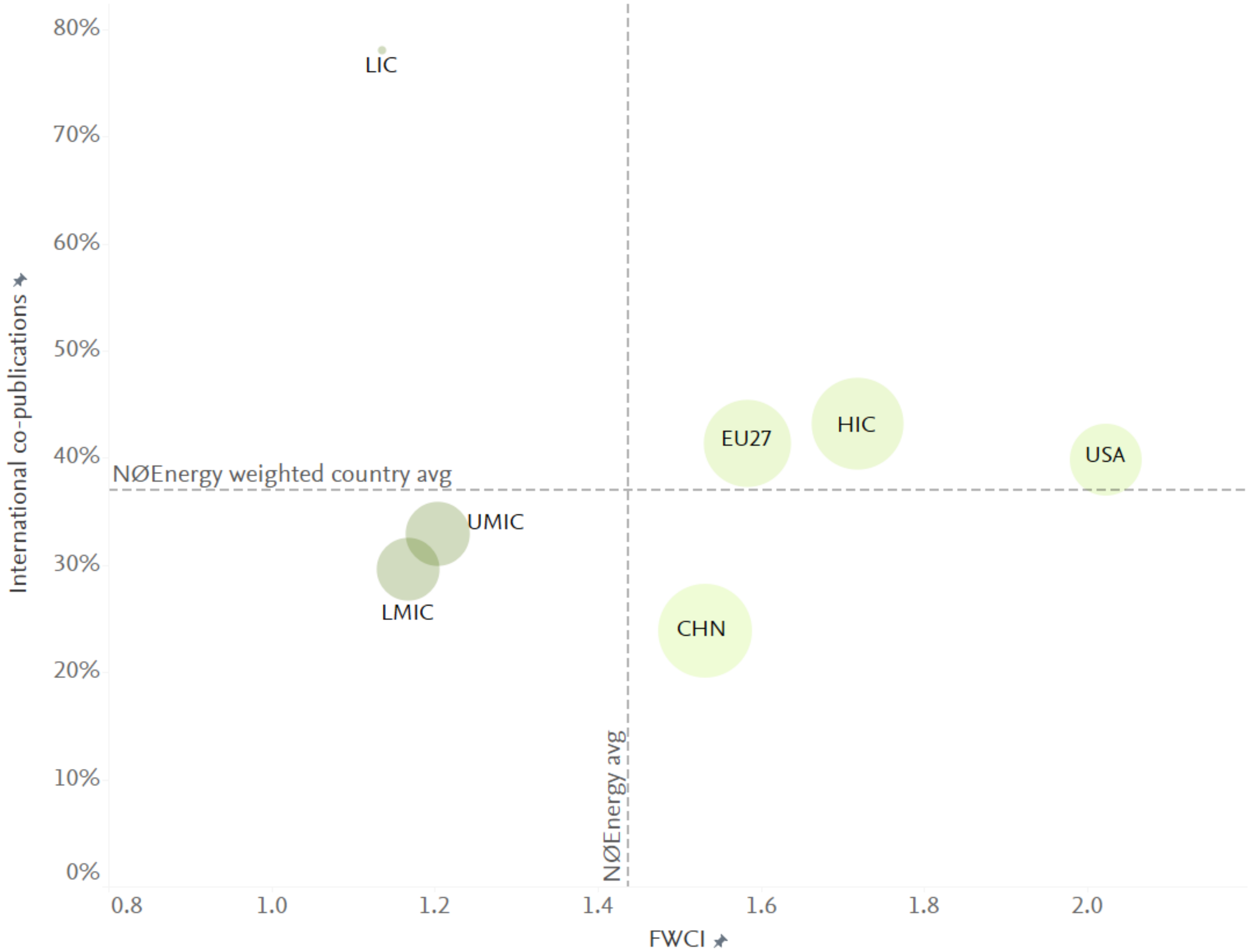


Figure 29
Overview of Global South (dark green) contributions to NØEnergy publications relative to Global North countries and other country groups (light green), for 2011–2020. FWCI: Field-weighted citation impact. Bubble size represents output volume.
Source: Scopus

Looking at Figure 29 in more detail, we see that Global South-based research tends to be taken up less by colleagues in other scientific communities, as shown by FWCI scores below the NØEnergy research average for all three income subgroups (scores of between 1.1 and 1.3). In contrast, the four Global North countries or country groups had FWCI scores of between 1.5 and 2.0.

A significant proportion of NØEnergy research from the Global South is shaped by collaborations with researchers from other countries, as shown by the scores of almost 80% for LICs (or 57% when taking into consideration only North–South co-publications, data not shown). This observation does not hold for UMICs and LMICs, however. A possible explanation could be that the capacity for national funding programs in NØEnergy research might be limited for LICs, forcing reliance on international collaboration to develop local knowledge.

Since 2001, the inclusion of and contributions from Global South countries have increased, but they still account for only a small proportion of the entire field. The percentage share of NØEnergy research with contributions from Global South countries, however, increased from just 13% to 31% during this period (Figure 30). The percentage share of international co-publications with at least one Global South-based collaborator also increased, from 4% to 11% (as a proportion of overall NØEnergy publications). Meanwhile, the proportion of NØEnergy publications including South fieldwork or applied to Global South regions increased from 4% to 6%. Overall, these findings show a clear upward trend in the inclusion of Global South-based researchers or interests in NØEnergy research.

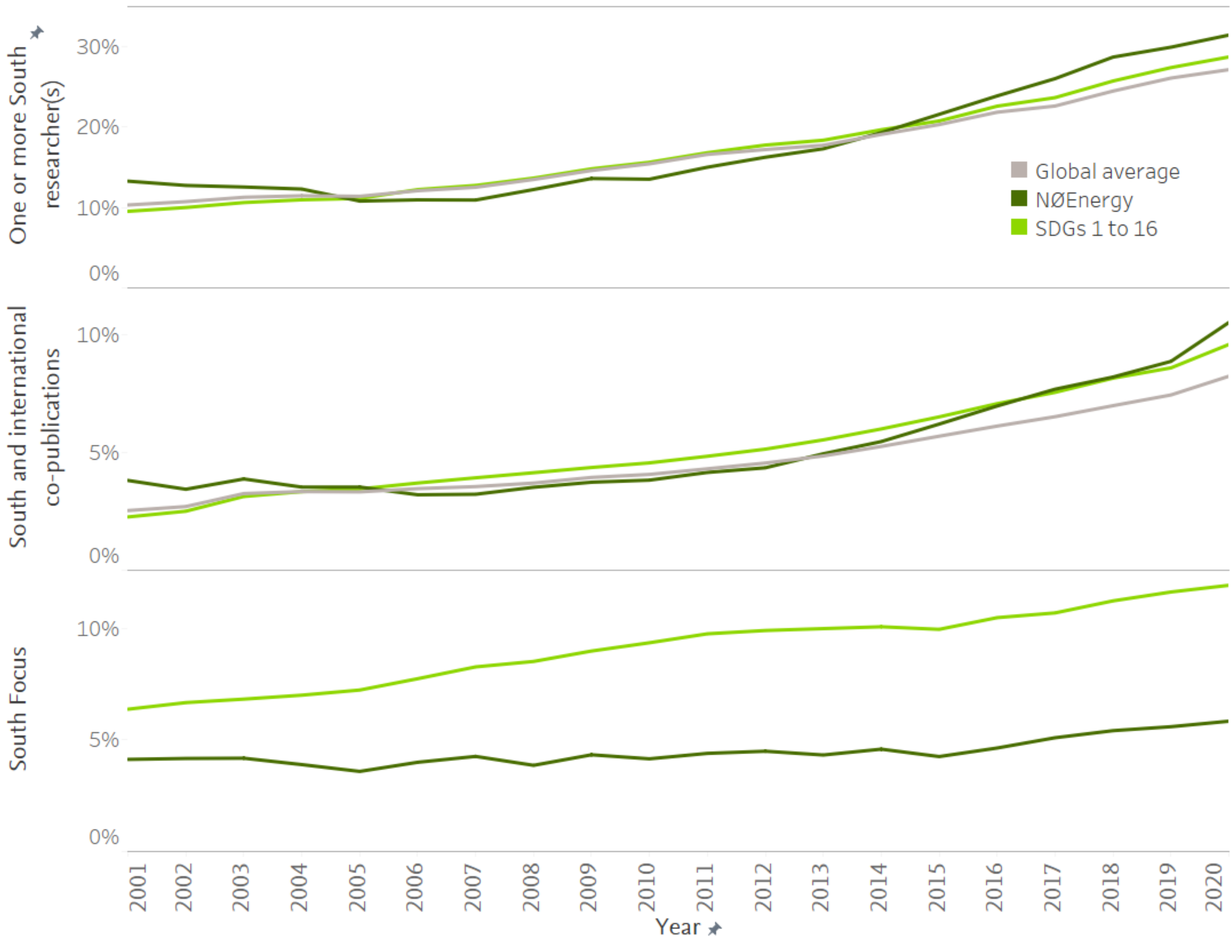


Figure 30
Overview of Global South trends, 2001–2020. *South researcher* indicates the share of publications with at least one Global South researcher (upper panel), *South international collaboration* indicates the share of international co-publications with at least one Global South co-author (middle panel), and *South focus* indicates mentions of Global South locations (lower panel). Global average not available for South focus, last indicator. *SDGs 1 to 16* data points capture global averages within all publications thematically related to SDGs 1 to 16.
Source: Scopus

The number of NØEnergy publications or international co-publications with at least one Global South author was not meaningfully greater than that of other SDG-oriented publications or average global publications, across the period, however. In terms of South focus, NØEnergy publications recorded scores that were about half the level of SDG-oriented publications overall in recent years (a global average is not available on this indicator).

North–South collaborations are often perceived as the best way of tackling science-related development challenges. If this is so, these collaborations can be expected to share other features commonly associated with successful development approaches: high levels of collaborative diversity (multidisciplinarity), high levels of local fieldwork and regional focus, and large numbers of publications from public–private partnerships. The next two figures assess these expectations for NØEnergy research by considering publications from North–South and South–South collaborations between LICs, LMICs, Upper-Middle-Income Countries (UMICs), and China, EU-27 countries or the United States.

Figure 31 reveals that all North–South and South–South co-publications had high or very high levels of multidisciplinarity (scores range from 1.2 to 1.9). Regional engagement was also high or very high in almost all collaborations (scores range from 11% to 63%, except for China+UMIC, which was only 6%).

"In the past, most climate change-related work done in the Global South was around climate adaptation. They had only a small voice when it came to mitigation and, consequently, to global climate negotiations. This was partially due to a lack of research being done in those regions. Global climate change mitigation is very much in the hands of the Global South countries, however. Apart from the major emitters such as China and India, other developing countries in South Asia and Africa have grown their economies and emissions dramatically over the past 10 years. It's vital for them to find a way to leapfrog to a transition to clean energy. Research on data and methods are the key elements before any application studies."

Dabo Guan, Distinguished Professor of Climate Change Economics, Tsinghua University; Chair at the Bartlett School of Construction and Project Management, University College London

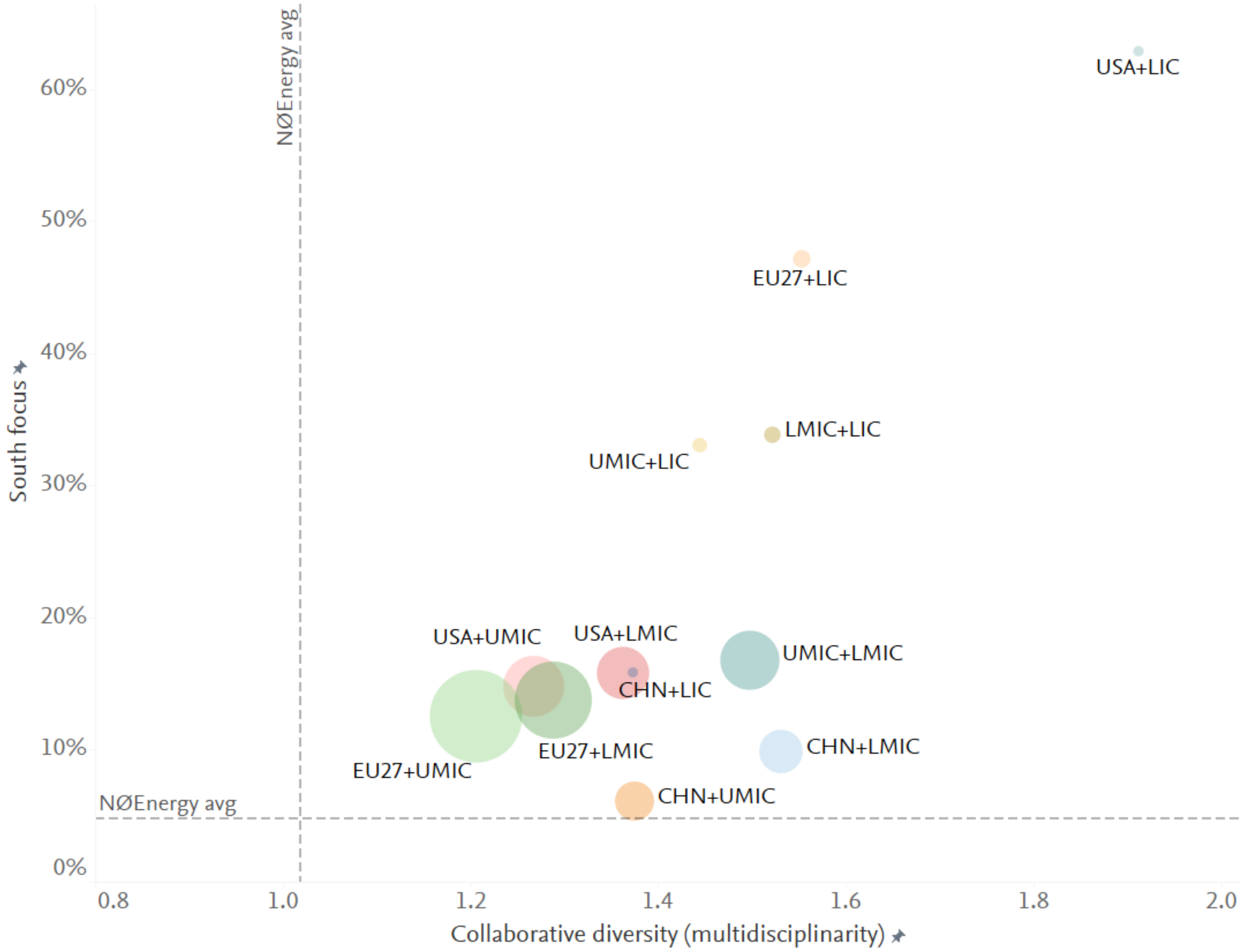


Figure 31
Collaborative diversity and percentage share of NØEnergy publications with a Global South study location, 2011–2020.
Bubble size represents output volume of the collaboration type.
Source: Scopus

Four of the strongest performers, on the basis of multidisciplinarity and regional engagement, included researchers from LICs as partners, as well as those from either EU-27 countries, LMICs, UMICS or the United States. However, these collaborations represent only very low volumes of publications—around 250, for example, from the top performing category of US–LIC co-publications.

Figure 32 aims to capture whether North–South collaborations also contained academic–private collaborations and collaborations across highly diverse disciplines. Most North–South collaborations performed below the NØEnergy average (close to 5%) for academic–private partnerships (scores range from 1.9% to 9.2%, with 9 out of 12 collaboration types below average). US research is often characterized by high levels of academic–private partnership, and this was indeed the case for US+UMIC and US+LMIC publications (scores of 9.2% and 8.4%, respectively). US+LIC publications, however, scored below the NØEnergy average (2.7%).

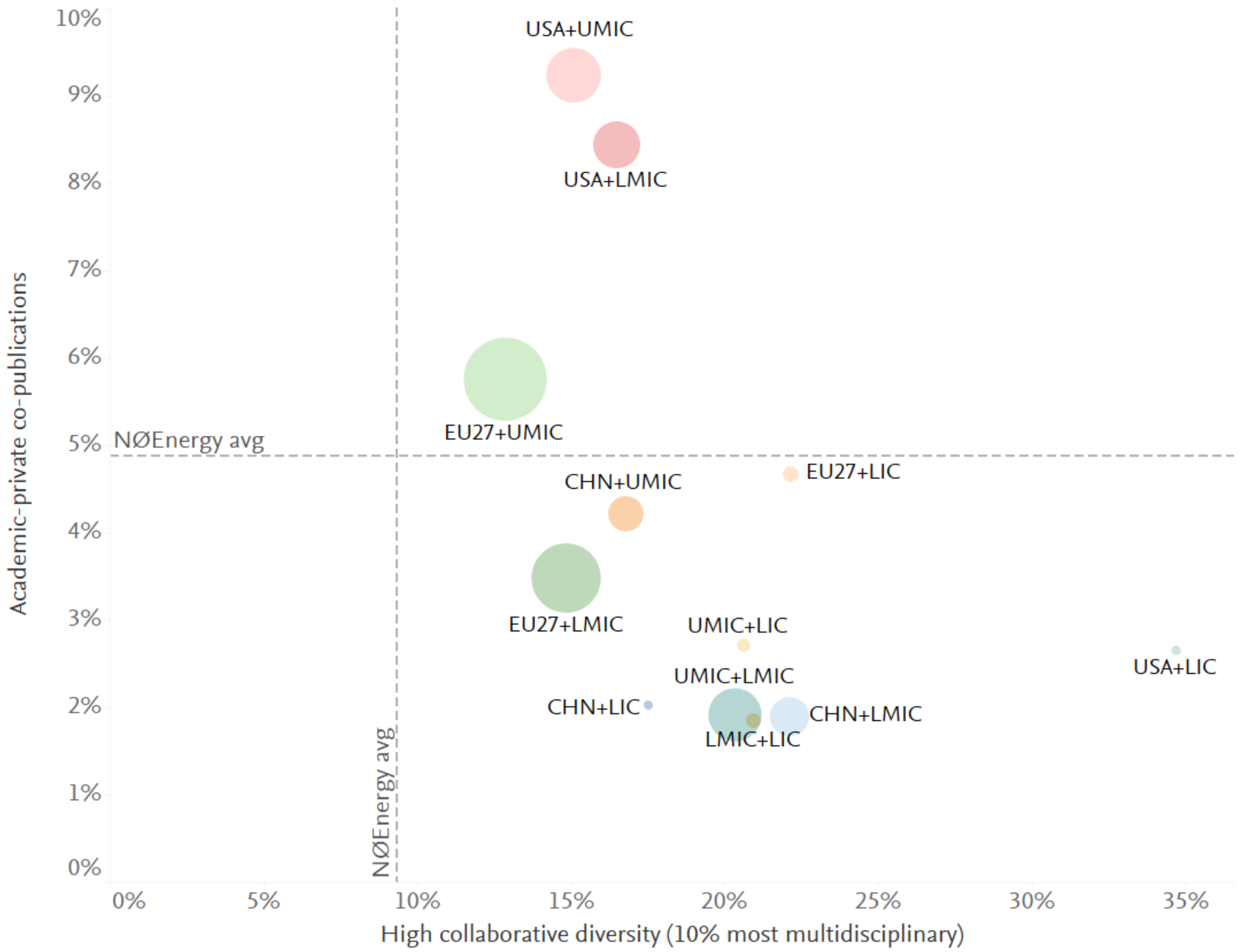


Figure 32
Share of academic–private co-publications versus share of publications with exceptionally high collaborative diversity, 2011–2020.
Source: Scopus

North–South collaborations and research conducted in Global South regions amounted to very small proportions of Global North countries' outputs (the South focus indicator), as can be seen in Figure 33. On average, Global North countries' publications included a Global South-based co-author in just 9% of cases (the South international co-publication indicator). Most countries and regions included in Figure 33 produced publications with a comparatively low level of South focus.

"The capacity to make progress seems too often to be concentrated in particular places. That's a challenge we're all facing."

Leon Clarke, Acting Director and Research Director, Center for Global Sustainability, University of Maryland at College Park

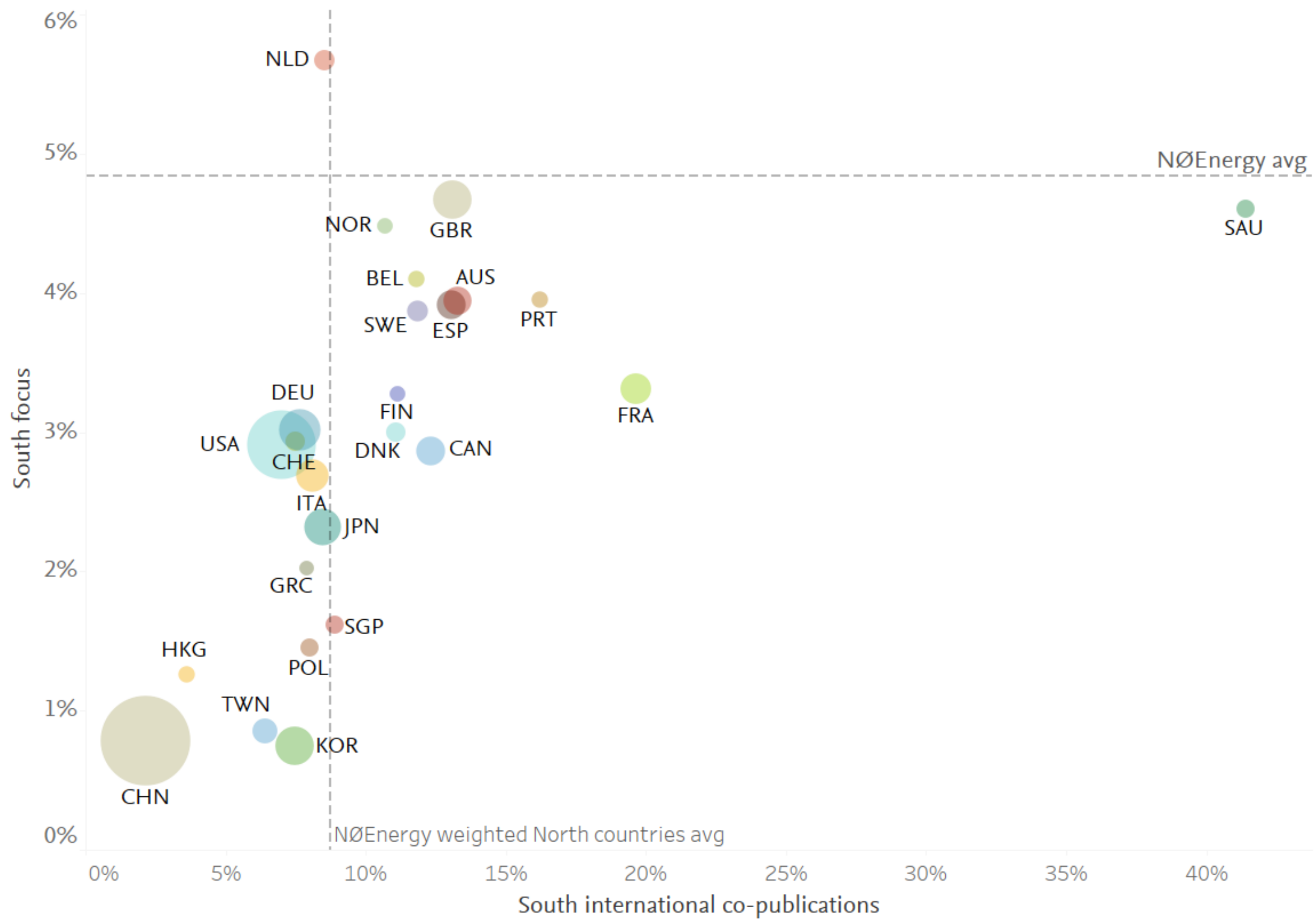


Figure 33
Global North countries' (largest producers of publications) share of co-publications with Global South countries and regions versus share of publications with a South focus, 2011–2020. Weighted average of South international co-publications was calculated for North countries only in this figure.
Source: Scopus

In terms of individual countries and regions (Figure 33), the Netherlands and Saudi Arabia stand out, each for a different indicator. The Netherlands was the only North country with a South focus (of 6%) above the NØEnergy average (of 5%). Saudi Arabia, meanwhile, had by far the largest share of publications including a South-based co-author (41%). The next best performer for share of publications was France: 20% of its publications included a South-based co-author. Scores for this indicator were pulled down by the poor performances of China (2%) and the United States (7%), the two largest producers of publications.

In light of the exceptional scores of some countries' South international co-publications in Figure 33, the top 10 performers were identified and the long-term trends in their collaborations were analyzed (Figure 34). For these North countries, led by Saudi Arabia, France, Portugal, Australia and the United Kingdom, strong North–South collaborations appear to be the result of long-term commitments. Trends have been stable over time, at least in terms of countries' positions relative to one another, with Saudi Arabia's strong performance in international collaboration driven by partnerships with Egypt, Pakistan, Malaysia, India and Tunisia, as well as Global North countries.

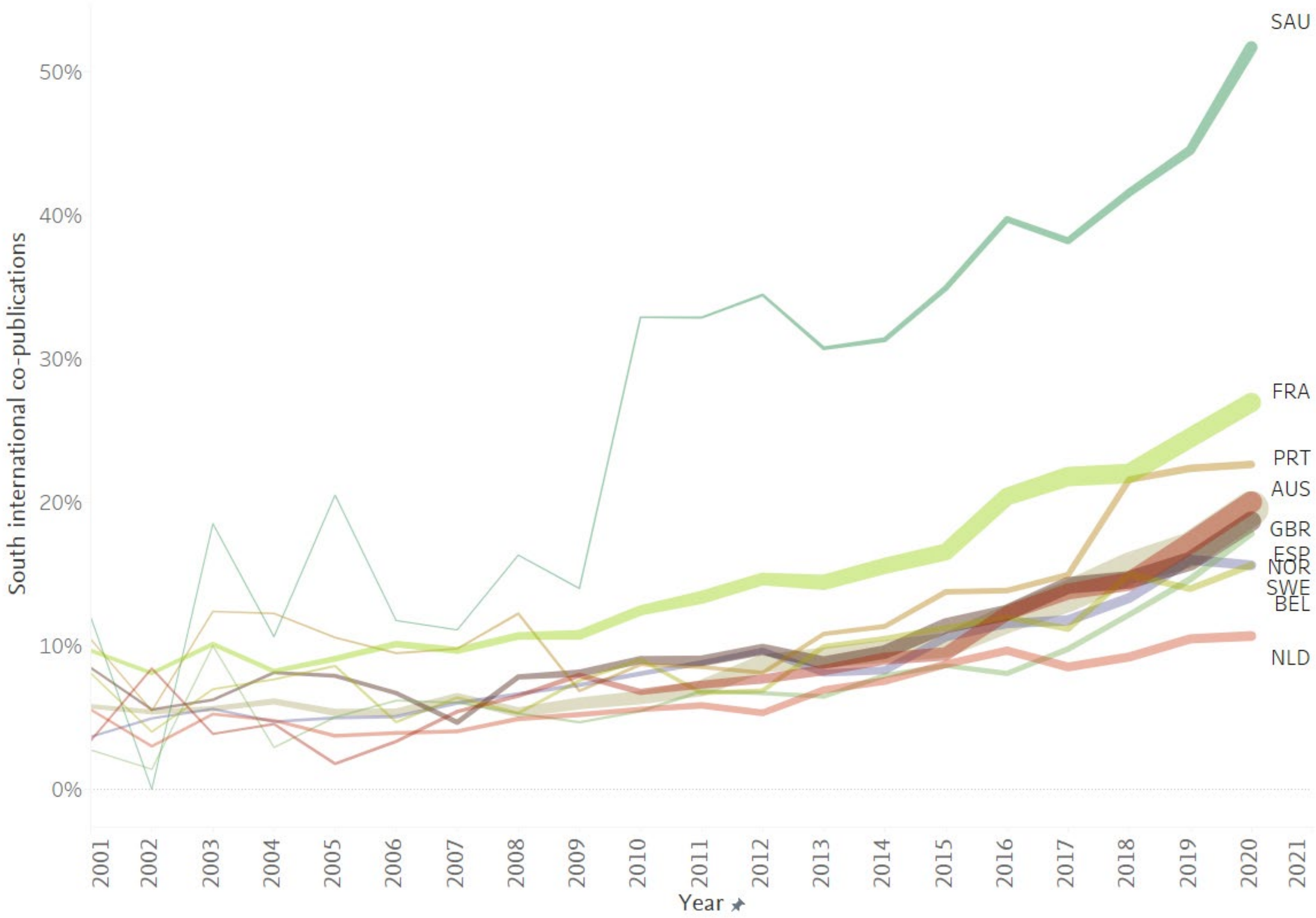


Figure 34
Global North countries' (largest producers of publications) share of co-publications with Global South countries, 2011–2020. Line thickness represents overall annual publication output.
Source: Scopus

The topic clusters in NØEnergy with a clear South focus and regional engagement are rather different to those with the largest overall output (Figure 35). The most South-focused topic cluster in terms of the number of publications, for example, is *Energy / Economics / Electricity*, which ranks fifth in NØEnergy publications overall. Other South-focused topic clusters include *Bioenergy / Biomass / Biofuels* (which ranks 20 positions higher in this category compared with NØEnergy publications overall), *Microbial Fuel Cells / Anaerobic Digestion / Bioreactors* (nine positions higher) and *Heat Pump Systems/ Rankine Cycle / Exergy* (also gaining nine positions).

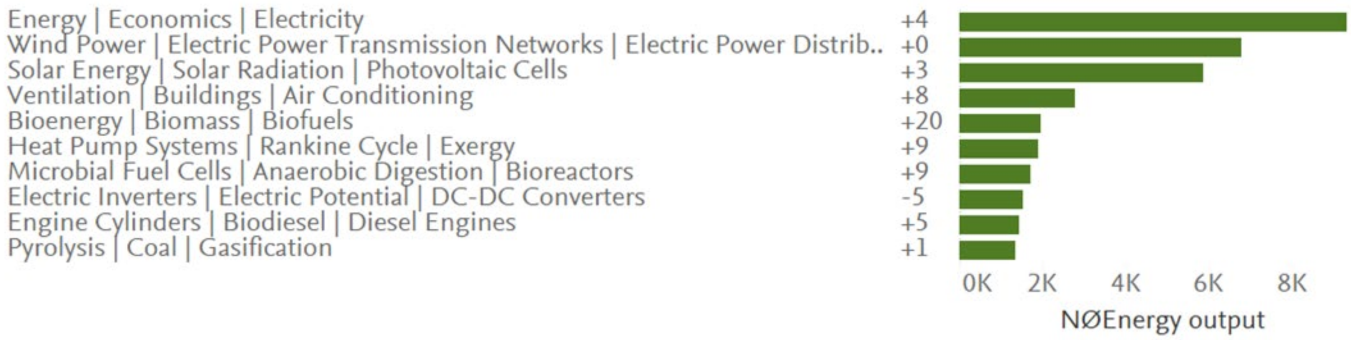


Figure 35
Top 10 topic clusters by South-focused output, 2011–2020. Ranking differential compared to global NØEnergy rankings provided on the left of the bars.
Source: Scopus

The top 10 topic clusters for Global South countries by income level are shown in Figure 36. For LICs, the largest topics in terms of output volume are very different to those in NØEnergy in general. The topic cluster *Air Pollution / Particulate Matter / Air Pollutants*, for example, moves up 72 places in this ranking compared with overall NØEnergy publications. *Microbial Fuel Cells / Anaerobic Digestion / Bioreactors* is also relatively more prominent within LIC publications, gaining 11 positions.

While in terms of overall NØEnergy output, the topic cluster L*ithium Alloys / Secondary Batteries / Electric Batteries* leads the way, it ranks much lower in importance in all categories for Global South countries. For LICs, it drops to 8th position; for LMICs, 8th position as well; and for UMICs, 7th.

Global South countries also show higher output volumes of bioenergy-related publications compared with NØEnergy overall. In addition to the increased importance of *Microbial Fuel Cells / Anaerobic Digestion / Bioreactors* to LICs highlighted above, *Engine Cylinders / Biodiesel / Diesel Engines* also makes gains in LICs, LMICs and UMICs compared with NØEnergy overall (notably, this topic gains ten positions in the ranking of UMIC publications).

These findings provide further support for the notion that South-based research capacity-building and North–South collaboration should consider the differing priorities of Global South countries.

> *"Budget plays a key role in the promotion of clean energy technologies, especially in developing countries".*
>
> Chukwuka Monyei, Research Fellow in Energy Justice and Transitions, University of Sussex

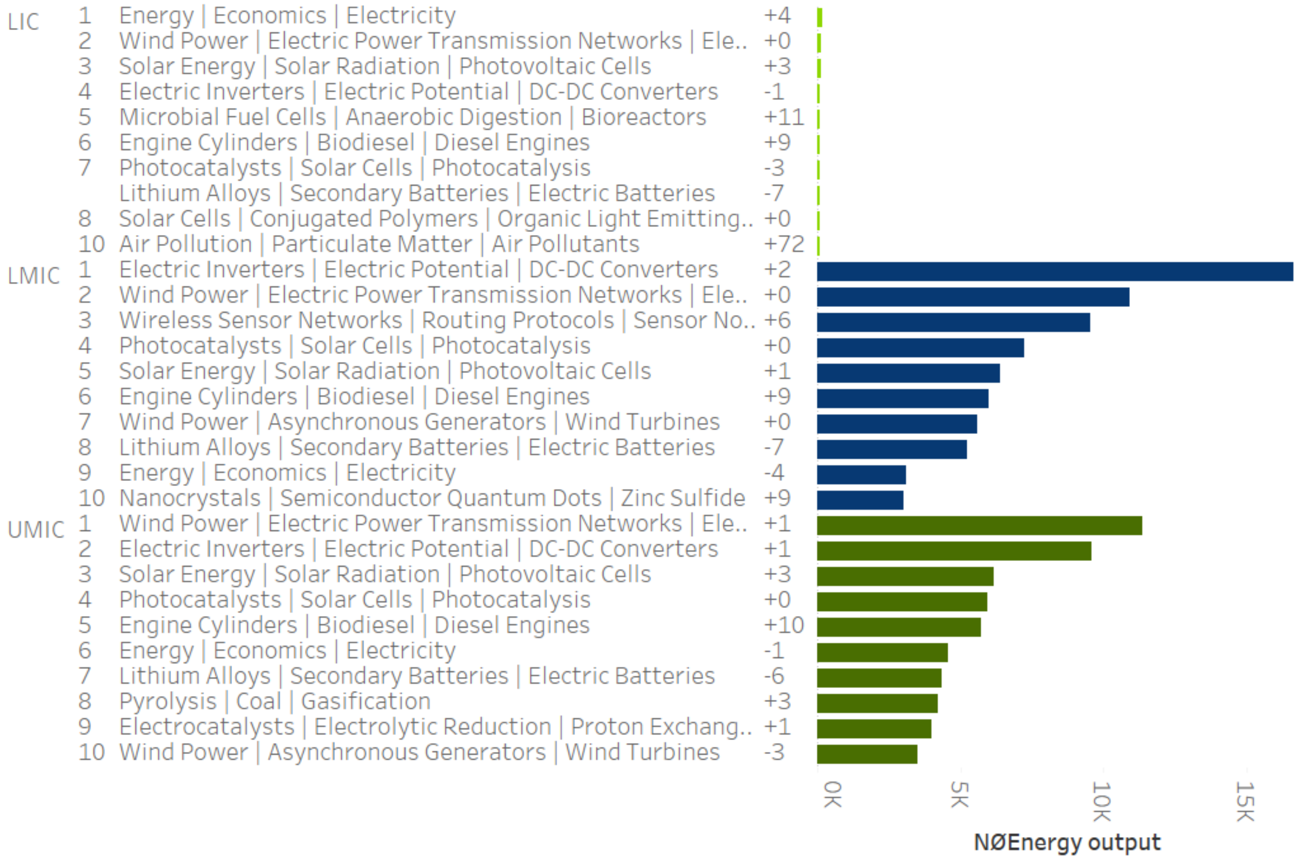


Figure 36
Top 10 topic clusters by output per income group within the Global South, 2011–2020. Ranking differential compared with global NØEnergy rankings provided on the left of the bars.
Source: Scopus

"As we make progress towards a clean energy transition to net zero, we must have significant plans in place to ensure that the Global South is able to buy into this particular part. And that would depend largely on what has been offered to them in terms of capacity development and, of course, in terms of knowledge transfer. These are very important aspects that must be considered, otherwise the whole idea of the transition will be wasted. Because the projected increase in energy usage is going to come from the Global South, having them buy-in early enough benefits our ability to sustain the whole energy transition."

Chukwuka Monyei, Research Fellow in Energy Justice and Transitions, University of Sussex

1.7 How mature is NØEnergy research?

Most NØEnergy publications fall within the category of applied technology, but publications in areas such as batteries, photocatalysts, OLEDs and fuel cells tend toward more basic scientific or applied research.

Globally, the share of basic scientific research in NØEnergy has remained roughly stable at 8%–9% over the last two decades. However, NØEnergy publications in applied technology have increased substantially, by more than 20 percentage points, over the same period (Figure 37). Meanwhile, the share of publications in applied research has declined considerably.

In this section, we analyze NØEnergy publications in more detail from the perspective of research levels,[28] aiming to provide policymakers and funders with an insight into the level of maturity of the research field and to identify areas that may need more time and investment to reach maturity. We classify research by its level of maturity, ranging from "basic scientific research", through "applied research" and "engineering–technological mix" to "applied technology" (see text box, next page).

"The role of research and development as an enabler of the energy transition is crucial. On the one hand, in the development of core technologies, such as those based on energy storage or renewable energy production, basic and applied research are fundamental. On the other hand, we must be able to integrate these new technologies into the energy system, which is a very complex system with a high degree of interdependence between the parts and agents that compose it. Developing engineering solutions that enable this coordinated integration is critical when it comes to achieving a change in the energy paradigm."

Pablo Arboleya, Associate Professor and Holder of the Smart Cities Chair, Universidad de Oviedo

[28] See Boyack, K. W., Patek, M., Ungar, L. H., Yoon, P., & Klavans, R. (2014). Classification of individual articles from all of science by research level. *Journal of Informetrics, 8*(1), 1–12. https://doi.org/10.1016/j.joi.2013.10.005, and Klavans, R., & Boyack, K. W. (2017). Research portfolio analysis and topic prominence. *Journal of Informetrics, 11*(4), 1158–1174. https://doi.org/10.1016/j.joi.2017.10.002

Research level classifications

Research can be categorized into different stages, ranging from the basic to more applied/clinical. Generally, research in physics, chemistry, biology and some aspects of medicine tends to be more basic, while engineering, computer science, social sciences and clinical medicine are more applied. In these areas, there is a positive correlation between citation count (impact) and research level: citation counts decrease during the transition from basic to applied research.

In this report, publications are assigned to a research level based on a model developed by Klavans and Boyack (see footnote 28), which uses the title, abstract and cited references to classify individual articles by research level. This model works best in the physical and life sciences, however, as the algorithm is less effective in the social sciences.

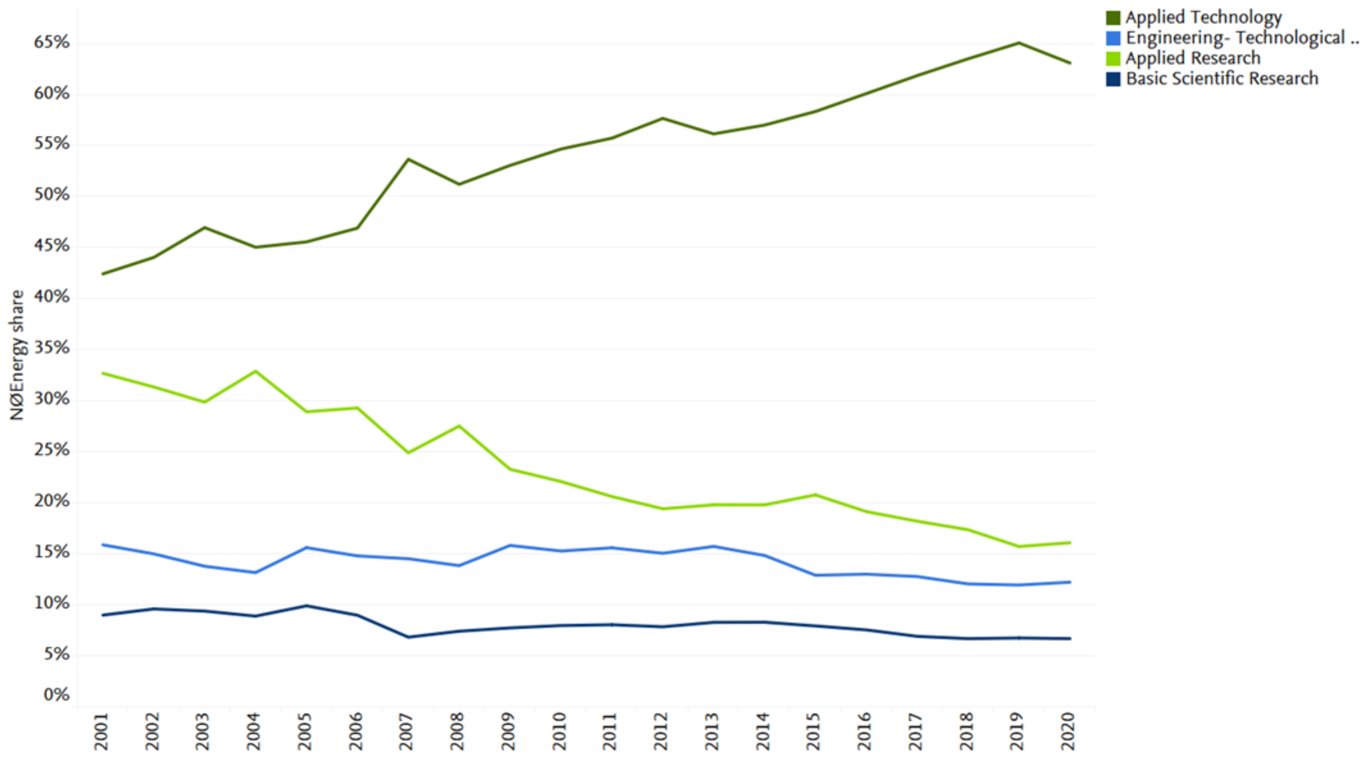


Figure 37
Distribution of global research levels in NØEnergy, 2001–2020.
Source: Scopus

The majority of publications in the largest NØEnergy topic clusters fall within the applied technology category (Figure 38). *Lithium Alloys | Secondary Batteries | Electric Batteries*, *Photocatalysts | Solar Cells | Photocatalysis*, *Solar Cells | Conjugated Polymers | Organic Light Emitting Diodes (OLEDs)* and *Electrocatalysts | Electrolytic Reduction | Proton Exchange Membrane Fuel Cells (PEMFCs)* stand out, however, because these topic clusters are mainly focused on basic scientific and applied research. Other topic clusters that display a larger share of basic scientific and applied research are presented in Figure 39.

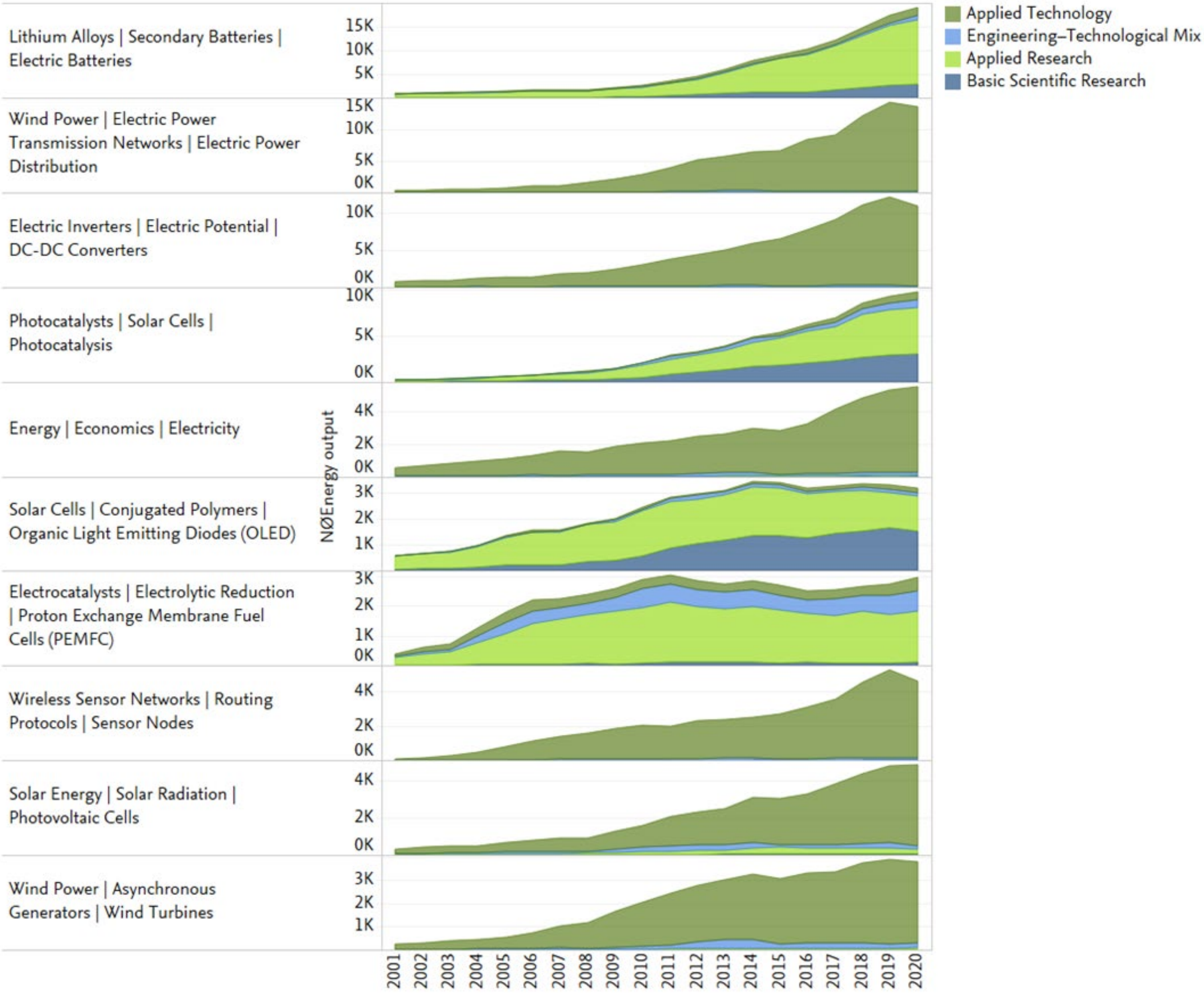


Figure 38
Distribution of output across research levels for the top 10 most published topic clusters in NØEnergy, 2001–2020.
Source: Scopus

"Real innovation in science and technology at the R&D stage usually takes place 10–20 years before any commercial application can happen. It's R&D on clean production and sustainable consumption that will determine how we address global climate change, irrespective of any technological innovation or economic mechanisms."

Dabo Guan, Distinguished Professor of Climate Change Economics, Tsinghua University; Chair at the Bartlett School of Construction and Project Management, University College London

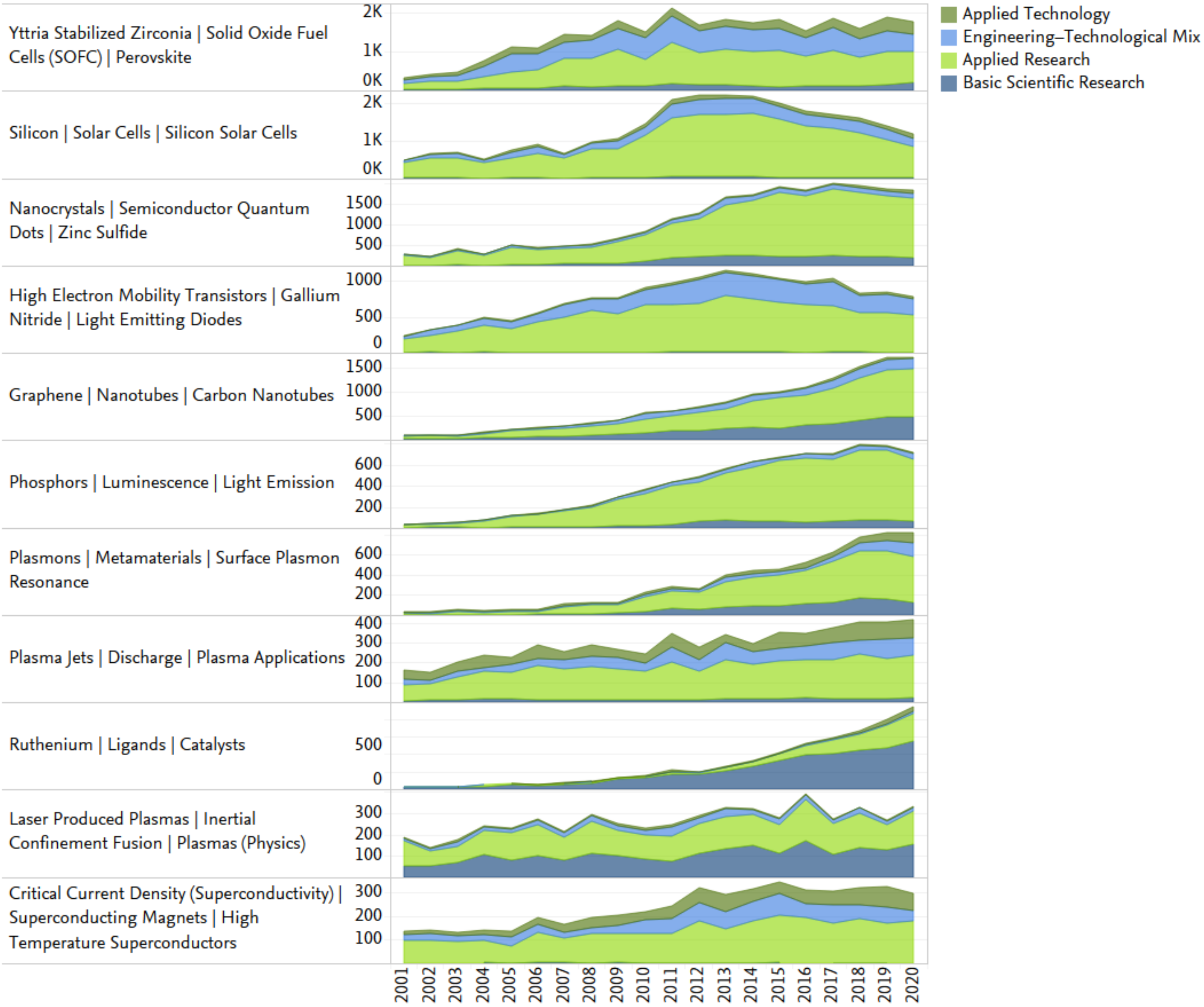


Figure 39
Selected topic clusters with more than 5,000 publications that have larger shares of basic scientific and applied research publications, 2001–2020.
Source: Scopus

> *"In the case of research carried out, for example, in electrical energy transport and distribution systems, this is practically 100% based on applied technology, while in other cases such as energy accumulation systems in electric batteries, the bulk of the research is applied research. The evolution of these percentage levels over time is a very strong indicator of the degree of maturity of the technology."*
>
> Pablo Arboleya, Associate Professor and Holder of the Smart Cities Chair, Universidad de Oviedo

Among the most published countries in NØEnergy, Singapore has the largest share of basic scientific research publications in NØEnergy for the period 2001–2020, followed by Switzerland, Russia and Japan (Figure 40). Malaysia, Iran and Turkey, however, show the smallest shares of publications in this category. South Korea and Japan have notably larger shares of publications in applied research, while applied technology accounts for the largest shares of publications from Denmark, Iran and Malaysia, at 66%.

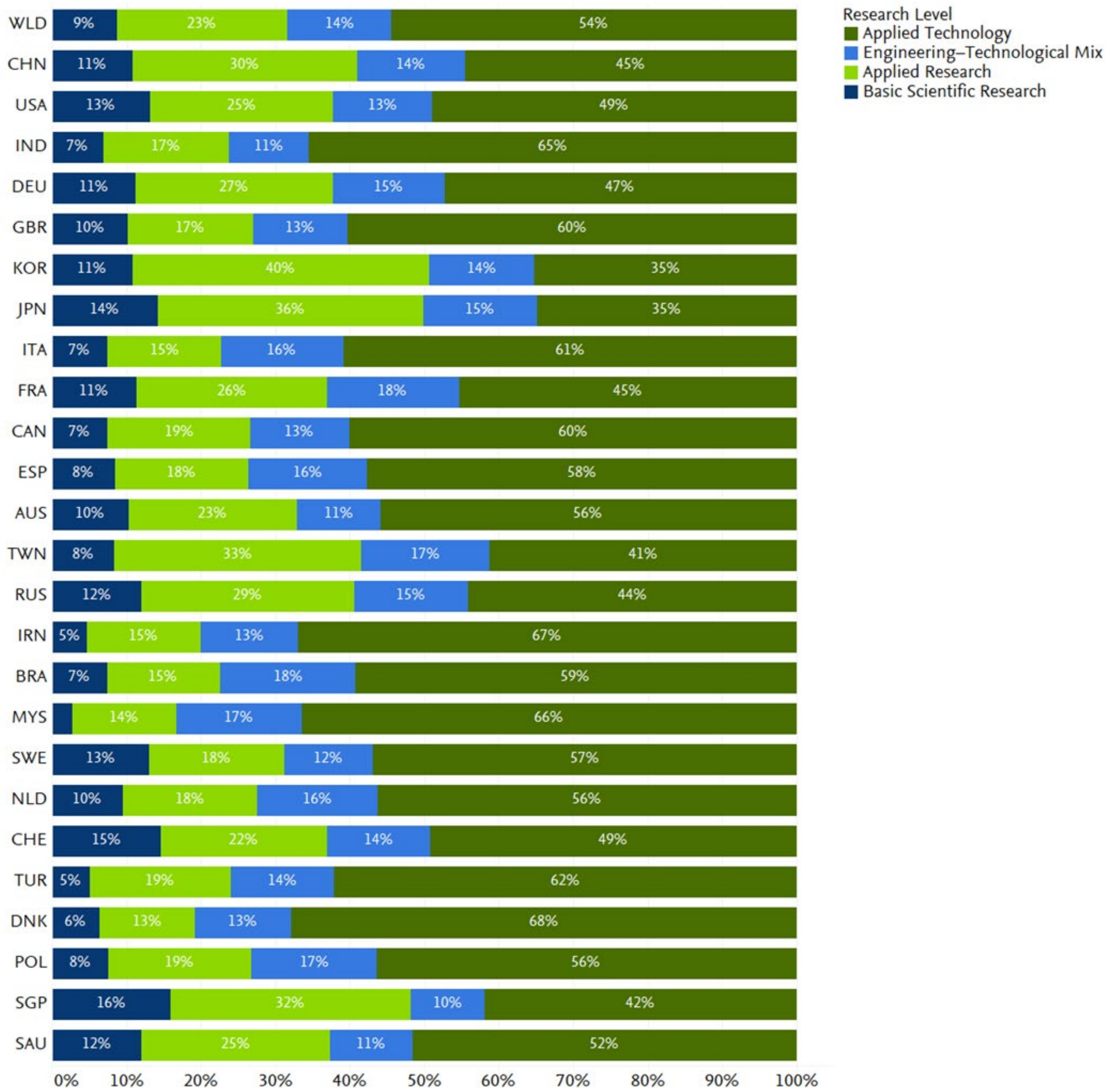


Figure 40
Research level distribution for those countries and regions contributing at least 1% of NØEnergy publications in 2011–2020. This period is presented to reflect the most recent trends.
Source: Scopus

As much as developing new research to push the frontiers on clean energy research is important, it is necessary that the research is transformed into application. The data presented in this section and further derivative analyses can provide insight into whether there is enough research in the applied side of the spectrum, particularly in those areas that are considered by government and leading intergovernmental organizations as important technology areas in achieving net zero targets. The next section focuses on one element of this transition: academic–corporate collaborations in research.

"We've got a lot of the technologies that we need to get to net zero, but they're not necessarily at the stage that we need them to be to contribute effectively to the net zero transition. About half the technologies are already maturing in the market, but the other half still need developing. The initial research phase is the start of it all: it's the genesis of everything. But then you need development and demonstration, and then deployment. All four of these phases must occur for the technologies to play their part in enabling us to get to net zero with decent living standards for all."

Joan MacNaughton, CB HonFEI (Lady Jeffrey), Chair, Climate Group

1.8 What are the academic–corporate collaboration trends in NØEnergy research?

Academic–corporate collaboration in NØEnergy research has increased over the last two decades, overtaking the global average and led by Switzerland and the Netherlands.

The net zero transition demands knowledge exchange between academia and industry to establish a dialogue around strategic priorities and support the translation of research into practical applications.

Our analysis reveals that while the total number of publications in NØEnergy resulting from academic–corporate collaborations has increased continuously over the last two decades, the overall share has remained relatively stable (Figure 41). This trend in NØEnergy academic–corporate collaborations echoes overall global research trends. In terms of scholarly impact, publications from academic–corporate collaborations tended to have higher FWCI values than the global average until 2019, after which the impact of these publications in NØEnergy fell below the global average.

What are academic–corporate publications?

In this report, academic–corporate collaboration refers to publications for which at least one author is affiliated with a corporation and at least one author is affiliated with an academic institution.

We acknowledge that the breadth of academic–corporate collaborations goes beyond joint publications.

"Given that large energy corporations are present in the integration phase, it is also necessary to promote and establish strong cooperative links between research organizations and these corporations so that research does not remain in the academic sphere but is transferred smoothly to the industrial sector."

Pablo Arboleya, Associate Professor and Holder of the Smart Cities Chair, Universidad de Oviedo

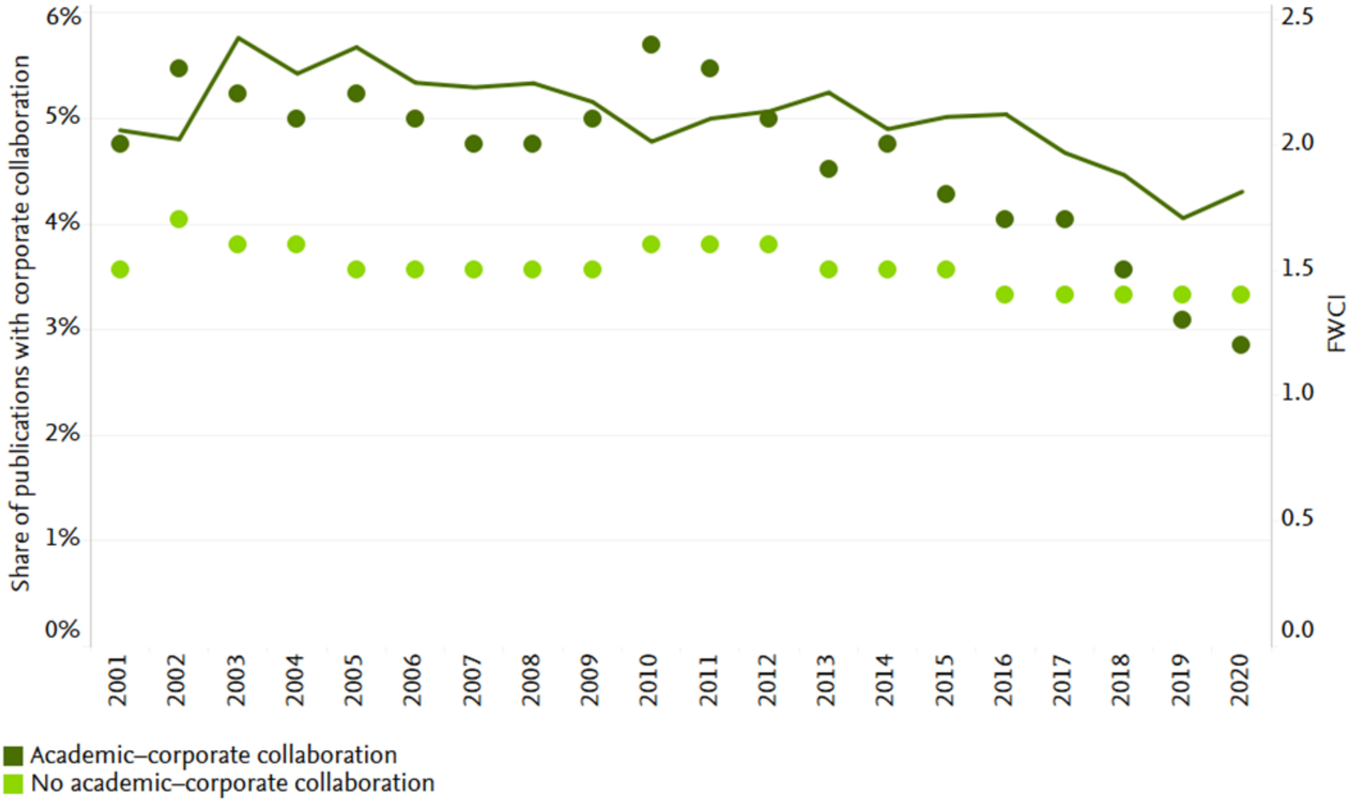


Figure 41
Share and impact of publications with academic–corporate collaboration, 2001–2020. Dark green line indicates the share of publications with academic–corporate collaboration, mapped to the left axis. The dots indicate the field-weighted citation impact, mapped to the right axis.
Source: Scopus

The share of NØEnergy publications with academic–corporate collaboration is generally higher than overall, at both the global and country/region levels. Our analysis indicates that academic–corporate collaboration is more prevalent in European countries, the United States, Canada, Japan and South Korea (Figure 42). In the period 2011–2020, Switzerland had the largest share of such publications in NØEnergy, with collaboration focused in the fields of *Electric Inverters / Electric Potential / DC-DC Converters*, *Wind Power / Electric Power Transmission Networks / Electric Power Distribution* and *Photocatalysts / Solar Cells / Photocatalysis*. The Netherlands, which had the second largest share of academic–corporate publications in NØEnergy in that period, was similarly concentrated on *Electric Inverters / Electric Potential / DC-DC Converters* and *Wind Power / Electric Power Transmission Networks / Electric Power Distribution*, as well as *Solar Cells / Conjugated Polymers / Organic Light Emitting Diodes (OLEDs)*.

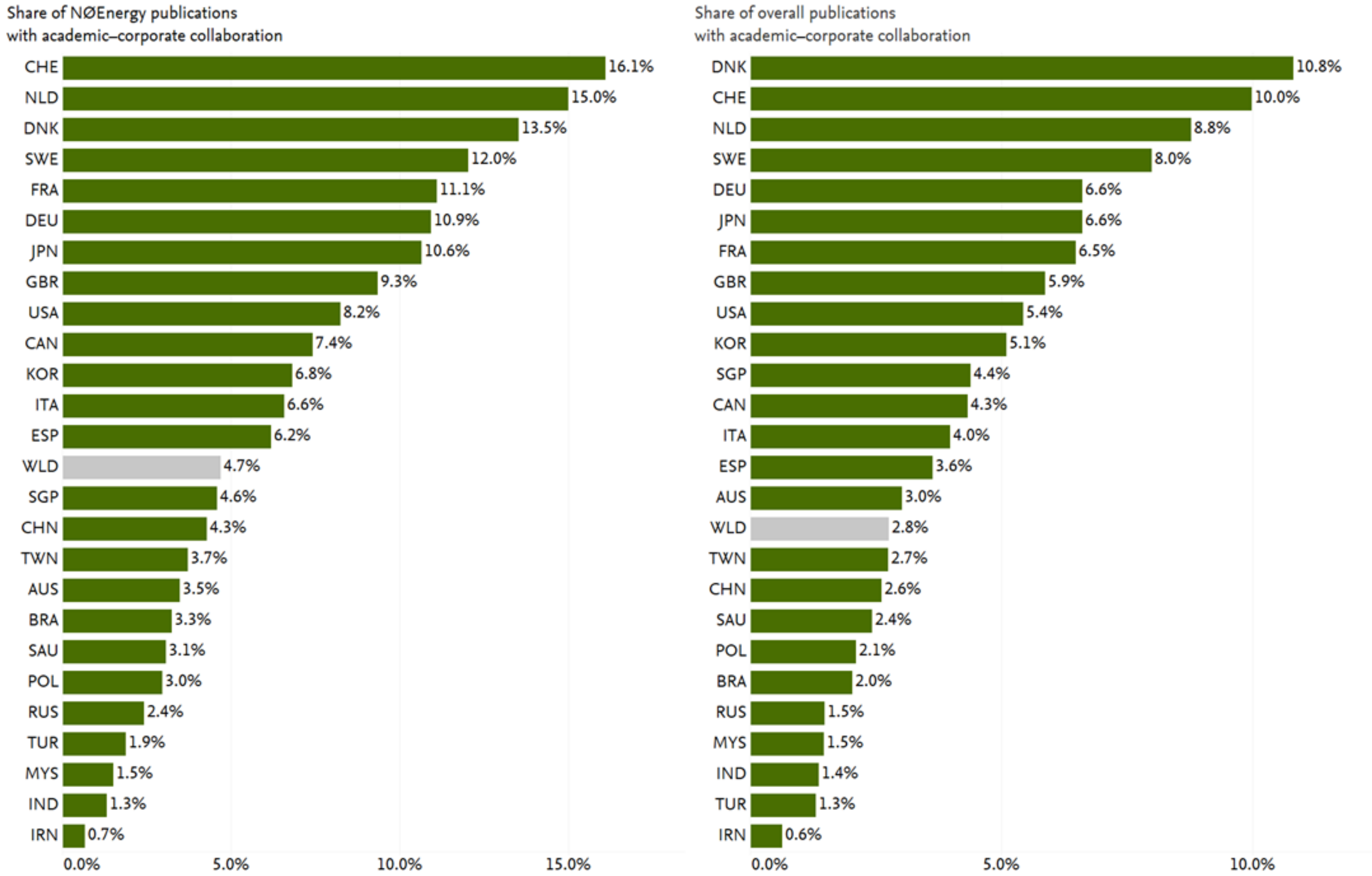


Figure 42
Share of NØEnergy publications with academic–corporate collaboration (left panel) for countries and regions accounting for at least 1% of publications in 2011–2020. Right panel shows the share of overall academic–corporate collaborations for the same countries and regions.
Source: Scopus

Some of the largest topic clusters in NØEnergy, such as *Magnetoplasma / Plasmas / Tokamak Devices* and *Wind Power / Electric Power Transmission Networks / Electric Power Distribution*, also demonstrate the highest levels of academic–corporate collaboration and saw their shares increase, decade on decade, from 2001–2010 to 2011–2020 (Figure 43). Most of the other major topic clusters with lower shares of academic–corporate collaboration show declining levels of collaboration over these periods, except *Energy / Economics / Electricity*, *Pyrolysis / Coal / Gasification*, *Ventilation / Buildings / Air Conditioning* and *Heat Pump Systems / Rankine Cycle / Exergy*.

Several other topic clusters with shares of academic–corporate publications above 10% are not shown on the chart. These include *Partial Discharges / Insulation / Power Transformers*, *CMOS Integrated Circuits / Variable Frequency Oscillators / Power Amplifiers*, *Oil Well Flooding / Hydraulic Fracturing / Reservoirs (Water)*, *Austenite / Microstructure / Steel*, *Electric Grounding / Lightning / Lightning Protection*, *MOSFET Devices / Insulated Gate Bipolar Transistors (IGBT) / Silicon Carbide*, *Data Storage Equipment / Applications / Program Processors* and *Manufacture / Industry / Automation*.

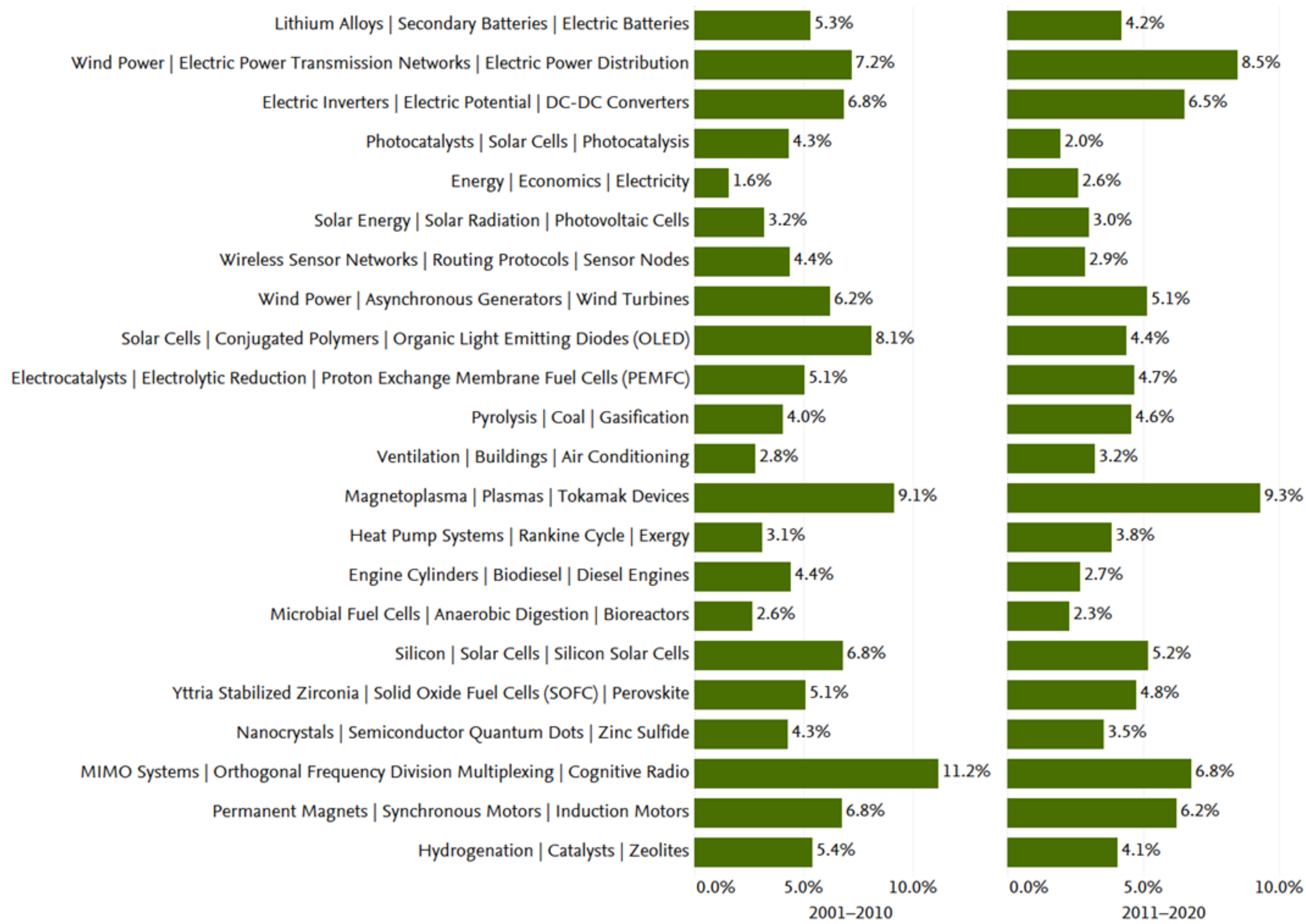


Figure 43
Share of publications with academic–corporate collaboration in topic clusters contributing more than 1% of all NØEnergy publications in 2011–2020. Left panel shows values for 2001–2010 and right panel values for 2011–2020.
Source: Scopus

> *"One of the things that corporates have, and that academia often doesn't, is an understanding of what the challenges are in the market. And so they can help academia to think about where the next priorities lie. They can shape the focus of the academic work, and then they can help to get it through into the market."*
>
> Joan MacNaughton, CB HonFEI (Lady Jeffrey), Chair, Climate Group

1.9 What role do corporates play in NØEnergy research?

European corporates produce a large share of NØEnergy publications, but Chinese organizations are starting to overtake. However, the share of NØEnergy publications from corporates is declining, and few of the largest emitters produce any significant research output.

Corporations have a very important role to play in achieving net zero, not only because they can be large emitters of CO_2 but also because they can bring new clean energy or mitigating technologies to market. Research by Richard Heede indicates "that nearly two-thirds of historic carbon dioxide and methane emissions can be attributed to 90 entities."[29]

In this section, we look in detail at the focus of and contribution from corporations to NØEnergy research. When we refer to output from corporates, we define this as publications that have at least one corporate author. An organization is classified as a corporate entity via their registration data, and this classification can include independent research organizations too.

The contribution from corporates to NØEnergy output declined from a share of 9% to 5% over the period 2011–2020, with a CAGR of 2.4%, considerably lower than the overall CAGR in NØEnergy publications of 8.2%. This decline in NØEnergy corporate output is not a global trend: corporate output from China across the board increased by 21% over the same period (Figure 44). The United States, however, showed a small decline of 4% in corporate output during this time.

Malaysia and Saudi Arabia also had very high CAGRs in corporate NØEnergy publications, partially as a result of their very low outputs at the beginning of the period. While Japan and Switzerland had the largest shares of corporate output overall, both had negative growth rates over the past 10 years. It is also worth noting that Norway, Finland and Austria, each of which contributed less than 1% to the total number of NØEnergy publications, had very large shares of corporate output of 29%, 22% and 13%, respectively.

> *"When research, technology development and innovation are combined with policy and market design, targeted to the actual needs of society and corporates, then innovative systems approaches can truly achieve net zero programs."*
>
> Yutao Wang, Professor, Department of Environmental Science and Engineering, Fudan University

[29] Heede, R. (2014). Tracing anthropogenic carbon dioxide and methane emissions to fossil fuel and cement producers, 1854–2010. *Climatic Change, 122*, 229–241. https://link.springer.com/article/10.1007/s10584-013-0986-y

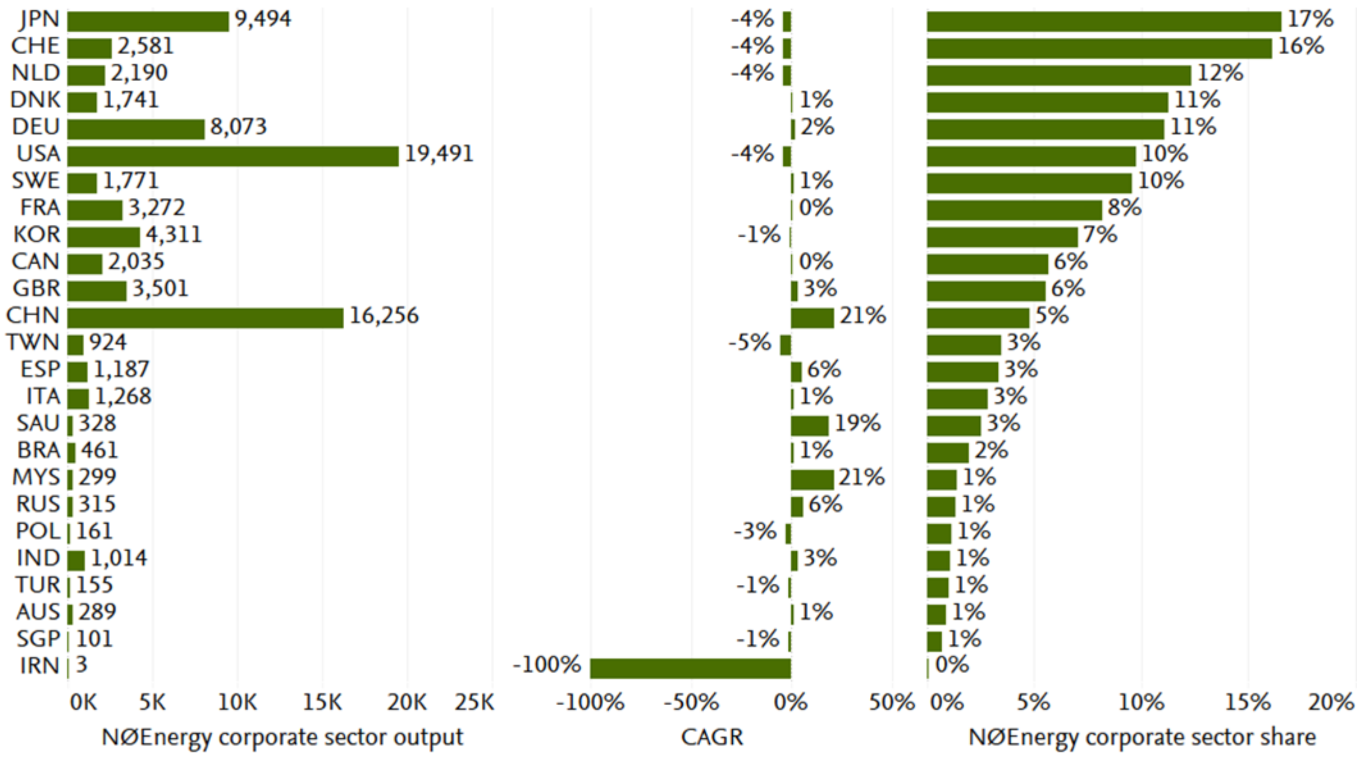


Figure 44
Corporate output of countries and regions contributing to at least 1% of NØEnergy publications, 2011–2020. The total output from the corporate sector is shown on the left, the CAGR of output is shown in the middle chart and the share of corporate output within NØEnergy is shown on the right.
Source: Scopus

The top 20 corporates with the largest shares of NØEnergy publications during two periods—2001–2010 and 2011–2020—are shown in Figure 45. The most prolific corporates during 2001–2010 were largely from the most productive countries and regions in terms of NØEnergy publications over the same period, with the notable exception of China. While China produced the second largest volume of publications in 2001–2010, its only corporate making it into the top 20 was China Electric Power Institute, ranking 19th. Conversely, while Dutch company Philips was the 6th most highly ranked corporate in 2001–2010, the Netherlands only ranked 14th overall. In fact, Philips contributed to over 8% of the Netherlands' total output in NØEnergy. Similarly, while Norway produced fewer than 2,000 publications in NØEnergy in 2001–2010, the Norwegian independent research organization SINTEF contributed to over 17% of the country's publications.

Over the last decade, 2011–2020, Chinese corporates such as State Grid Corporation of China and China Electric Power Research Institute have led the way in NØEnergy publications. State Grid's annual output grew exponentially from 2001 to 2020. Meanwhile, SINTEF's output increased sixfold, taking it to third position in the corporate ranking and contributing to over 20% of Norway's total output. Companies including IBM and Intel also increased their output considerably and moved up the rankings.

Several corporates produced at least 100 publications during the period 2011–2020, achieving average FWCI values of over 3.0, but are not among the top 20 in terms of output. These include Nvidia, Lucent and Microsoft from the United States; Panasonic Corporation from Japan; Nokia from Finland; BASF from Germany; Ericsson and RISE ICT from Sweden; SK Corporation from South Korea; and Huawei Technologies from China.

2001–2010

General Atomics	USA	1,499
Samsung	KOR	1,262
VTT Technical Research Centre of Finland Ltd.	FIN	634
Siemens	DEU	609
General Electric	USA	606
Koninklijke Philips N.V.	NLD	579
General Motors	USA	525
Hitachi	JPN	479
Toshiba	JPN	457
ABB Group	CHE	438
Alstom	CHE	433
LG Corporation	KOR	429
Ford Motor Company	USA	381
Nippon Telegraph & Telephone	JPN	368
IBM	USA	367
SINTEF	NOR	347
Toyota Motor	JPN	326
Hydro-Quebec	CAN	319
China Electric Power Research Institute	CHN	315
Électricité de France S.A.	FRA	295

2011–2020

State Grid Corporation of China	CHN	5,111
China Electric Power Research Institute	CHN	4,427
SINTEF	NOR	2,078
Samsung	KOR	1,929
General Atomics	USA	1,655
Guangdong Power Grid Corporation	CHN	1,573
IBM	USA	1,450
VTT Technical Research Centre of Finland Ltd.	FIN	1,429
Siemens	DEU	1,134
General Motors	USA	986
ABB Group	CHE	967
Électricité de France S.A.	FRA	964
General Electric	USA	916
Intel	USA	914
LG Corporation	KOR	889
SINOPEC	CHN	846
E.ON	DEU	756
Hydro-Quebec	CAN	697
Hitachi	JPN	680
Toyota Motor	JPN	629

FWCI 0.0 – 4.0

Figure 45
Top 20 corporates in terms of number of NØEnergy publications for 2001–2010 (left panel) and 2011–2020 (right panel). Color indicates the average field-weighted citation impact; blue is below the world average (1.0) and green is above the world average.
Source: Scopus

The topic clusters with the largest proportion of corporate publications tend to match those with the highest number of NØEnergy publications, although the rankings differ (Figure 46). However, the largest topic cluster on both counts is *Wind Power / Electric Power Transmission Networks / Electric Power Distribution*, driven mainly by Chinese corporates. Corporates also contribute to over 10% of publications in *Magnetoplasma / Plasmas / Tokamak Devices*, primarily the US corporate General Atomics. The topic cluster *High Electron Mobility Transistors / Gallium Nitride / Light Emitting Diodes* also has corporate publications of more than 10%, primarily from Samsung, LG, Osram and EPISTAR Corporation.

Unsurprisingly, *Fuel Economy / Hybrid Vehicles / Electric Vehicles* has a large share of corporate publications from automotive manufacturers such as General Motors, Ford Motor Company and AVL List GmbH. Two related topic clusters, *Electric Inverters / Electric Potential / DC-DC Converters* and *Lithium Alloys / Secondary Batteries / Electric Batteries*, are also among the fastest growing in terms of corporate publications, along with *Wind Power / Electric Power Transmission Networks / Electric Power Distribution*.

Although output in the topic cluster *Photocatalysts / Solar Cells / Photocatalysis* has also grown very rapidly overall, this is not reflected in corporate output. In most of the above-mentioned topic clusters, research tends to be focused on applied technology (see Section 1.7).

A few topic clusters have a smaller share of applied technology publications but a relatively large corporate presence. In the battery-related field, *Lithium Alloys / Secondary Batteries / Electric Batteries*, Samsung (South Korea), General Motors and Ford Motor Company (United States), Hydro-Quebec (Canada), Toyota Motor Corporation and Toyota Central R&D Labs (Japan), BASF, BMW Group and Robert Bosch GmbH (Germany), China Electric Power Research Institute and GRINM Group (China) each have more than 100 publications. The US organization General Atomics and VTT Technical Research Centre of Finland Ltd. produced more than 100 publications in *Magnetoplasma / Plasmas / Tokamak Devices*. General Motors, Ballard Power Systems from Canada and Nissan Motor Co. Ltd. from Japan also notched up more than 100 publications each in *Electrocatalysts / Electrolytic Reduction / Proton Exchange Membrane Fuel Cells (PEMFCs)*. In *Solar Cells / Conjugated Polymers / Organic Light Emitting Diodes (OLED)*, Samsung and LG Corporation from South Korea produced more than 100 publications.

Meanwhile, SINTEF from Norway, LG Corporation and Samsung from South Korea, CSEM SA from Switzerland, and Total S.A. from France each report more than 50 publications in *Silicon / Solar Cells / Silicon Solar Cells*. Over 50 publications were also contributed by Samsung in *Photocatalysts / Solar Cells / Photocatalysis* and *Yttria Stabilized Zirconia / Solid Oxide Fuel Cells (SOFC) / Perovskite*, along with SOLIDpower from Italy, Haldor Topsoe from Denmark, and VTT Technical Research Centre of Finland.

“The academic–corporate collaboration data show that such collaborations have been increasing in clean energy research over the last 20 years, but the data on corporate publications show that their share in the field has been declining since 2010. In short, corporates are publishing less, but they are collaborating more with academia when they do so.”

Yutao Wang, Professor, Department of Environmental Science and Engineering, Fudan University

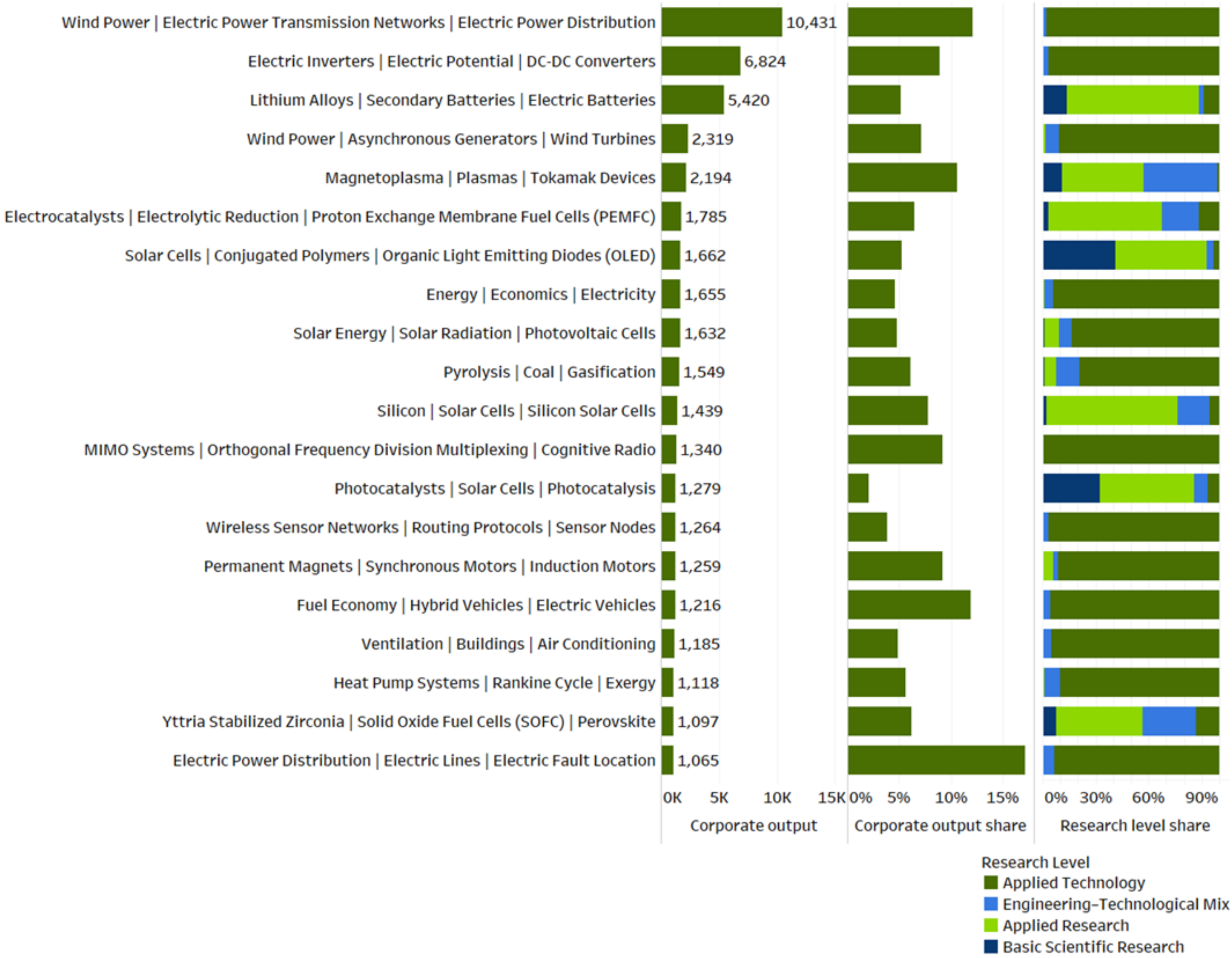


Figure 46
Top 20 topic clusters in terms of corporate output and their share of the overall topic cluster. Right-hand chart shows the distribution of all NØEnergy publications within the topic cluster across research levels, 2011–2020.
Source: Scopus

> *"In Japan solar power is an efficient electricity source, yet uptake of renewables in general is only now gathering pace. Some parts of society do not necessarily desire rapid change, and companies prefer to initiate it themselves rather than being told to change. As researchers, we need to consider how we navigate our societal systems to be able to effect change."*
>
> Hiroshi Komiyama, Chairman, Mitsubishi Research Institute, Inc.; President, Platinum Society Network; 28th President, University of Tokyo

Figure 47 shows the topic clusters with the largest shares of corporate output. Most of these topic clusters contain very few publications in basic scientific or applied research.

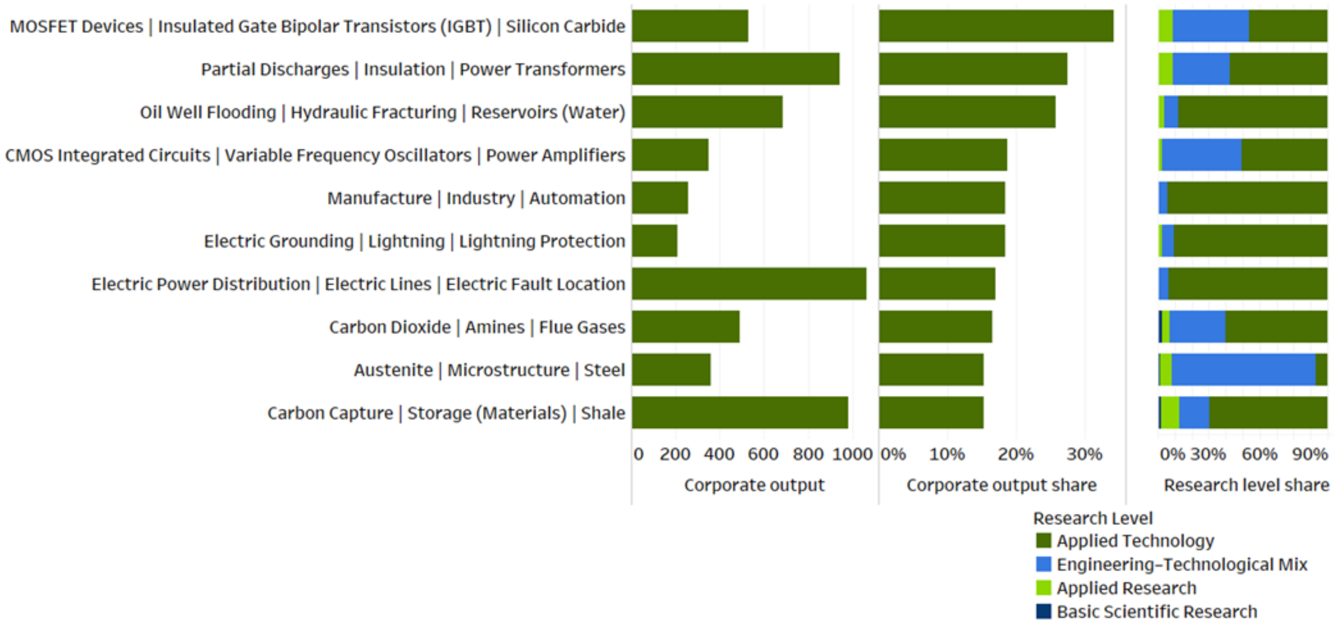


Figure 47
Topic clusters with a corporate output share of more than 15%, 2011–2020.
Source: Scopus

The topic clusters with at least 10 publications from the 20 largest corporate emitters of GHGs[30] are presented in Figure 48. The figure shows that the top emitters focus their research on a more limited number of topic clusters than is the case for the NØEnergy field overall. The largest number of publications are focused on oil (*Oil Well Flooding / Hydraulic Fracturing / Reservoirs (Water)* and *Well Drilling / Drilling Fluids / Drilling*) and carbon capture (*Carbon Capture / Storage (Materials) / Shale*), as well as *Energy / Economics / Electricity*. However, it is noteworthy that these corporates also have interests in alternative fuels such as biodiesel (*Engine Cylinders / Biodiesel / Diesel Engines*, *Bioenergy / Biomass / Biofuels*) and hydrogen (*Hydrogenation / Catalysts / Zeolites*), as well batteries (*Lithium Alloys / Secondary Batteries / Electric Batteries*). There is also some attention directed at *Pyrolysis / Coal / Gasification* and *Reservoir / Basin / Shale*. Of the more well-established renewable energy areas, there is more output in photovoltaics (*Silicon / Solar Cells / Silicon Solar Cells*, *Solar Energy / Solar / Photovoltaic Cells*) than wind power. Overall, corporates seem to publish in a more concentrated set of topic clusters, compared to the breadth observed in the overall NØEnergy field.

No publications in NØEnergy were identified from National Iranian Oil, Coal India, Pemex, Petroleos de Venezuela, Peabody Energy or Iraq National Oil Company. Our analysis also failed to find any topic clusters with more than 10 publications from Gazprom, ConocoPhillips, Kuwait Petroleum Corp., Sonatrach or BHP Billiton, although they performed slightly better overall than the previous group.

30 Taylor, M., & Watts, J. (2019, October 9). Revealed: the 20 firms behind a third of all carbon emissions. *The Guardian*. https://www.theguardian.com/environment/2019/oct/09/revealed-20-firms-third-carbon-emissions

	SAU Saudi Aramco	USA Chevron Corporation	USA ExxonMobil	GBR BP plc	NLD Royal Dutch Shell PLC	CHN China National Petroleum Corporation	ARE Abu Dhabi National Oil Company	FRA Total S.A.	BRA Petrobras
Oil Well Flooding | Hydraulic Fracturing | Reservoirs (Water)	52	15			20	74	14	15	12
Engine Cylinders | Biodiesel | Diesel Engines	14			11	24	10			20
Carbon Capture | Storage (Materials) | Shale					36	30		37	20
Energy | Economics | Electricity			12	18	14	11			
Hydrogenation | Catalysts | Zeolites	10				12	14			17
Lithium Alloys | Secondary Batteries | Electric Batteries					14	36		15	
Pyrolysis | Coal | Gasification					21	11			18
Silicon | Solar Cells | Silicon Solar Cells								56	
Reservoir | Basin | Shale						27			
Well Drilling | Drilling Fluids | Drilling						17			
Wind Power | Electric Power Transmission Networks | Electric Power Distribution	13								
Optimization | Distillation | Distillation Columns	12								
Bioenergy | Biomass | Biofuels					12				
Electric Inverters | Electric Potential | DC-DC Converters								11	
Solar Energy | Solar Radiation | Photovoltaic Cells								11	
Nanocrystals | Semiconductor Quantum Dots | Zinc Sulfide					11				
Liquefied Natural Gas | Gases | Liquefaction			11						

Figure 48
Topic clusters for top corporate GHG emitters, with more than 10 NØEnergy publications for 2011–2020.
Source: Scopus

"Looking at Figure 48, clearly there is a lot of interest in oil/CCS and energy economics. But I think it is interesting that there is also interest in biodiesel/engines (perhaps showing a desire to use a fuel substitute in existing infrastructure). Beyond that, it is solar and wind, mostly, with a little bit about substitute gas. What's interesting is that there is nowhere near the level of diversity seen in the main NØEnergy topic list, perhaps suggesting a more strategic/limited corporate focus."

Patricia Thornley, Director, Energy and Bioproducts Research Institute, Aston University

1.10 How does NØEnergy research translate into patents?

Patents citing NØEnergy research increased greatly from 2001 to 2020, dominated by the United States, Japan and Germany. China's patent portfolio has grown exponentially over the same period.

NØEnergy research can ultimately only help tackle climate change if it makes a successful transition to real-world applications. Moreover, the ability of nations to invent and develop innovative clean energy technologies and use these innovations to support local clean energy infrastructures could form the basis of thriving economies.

In this report we look at patents from two angles to see how NØEnergy research translates into applications. Initially, we determined how many patents cite NØEnergy research publications. However, not all patents cite academic literature. Therefore, to capture the corporate sector's contribution, we also explore patents directly and categorize them by topic. By analyzing NØEnergy research in terms of academic output, academic co-publications, patent citations and patenting activities, we are able to get a more complete picture of how different countries contribute.

Initially we examined patents citing NØEnergy publications filed at five patent offices: the United States Patent and Trademark Office (USPTO), the European Patent Office (EPO), the World Intellectual Property Organization, the Japan Patent Office and the United Kingdom's Intellectual Property Office. However, the China National Intellectual Property Administration (CNIPA) is not included in this analysis, so only Chinese patents that have been filed globally under the Patent Cooperation Treaty are included. In general, most Chinese patents are only filed locally at the CNIPA, so the statistics presented for China in the first part of this section are an underestimation.

Active patent families were analyzed using LexisNexis PatentSight, a powerful and easy-to-use analysis platform compiling bibliographic patent data from over 95 authorities worldwide (see Appendix C). Inactive patents, which cannot be enforced or monetized, are excluded from our analysis.

> *"Technological development is fundamental. Reducing the costs of energy storage systems is critical to the electrification of systems, as storage systems will provide the necessary flexibility to the energy system to be able to massively integrate renewable generation."*
>
> Pablo Arboleya, Associate Professor and Holder of the Smart Cities Chair, Universidad de Oviedo

Patent citations and patent publishing

A citation of a publication by a patent is a relatively rare event compared with a citation by another scientific publication. Citation by a patent also takes longer because of the time required to develop an invention to the point where it is ready to be patented. Patent applications must be filed with a patent office, which then "publishes" the patent sometime later. The granting of a patent takes even longer. In this report, we count patents that have reached the point of publication.

Patent families

A patent family is a set of related patents that are filed at multiple patent authorities to protect the same invention in more than one country.

Portfolio size

Portfolio size indicates the number of patent families attributable to an entity—for example, a country or region, or a topic cluster, or the overall total.

Commercial value of patents

Several indicators are used to assess the commercial value of a patent, including the geographical market size or *market coverage*, where the bigger the market, the higher the value of the patent, and citations to other patents or *technology relevance*, in which the more patents that cite an older patent, the higher its value. In this report, we also use a composite indicator, *competitive impact*, to assess the value of individual patent families. This indicator is the product of market coverage and technology relevance.

Patent asset index

The patent asset index (PAI) indicates the value of a patent portfolio. The PAI is a composite indicator, taking into account the portfolio size, technology relevance and market coverage.

Inventor country or region

In this section, we use the term "inventor country or region". While technically a country or region is not an inventor, it can be helpful to infer the country or region of origin of a patent from the address of the inventor. The term is shorthand for all the patents originating from a specific country or region.

How the patent literature cites NØEnergy publications

Our analysis shows there has been strong growth in the portfolio size of patents citing NØEnergy publications over the last two decades (Figure 49). From the total of over 1.6 million publications in NØEnergy, just over 286,000 publications (~15%) have been cited by nearly 82,000 patent families. Of these, over 62,000 patent families were still active at the end of 2020. Annual patent publications hit a peak of 5,390 in 2014, with a second high point of 5,363 in 2017 (not shown in graph). The slower growth seen in more recent years is likely the result of the lag between patent application and publication, which varies between national patent authorities. For example, patents at the EPO take an average of 18 months to complete the process from filing to publication.

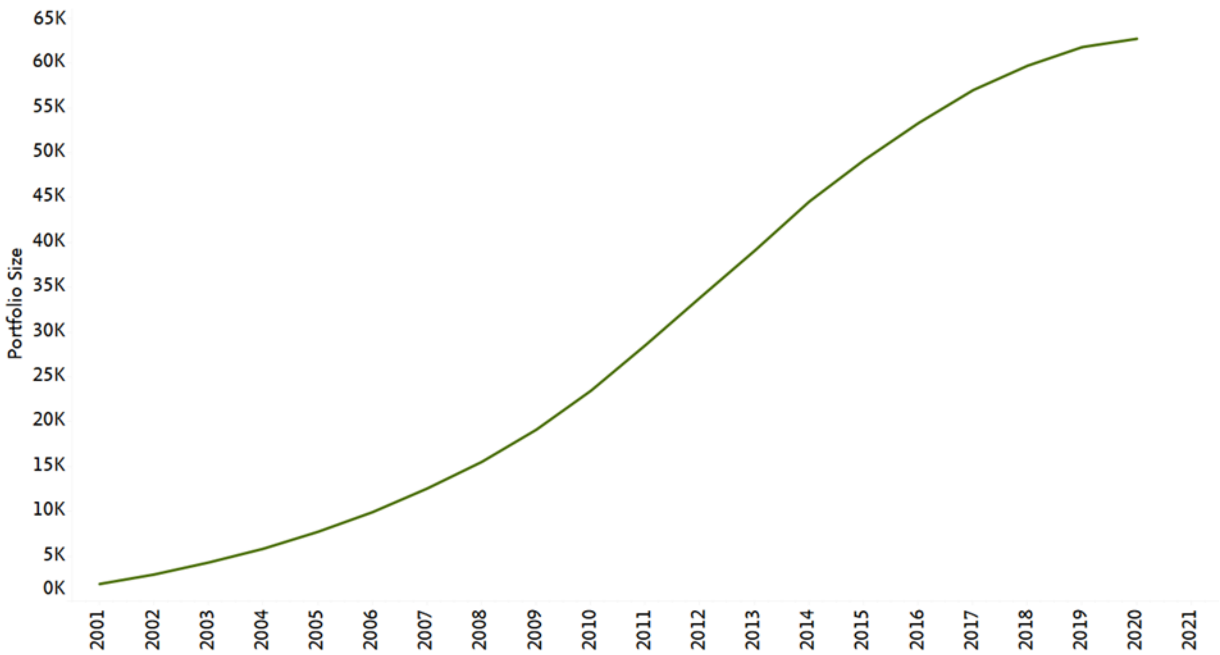


Figure 49
Global patent portfolio size, 2001–2020, for patents citing NØEnergy research publications.
Source: PatentSight

"The IEA published a report earlier this year that showed that the growth in international patent families has been more than double for clean technologies generally, compared with those for fossil fuel technologies. That's quite a shift. And in the latest year for which they quote a figure, 2019, it's probably not far short of three times the gross. We have to bear in mind that it's starting from a lower base, but it shows an important trend in the significance of these technologies and the significance of research development in them".

Joan MacNaughton, CB HonFEI (Lady Jeffrey), Chair, Climate Group

Most active patent families (75%) are owned by corporates, followed by academia with 26% and inventors with 15% (Figure 50). The share of patents from academia citing NØEnergy research is well above the global average for this sector, which is around 14%. This could be because academic researchers are more heavily reliant on and familiar with research publications than corporate researchers.

It should be noted here that ownership percentages do not add up to 100%, because a patent may be owned by more than one of the three groups simultaneously. For example, a patent could be filed by individual researchers together with their institutions or jointly by a corporate and an academic institution. Inventors' patents are owned by individuals in some cases and not always jointly with academic or corporate institutions. Inventor patents peaked in 2013 and have steadily declined since then, which could, in part, be the result of changing internal policies, especially in academia, regarding the transfer of intellectual property rights from an employee inventor to their institution.

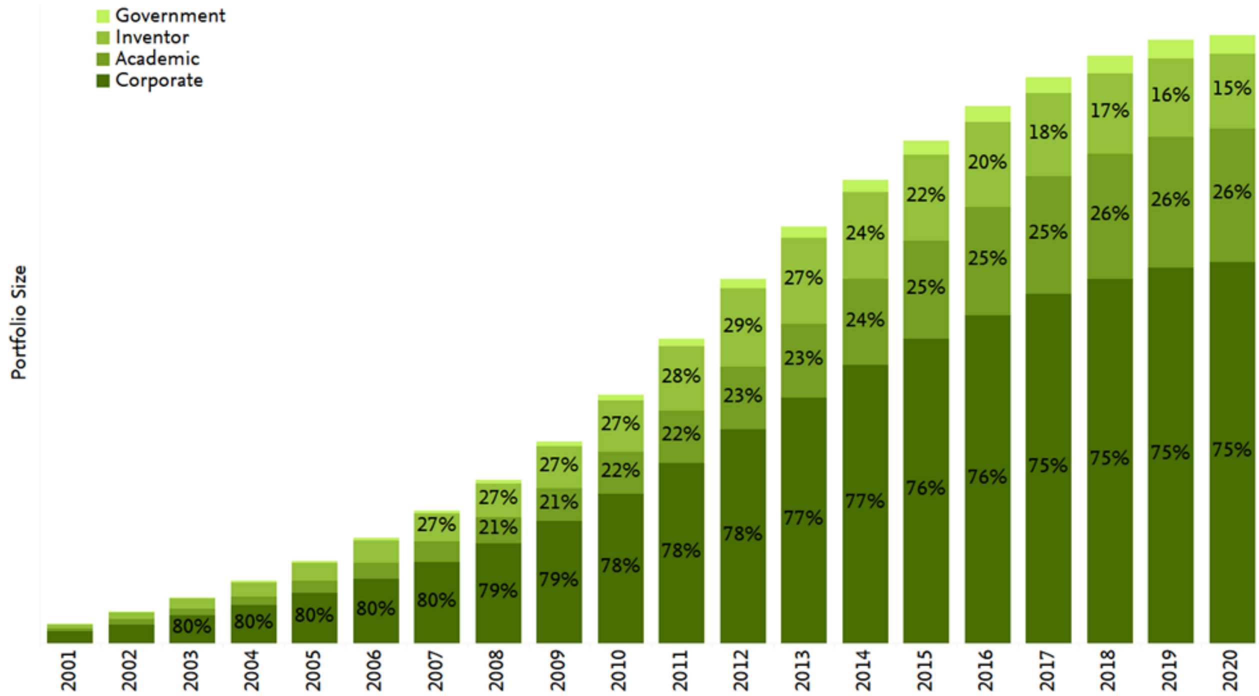


Figure 50
Shares of patent owners by sector for patents citing NØEnergy publications, 2001–2020; percentages may not add up to 100% as a patent can have multiple owners.
Source: PatentSight

The United States has the largest portfolio of active patents citing NØEnergy publications, followed by Japan, South Korea, Germany and China (Figure 51). While our previous analyses indicate that European countries have the largest share of academic–corporate collaboration (see Section 1.8), the region falls behind in the number of patents citing NØEnergy publications. However, the citation practices of individual national patent offices may bias our findings toward the United States. Patents from the USPTO have, on average, many more citations (over 20) than patents from the EPO (4–5, on average). If the CNIPA was included in our analysis, the numbers for China would likely be much higher than reported. Overall, countries with the largest patent portfolios closely match those with the largest scholarly output.

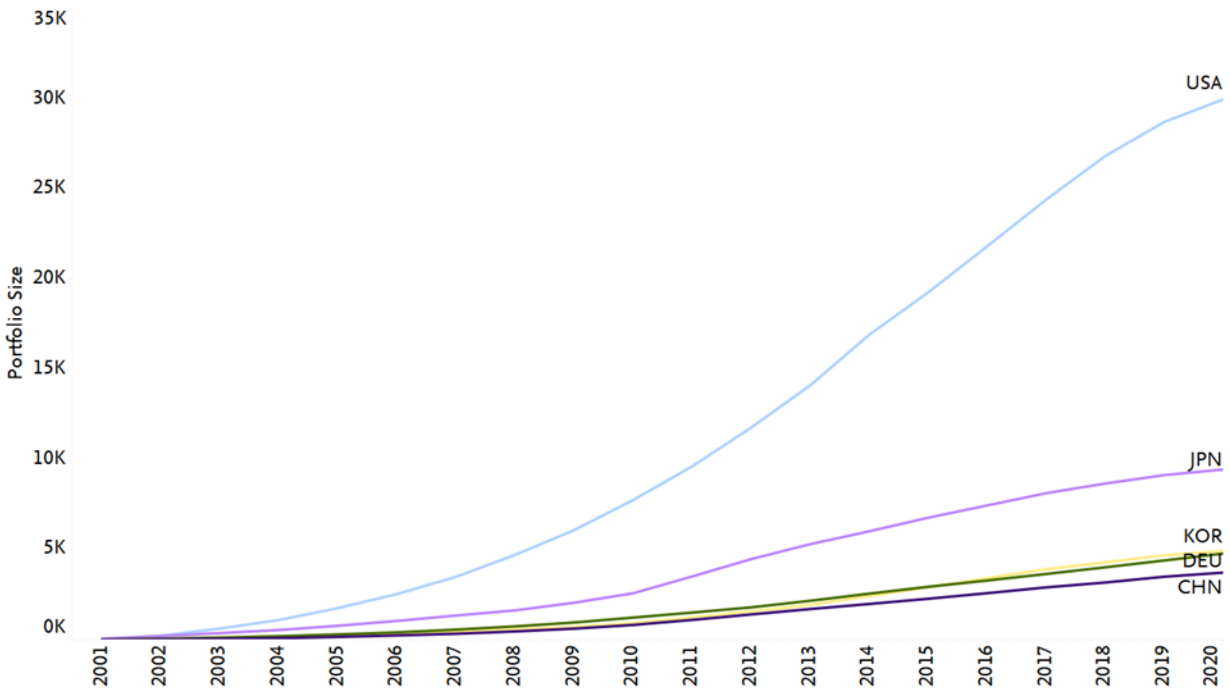


Figure 51
Number of patents citing NØEnergy publications for five inventor countries with the largest active patent portfolios, by year for 2001–2020.
Source: PatentSight

In our analysis, the United States is the leading nation not only in patent portfolio size but also in patent value, followed by Japan and Germany (Figure 52). China ranks 4th and South Korea 5th, although their regional patent authorities fall outside our analysis. However, South Korea makes many of its filings at the USPTO, which is covered here. China's strong performance is noteworthy despite the bias in our methodology.

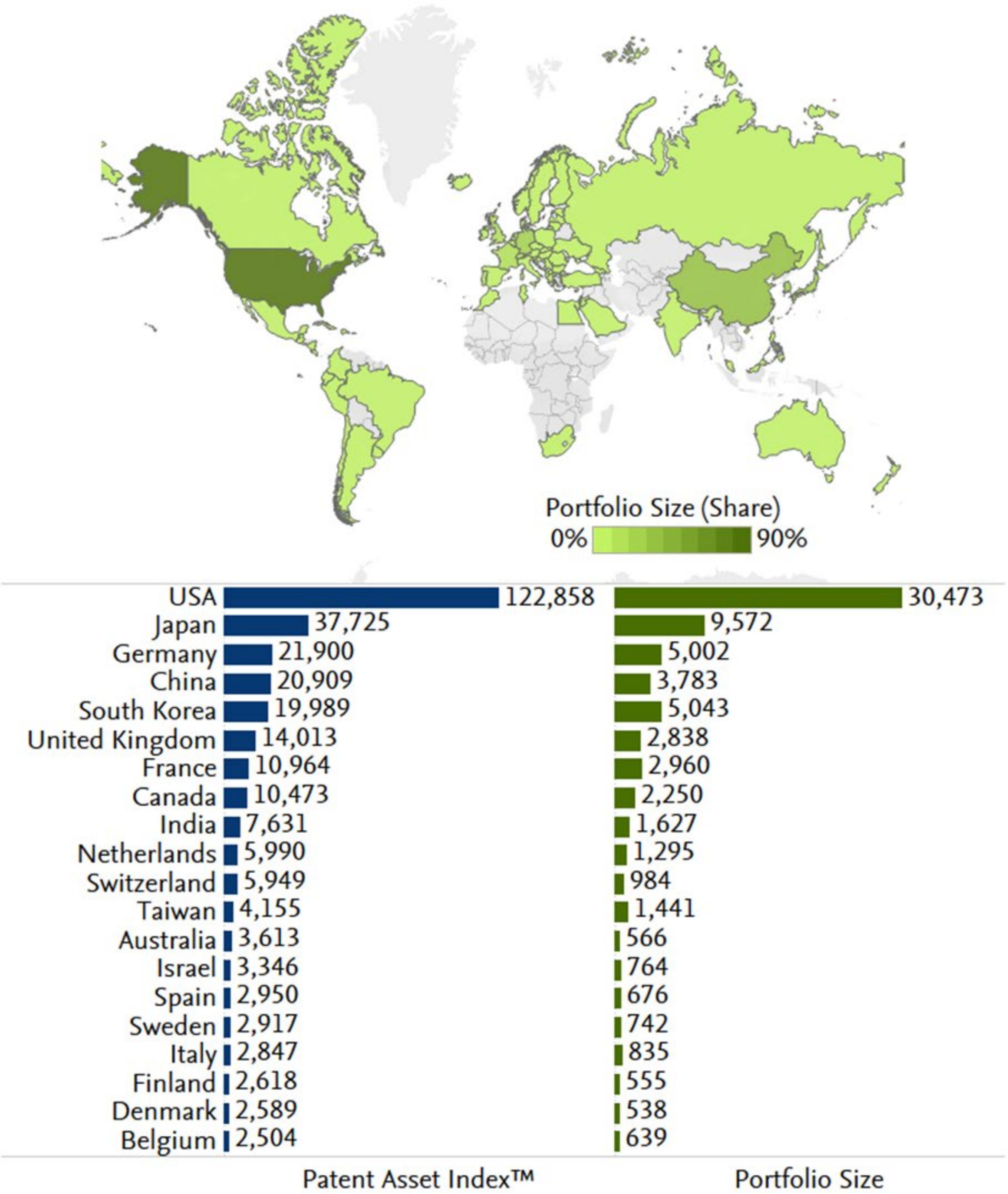


Figure 52
Aggregated patent portfolio for patents citing NØEnergy publications by inventor country or region for 2001–2020.
Source: PatentSight

Analyzing citing patents in NØEnergy by technology cluster

Patent output can also be analyzed in terms of "technology clusters" using an AI-driven approach to define relevant areas. A patent family is assigned to one specific technology cluster, giving an insight into the areas in which a patent portfolio is focused. In our analysis, the largest shares of patents citing NØEnergy publications are found in *Electronics, Electric Power and Semiconductors* (43%), *Chemistry* (23%) and *Information Technologies* (12%) (Figure 53). *Physics* (8%) and *Telecommunications* (5%) follow, with other technology clusters making up less than 5% (not shown). Surprisingly, *Machines*, which includes wind turbine generators, heat exchangers and the like, has a share of less than 2%.

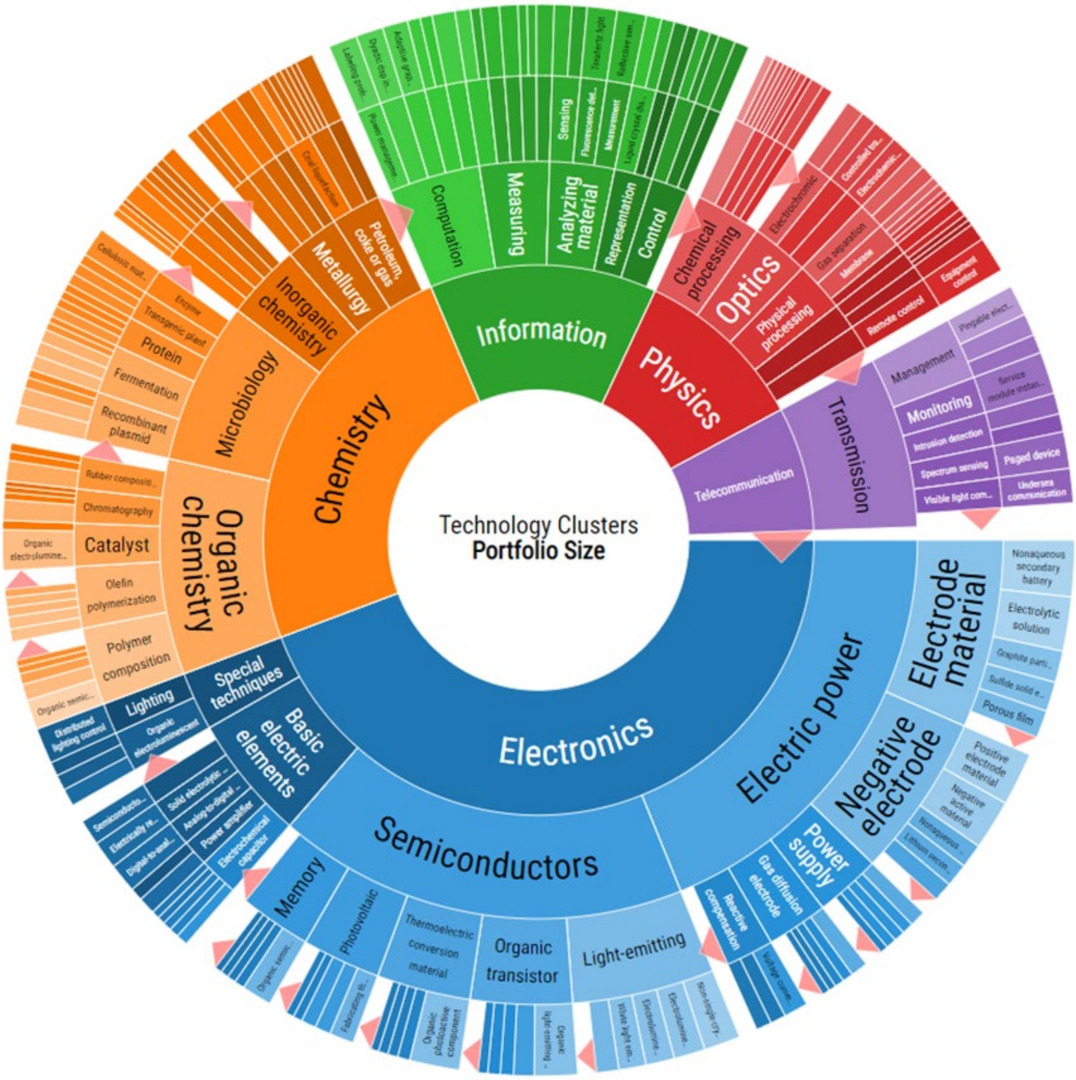


Figure 53
Technology clusters for active patent families citing NØEnergy publications, 2020.
Source: PatentSight

The technology focus of the patent portfolios of Japan, the United States, China, South Korea and Europe are strikingly different (Figure 54). While the United States and Europe have quite similar shares of the major technology clusters (close to the global breakdown shown in Figure 53), Japan has a much larger share in *Electronics*, with almost two-thirds of its patents citing NØEnergy publications in this category. South Korea has a similar focus to Japan, with China falling somewhere in between the two.

Figure 54
Technology clusters for active patent families citing NØEnergy publications from the United States, Europe, Japan, China and South Korea, 2020.
Source: PatentSight

The differences in technology focus of national patent portfolios shown in Figure 54 most likely reflect the specialization of corporations in those countries since they own the majority of patents. Semiconductor Energy Labs in Japan, for example, has the largest portfolio of patents citing NØEnergy publications, followed by technology giants Samsung and LG in South Korea and GE in the United States. These organizations all have large general patent portfolios and are well-known for generating intellectual property from research. However, looking at the share of patents citing NØEnergy publications out of the total portfolio reveals a different picture (Figure 55). Half of the patents owned by Universal Display (based in the United States) cite NØEnergy publications, while less than 5% of those held by Samsung and LG do so. Elsewhere, academic and governmental research organizations including Massachusetts Institute of Technology (MIT) and Battelle in the United States, along with CEA in France, hold large shares of patents citing NØEnergy research.

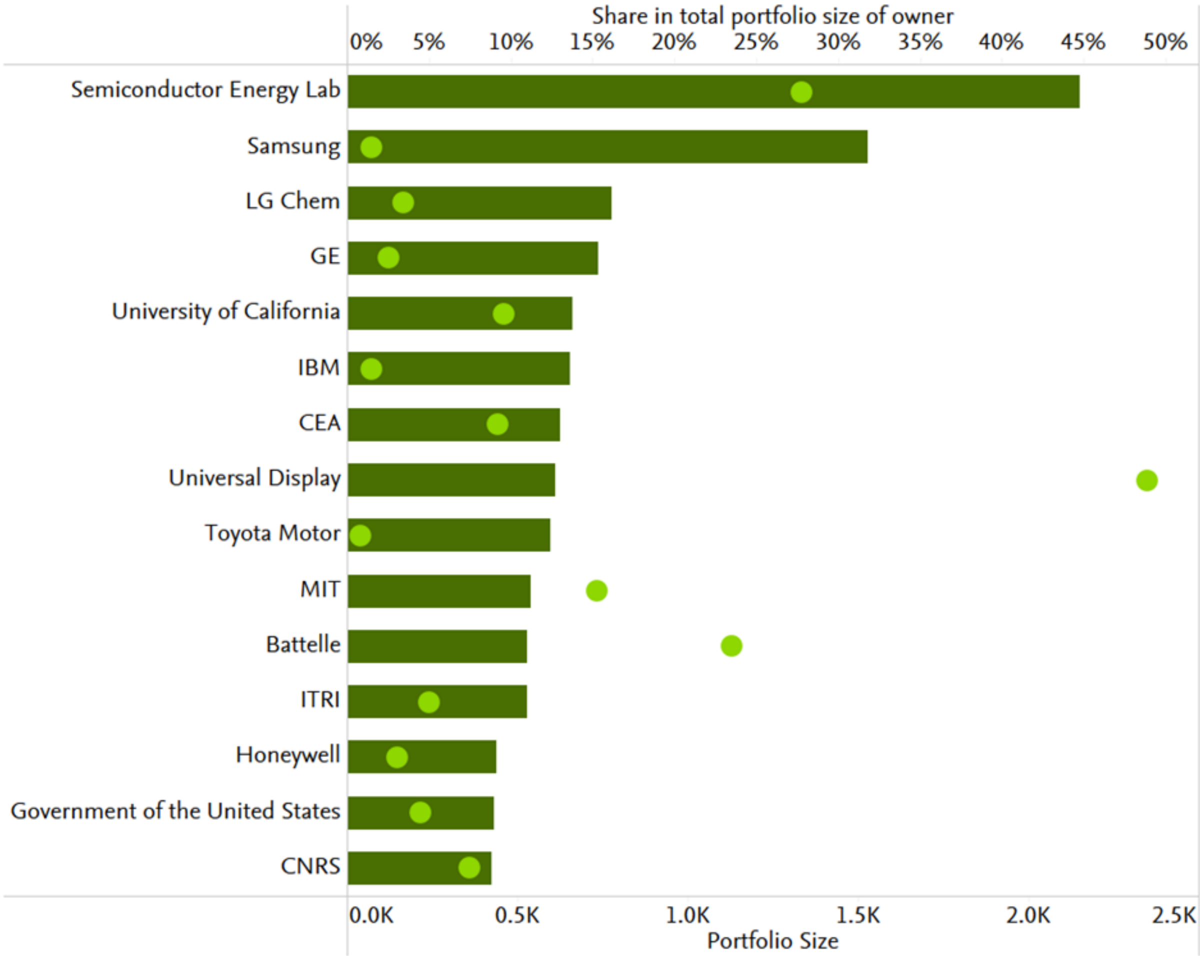


Figure 55
Patents citing NØEnergy publications by portfolio size (dark green bar and bottom scale) and by share of the total portfolio (light green dots and top scale) for the top 15 patent owners globally, 2020. GE = General Electric (USA), CEA = Commissariat à l'Énergie Atomique et aux Énergies Alternatives (FRA), MIT = Massachusetts Institute of Technology (USA), ITRI = Industrial Technology Research Institute (CHN), CNRS = Centre National de la Recherche Scientifique (FRA).
Source: PatentSight

Identifying NØEnergy patents directly

To provide a more detailed view, we complement our analysis of patents citing NØEnergy publications by looking at patent filings directly. Since patent language is quite different from the vocabulary used in research publications, search queries defining topics of interest in academic literature are difficult to translate directly into patent queries. We have, therefore, taken an approach developed by PatentSight to identify patents relevant to SDG 7 through a combination of AI and manual curation of patents. This approach maps patents based on the targets, indicators and metadata of SDG 7 and is similar, but not identical, to the approach used for research publications. Moreover, looking directly at patent activity enables the inclusion of almost all Chinese patents in our analysis.

We categorize the resulting set of patents into 11 subcategories that match themes defined within SDG 7 (Affordable and Clean Energy). These are *Energy Efficiency*, *Wind Energy*, *Solar Energy*, *Geothermal*

Energy, *Ocean Energy*, *Energy from Waste*, *Nuclear Energy*, *Biomass Energy and Biofuel*, *Improvement in Fossil Fuel Technology*, *Resilient Building* and *GHG Emission Reduction*.

Overall, active patents in NØEnergy totaled 800,000 by the end of 2020, with the number published annually increasing to more than 100,000 (Figure 56). This growth is consistent with that observed for patents citing NØEnergy publications, as shown in Figure 49. The annual growth in the number of patents identified in this analysis was relatively stable between 2001 and 2010 but started to grow almost exponentially in 2008, with the number of active patents tripling in just 10 years.

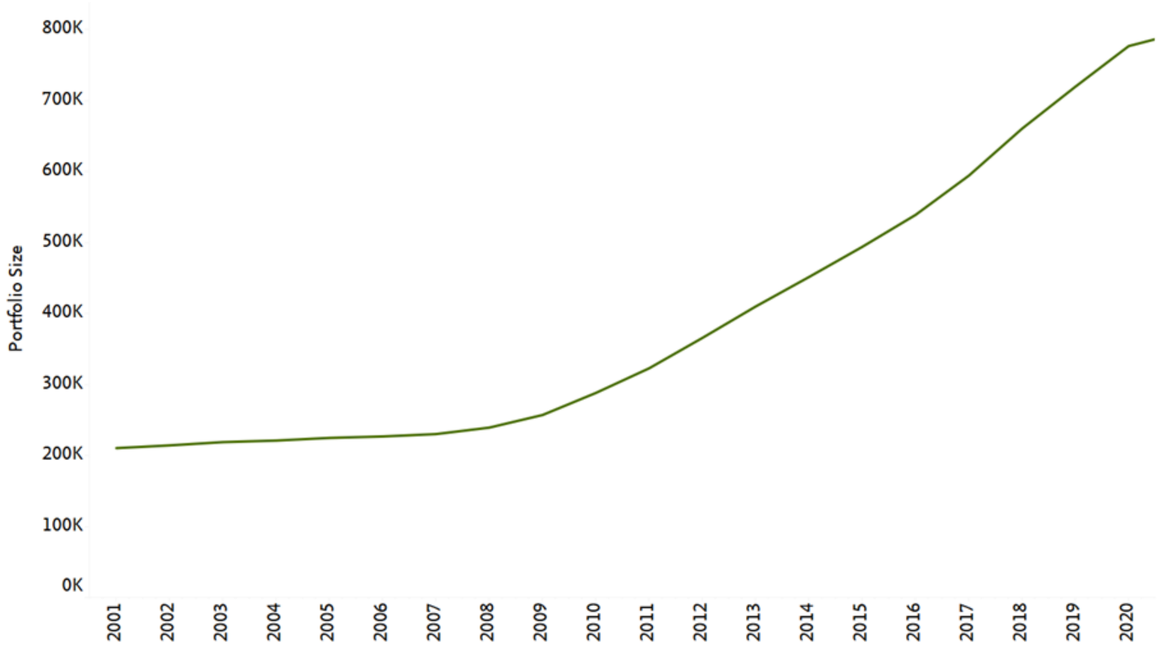


Figure 56
Number of active patents in NØEnergy, 2001–2020.
Source: PatentSight

China's almost exponential growth in annual patent publications, which also took off in 2008, is largely responsible for driving global growth (Figure 57). Among the top 10 patent-holding countries and regions, China had the largest patent portfolio in NØEnergy by 2015, surpassing the United States in 2012 and Japan in 2014. By the end of 2020, almost half of all global active patents originated in China.

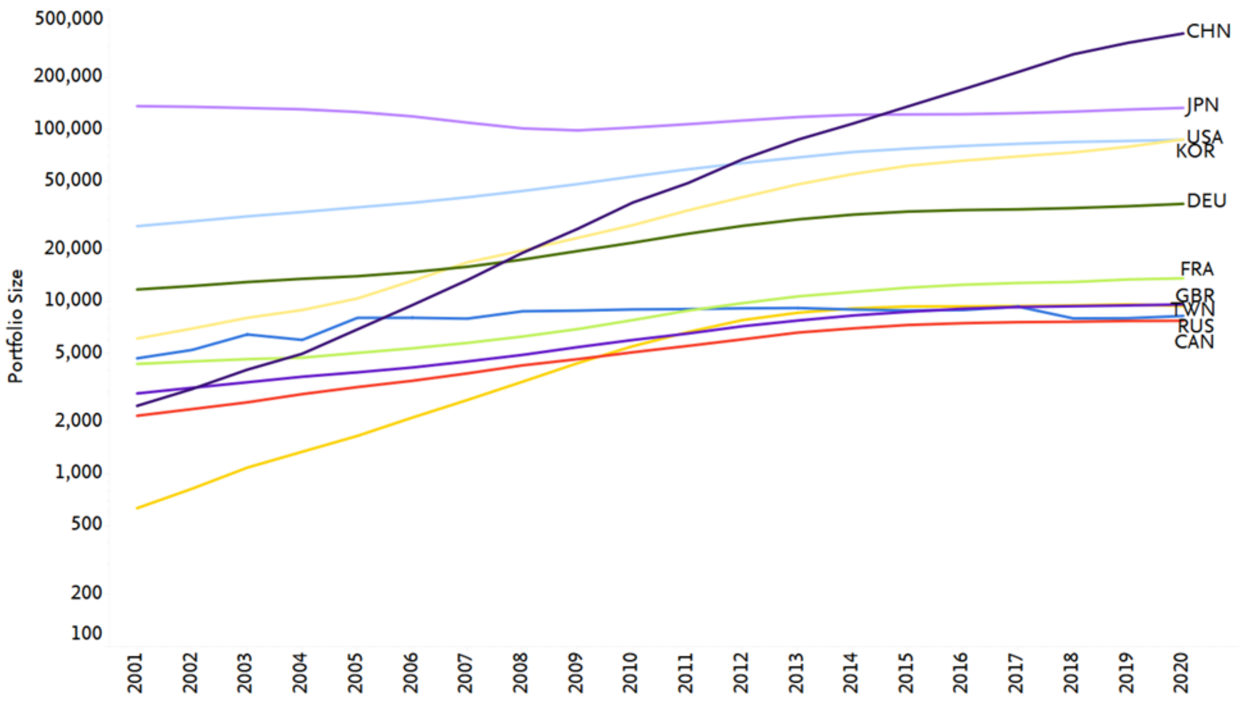


Figure 57
Number of NØEnergy patents by country and region for the top 10 by portfolio size, 2001–2020. Portfolio size is in logarithmic scale and starts at 100.
Source: PatentSight

China, as noted previously, pursues a local filing strategy, so 320,000 of its 362,000 patents in 2020 were active only in its national market and not globally. This local strategy is also reflected in the value of its patent portfolio. Although China has by far the largest portfolio, its value is less than that of other leading inventor countries and regions. Despite having one of the largest markets, filing patents locally significantly affects the value of China's portfolio. Other inventor countries and regions file more than 50% of their patents outside their home market, thereby increasing their portfolio value (Figure 58).

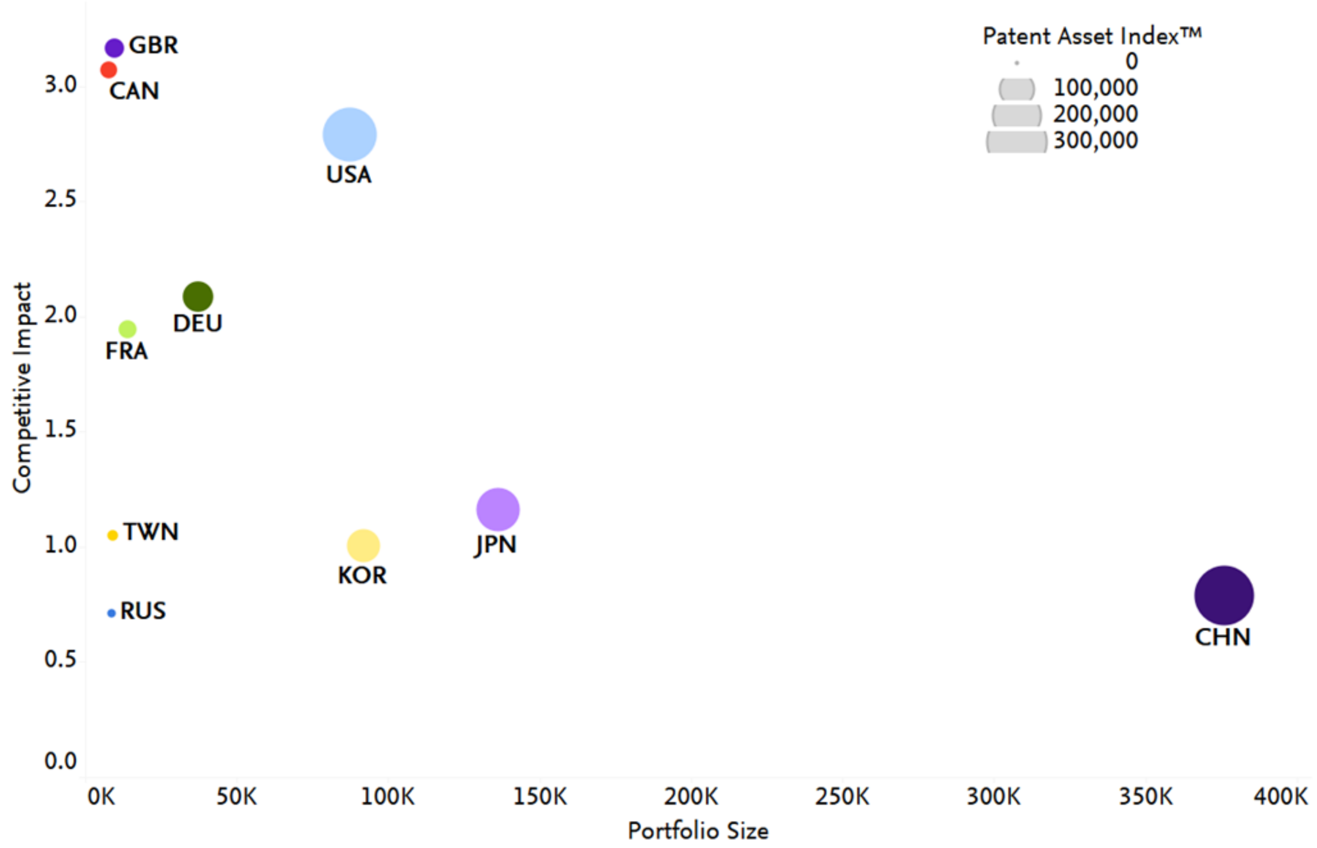


Figure 58
Portfolio size and competitive impact of NØEnergy active patents for the top 10 countries and regions by portfolio size, 2020. Size of the bubbles indicates the patent asset index.
Source: PatentSight

Our analysis of the technological focus of NØEnergy patents (Figure 59) reveals a strong focus on *GHG Emission Reduction*. By the end of 2020, two-thirds of all patent families fell within this area, followed at some distance by *Solar Energy*, *Improvement to Fossil Fuel Technology* and *Wind Energy*. The portfolio size of *Solar Energy*, however, doubled between 2008 and 2011, from 20,000 to more than 40,000 patents. *Nuclear Energy* and *Energy from Waste* declined at the beginning of the period but picked up again from 2008 onwards.

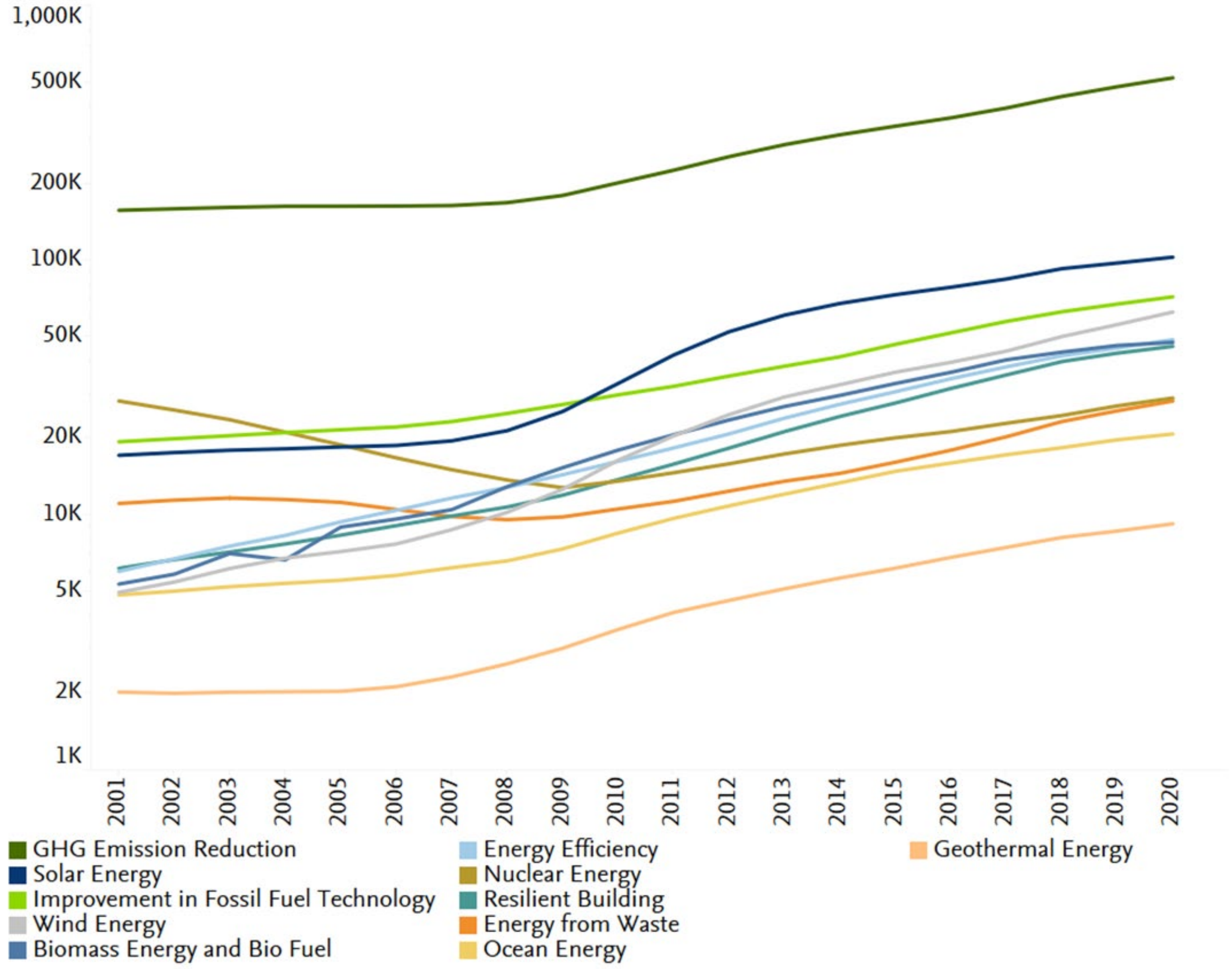


Figure 59
Number of patents by NØEnergy subcategory, for 2001–2020. Portfolio size is on a logarithmic scale.
Source: PatentSight

To assess whether the patent portfolios of individual countries and regions focus on specific NØEnergy topics, we calculated a RAI (the share of patents in a subcategory from a particular country divided by the total global share in the same subcategory). Figure 60 reveals that the main focus of the portfolios of Japan, South Korea and Germany is *GHG Emission Reduction*, whereas for China it is *Energy from Waste* and *Improvement in Fossil Fuel Technology*. The United States' portfolio, meanwhile, is more concentrated on *Solar Energy*, *Improvement in Fossil Fuel Technology*, *Energy Efficiency*, *Resilient Building* and *Biomass Energy and Biofuel*. A similar emphasis on *Improvement in Fossil Fuel Technology* and *Biomass Energy and Biofuel* is observed for Russia, reflecting these nations' major resources in oil and gas. Russia, and to a lesser extent the United States, also has interests in *Nuclear Energy*.

	CHN	JPN	USA	KOR	DEU	FRA	GBR	TWN	RUS	CAN
GHG Emission Reduction	0.9	1.3	0.8	1.2	1.2	1.1	0.9	0.9	0.6	0.8
Solar Energy	1.1	0.8	1.4	1.1	1.1	1.3	1.4	1.8	0.8	1.2
Improvement in Fossil Fuel Technology	1.2	0.5	1.4	0.9	0.8	0.9	1.5	0.6	2.0	2.0
Wind Energy	1.1	0.4	1.0	0.7	0.9	1.0	1.3	1.1	0.9	1.1
Energy Efficiency	1.0	0.5	1.3	0.7	0.5	0.9	1.4	1.7	0.8	1.4
Resilient Building	1.0	0.5	1.6	0.8	0.5	1.2	1.2	1.7	0.6	1.3
Biomass Energy and Bio Fuel	1.2	0.7	1.5	0.6	0.9	0.8	0.9	0.5	2.2	1.0
Nuclear Energy	0.9	0.5	1.2	0.6	0.5	1.0	0.9	0.8	1.8	1.0
Energy from Waste	1.4	0.6	0.6	1.0	0.5	0.9	0.9	0.7	0.6	0.7
Ocean Energy	1.1	0.6	0.6	0.9	0.4	0.8	1.4	0.6	0.8	0.8
Geothermal Energy	1.0	0.5	1.0	1.2	0.9	1.3	1.0	0.4	1.1	1.4

Relative Activity Index (based on patents)
0.4 – 2.2

Figure 60
Relative patent activity of the top 10 countries and regions (by portfolio size) with active NØEnergy patents, 2020.
Source: PatentSight

"Efficiency remains important. If you think about the cost of solar panels, the most expensive part is not the active layer (which produces electricity) but the surrounding frame, for example, or the glass panel that covers the active layer, or the steel that supports the panel. In short, the installation materials are very costly. So, if the energy efficiency doubles, you get double the power per installation, halving costs."

Hiroshi Komiyama, Chairman, Mitsubishi Research Institute, Inc.; President, Platinum Society Network; 28th President, University of Tokyo

1.11 How much policy and media attention does NØEnergy research receive?

NØEnergy research receives only slightly more attention from policymakers and online news than other research fields.

Given the urgency of addressing climate change through NØEnergy research, the field should be grabbing the attention of policymakers, online media and knowledge sources. In its *Global Renewables Outlook* report, the International Renewable Energy Agency argued directly for an interdependency between technology transfer and broader knowledge transfer, stating that "[i]ncreased support is needed for innovation across the innovation chain (research, development and demonstration) including taking a systemic approach to innovation where technology development is partnered with innovations in business models and changes in the way processes operate, and is enabled by innovative approaches to policy and market design."[31]

Our analysis of how NØEnergy research publications are covered by policy-related and online news channels reveals several interesting findings. As part of scientific advice and policymaking activities, NØEnergy research is taken up by governmental agencies such as the European Commission, the US government and the German Umwelt Bundesamt. NØEnergy research also informs the work of intergovernmental organizations (IGOs) and think tanks, including the World Bank, the Wuppertal Institut and the IPCC. Research from smaller European countries, including the Netherlands, Switzerland, Belgium, Austria and Denmark, tends to receive more news mentions and policy uptake.

Although our analysis finds that, overall, NØEnergy publications receive only average levels of policy-related uptake and news mentions, research in smaller topic clusters fares better. Publications in emerging areas such as biofuels, as well as carbon capture and energy economics, are mentioned more often in online media and policy documents than those in other NØEnergy areas.

To get a sense of how near or far NØEnergy research is from realizing policy-related or other societal outcomes, this section considers how research in this field is cited or mentioned in online repositories of policy advice and policymaking, or in journalist-generated news or social media platforms: an approach

> *"While R&I are important for achieving clean energy transition, political will in terms of government activities and, of course, support is equally critical."*
>
> Chukwuka Monyei, Research Fellow in Energy Justice and Transitions, University of Sussex

[31] International Renewable Energy Agency. (2020). *Global renewables outlook. Energy transformation 2050.* https://irena.org/publications/2020/Apr/Global-Renewables-Outlook-2020

known as *altmetrics*. Further information on altmetrics approaches and their limitations can be found in the two accompanying text boxes.

There is a relatively low uptake of NØEnergy research in policy-related literature, news articles, blogs and Wikipedia. Only 2.5% of NØEnergy publications are cited in policy-related literature, a mere 1% are mentioned in news items or blogs and only 0.8% by Wikipedia.

These figures may appear very low, but online mentions of research findings are rare events, especially in applied sciences and engineering. Of all the energy-related publications in Scopus (not just NØEnergy) just 3.2% are mentioned in policy-related documents, for example.[35] In applied sciences that figure is even lower, at 2.5%.

The number of mentions of NØEnergy research in Wikipedia is comparable with related fields, while those in the news are higher (the share of applied science and engineering publications receiving news mentions is around 0.5%). On balance, NØEnergy research receives as much or slightly more attention from the wider media than comparable applied sciences and engineering fields.

Figure 61 shows that between 2001 and 2020 NØEnergy publications in Climate Action (SDG 13) were much more likely to be taken up than those in Affordable and Clean Energy (SDG7). Mentions in policy-related documents have declined over time, which is to be expected given the typical time lag of 3–4 years between the publication of a peer-reviewed article and its citation in policy-related material.[36] Reference to NØEnergy research on news websites has increased in recent years, which could be the result of sectoral or indexing trends as well as the relevancy of the research itself.

Altmetrics indicators

This section presents findings on citations and mentions of NØEnergy publications outside of Scopus—for example, in repositories of policy-related literature (such as the UK Parliamentary Office of Science and Technology), online news portals (such as *The Conversation* or the *New York Times*) or social media platforms (e.g., Wikipedia).

When we refer to *news* or *journalistic mentions*, we define this as content generated by journalists, or scientific news aggregators with editorial oversight.

Scientific and policy leaders recently called for an increased focus on *synoptic science*,[32] which refers to syntheses of evidence from research material produced with the aim of helping policymakers. Policy-related documents made up of technical advice and evidence syntheses are known as *synoptic science documents*.

We use the PlumX[33] and Overton[34] databases to produce our altmetrics indicators. Both databases mix automated coding and parsing methods with some manual curation to link peer-reviewed publication records to those from selected online repositories and aggregators.

Our analysis captures discussion of NØEnergy findings outside of the academic community, among policymakers or government scientists, scientific educators, and a broad audience of the science-news-reading public. Qualitative case studies remain the methodological benchmark for capturing societal outcomes of research; however, they cannot be conducted at the scale of this report.

32 Science|Business. (2021). *Bridging the gap between climate science and policy*. See https://sciencebusiness.net/report/bridging-gap-between-climate-science-and-policy

33 See https://plumanalytics.com/learn/about-metrics/mention-metrics/

34 See https://www.overton.io/

35 Pinheiro, H., Vignola-Gagné, E., & Campbell, D. (2021). A large-scale validation of the relationship between cross-disciplinary research and its uptake in policy-related documents, using the novel Overton altmetrics database. *Quantitative Science Studies*, 1–40. doi:10.1162/qss_a_00137

36 Ibid.

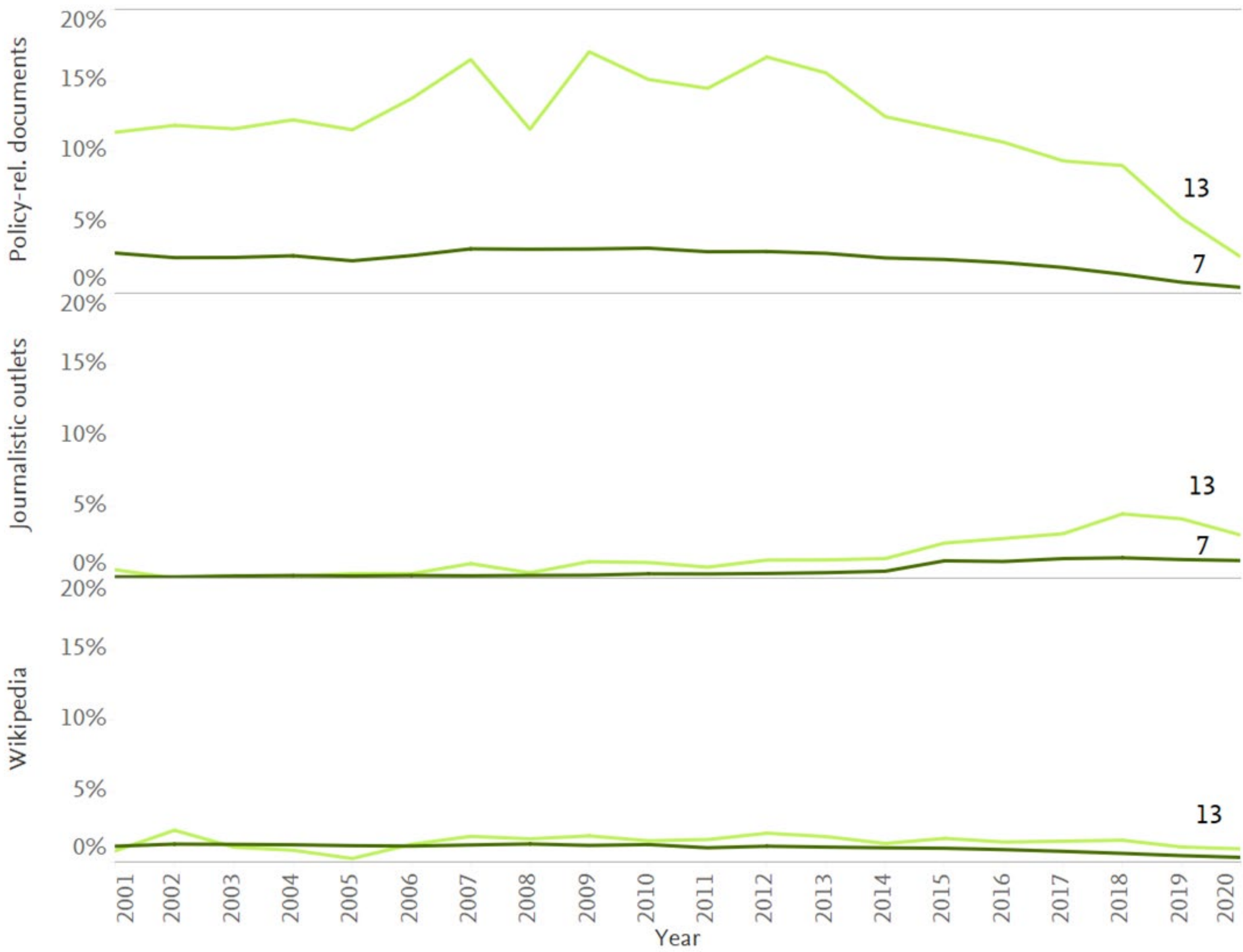


Figure 61
Trends in policy and news mentions of NØEnergy research, by SDG area, 2001–2020. Percentage shares capture the proportion of articles mentioned or cited at least once by the types of documents listed on the left.
Source: Scopus and PlumX data

In policy-related literature, NØEnergy research is cited in publications from a variety of governmental, intergovernmental and think tank organizations (Figure 62). Reports from the European Commission include by far the most citations of NØEnergy publications (almost 7,000). The European Joint Research Centre comes in as the second largest policy-related citing organization. Reports and documents from the US Government Publishing Office and the US House Committees are also major users of NØEnergy publications (with 2,000 and 1,000 mentions respectively). The Analysis & Policy Observatory, while not a policymaking agency itself, nevertheless captures mentions of NØEnergy research in policy-related documents from multiple Australian and New Zealand agencies.

Other major users of NØEnergy research in the IGO sector include the World Bank (almost 2,000 NØEnergy publications mentioned), the IPCC (over 1,000 publications) and the International Renewable Energy Agency (over 1,000 publications). Think tanks and foundations are also represented in this list—for example, the Wuppertal Institut (close to 2,000 publications mentioned).

Limitations to altmetrics—language and geography

While the altmetrics approaches used here are not altogether new as of 2021, their limitations are still being actively investigated. In this report, we have made cautious use of related indicators, restricting calculations to shares of publications cited or mentioned at least once on altmetrics platforms. Intensities of citations have not been used here.

Even so, an important caveat remains: altmetrics databases have much better coverage of sources archiving documents in Western languages. In fact, sources in languages such as Mandarin are not covered at all in terms of policy-related content. Journalistic mentions from some Asian sources are included in PlumX, but it is not yet known to what extent coverage can be directly compared to those of English-language sources. Therefore, cautious expectations would be for the findings in this section to tend to favor English-speaking countries or regions and, to a lesser extent, European countries and Japan (which have fair coverage in Overton). Wikipedia references can be processed irrespective of language. Because of these limitations, altmetrics findings for Global South and Asian countries and regions are likely to capture only a subset of mentions in documents aimed at an international audience.

"The clean energy transition requires thinking about two things. One of these is which avenues are going to be most successful. What are going to be the investments you want to make, the policies you want to put in place that are going to have the most bang for your buck and would have the biggest effect? And you need research to articulate what those innovative technologies are or which innovative policies work. The second thing, because this is all very uncertain, is to ensure you're not making investments that are going to lock you in to pathways that might not be consistent with a clean energy transition or that will make it difficult for you to follow it. An obvious example is investing in fossil fuel infrastructure. Understanding from research whether you're going to be investing in technologies that may not be on the long-term path or if you're putting in place policies that might get you off that path is really important."

Leon Clarke, Acting Director and Research Director, Center for Global Sustainability, University of Maryland at College Park

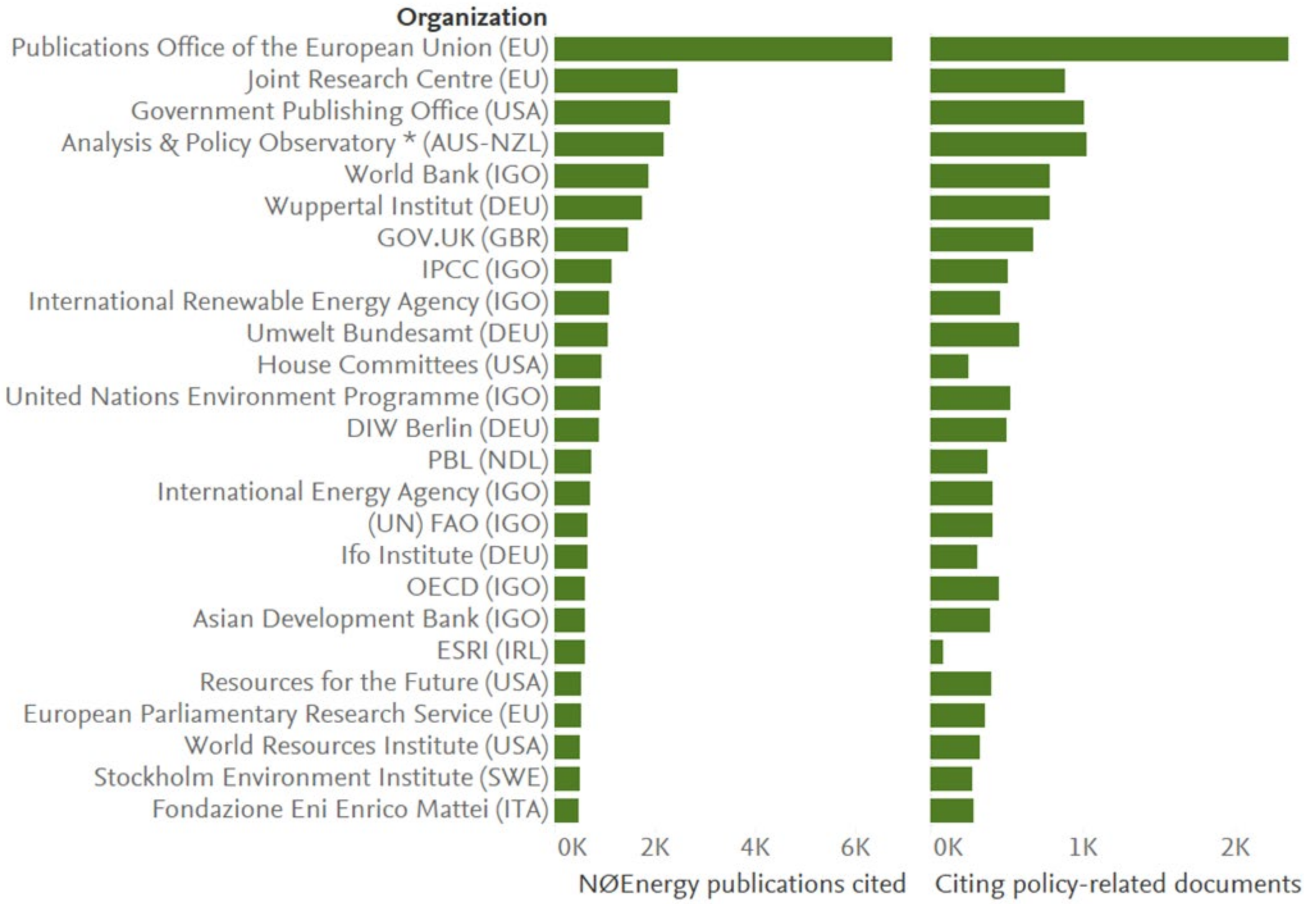


Figure 62
The 25 main organizations citing NØEnergy research publications in policy-related reports, 2011–2020. Note that the Analysis & Policy Observatory is an organization that maintains a repository of policy-related documents, rather than being a policy agency itself.
Source: Scopus and Overton

IGOs make the most use of NØEnergy publications, closely followed by the European Union and the United States (Figure 63). Bars on the graph represent the volume of publications by country (right column) cited in the policy-related document of a specific organization or country (left column). Our analysis shows the role of IGOs in NØEnergy-associated knowledge transfer. With governmental agencies disaggregated by country, IGOs and the European Union are revealed as the largest policy-related citers of NØEnergy publications. The multinational directions of these connections are also evident. Policy-related agencies, regardless of location, take up research findings from many different countries rather than just their own. For instance, German policy-related documents cite US publications just as often as native ones. US policy-related documents, however, do tend to refer to home-generated scientific publications more often. Nevertheless, this pool of articles still amounts to less than 50% of the total referenced by US policy-related documentation. French, Dutch, Swedish and Australian policy-related documents do not appear to favor publications from any particular country, including their own. This is surprising given the biases in coverage toward English-language or European policy-related documents in the Overton database.

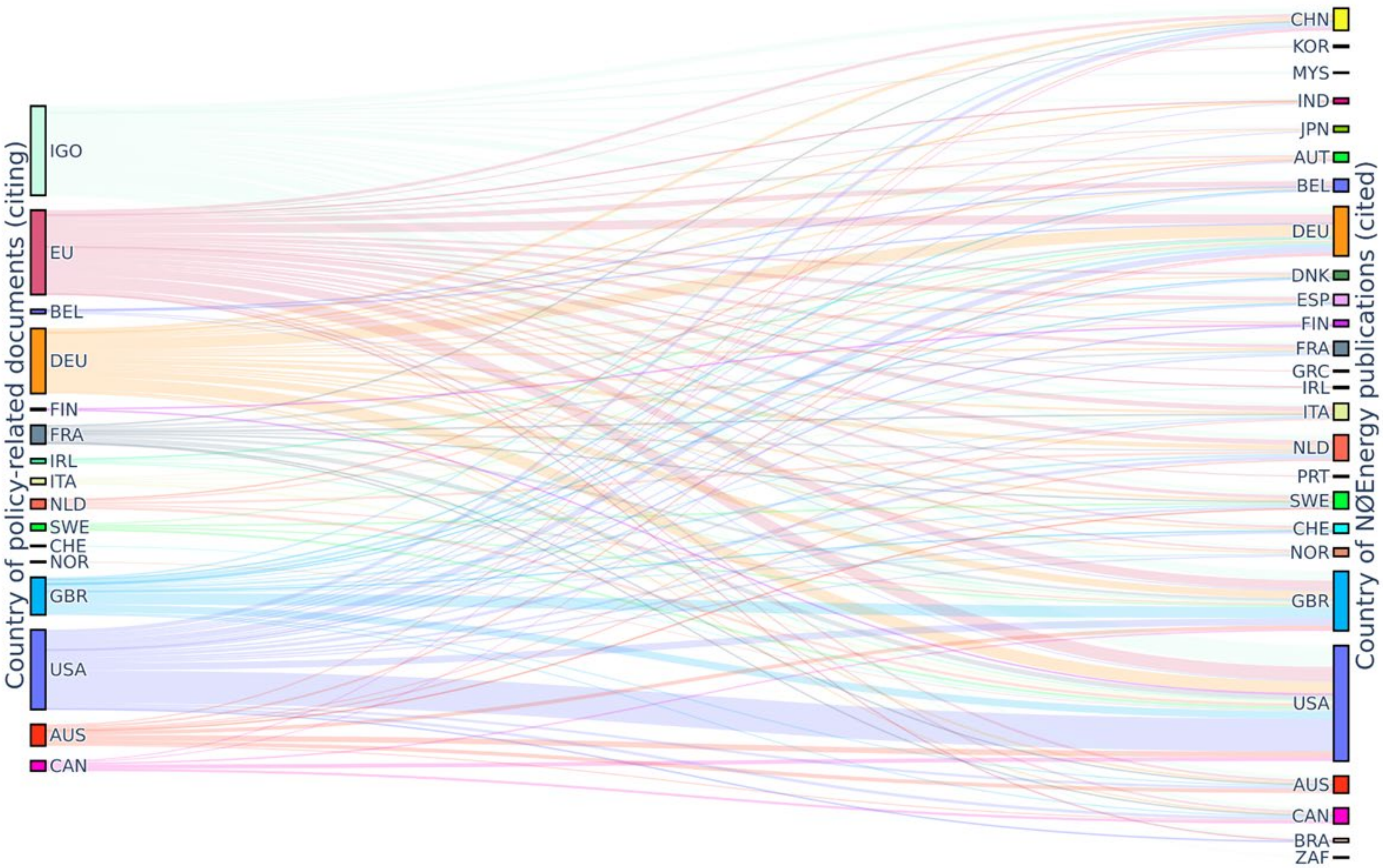


Figure 63
Relationships between countries and organizations in policy-related uptake of NØEnergy research, 2011–2020. Policy-related documents aggregated by country are denoted on the left. NØEnergy publications aggregated by country are denoted on the right. The connections between left and right columns are citations of NØEnergy publications by policy-related documents. IGO: Intergovernmental organization.
Source: Scopus and Overton

Policy-related and news uptake of NØEnergy research in selected breakdowns of North–South collaborations (using the same categories explored in Figure 31 and Figure 32) are shown in Figure 64. This analysis can be used to indicate whether these collaborations are likely (or not) to contribute to the development of solutions to the challenges faced by Global South countries.

NØEnergy research conducted in collaboration with LICs and US-based researchers is the most likely to result in policy-related or news uptake. A small group of just over 250 USA+LIC co-publications produced by far the largest number of mentions in both types of documents (20% policy-related; 10% news). It is worth noting that this group of publications also scored highly for collaborative diversity and South focus in Figure 31. Publications involving researchers from LICs and EU-27 countries make up the next most-mentioned group. For these EU+LIC collaborations, which account for 700 articles, the figures are 12% for policy-related documents and 4% for news. Almost 650 publications are LMIC+LIC collaborations, of which 9% were referenced in policy-related documents and 3% in news coverage. LIC+UMIC, US+UMIC and US+LMIC collaborations also rank above or well above the overall NØEnergy average for mentions in policy-related and news articles (2.5% and 1.1%, respectively). Collaborations between different groups of Global South countries and China were mentioned less, but the findings are potentially limited by the biases of the altmetrics databases.

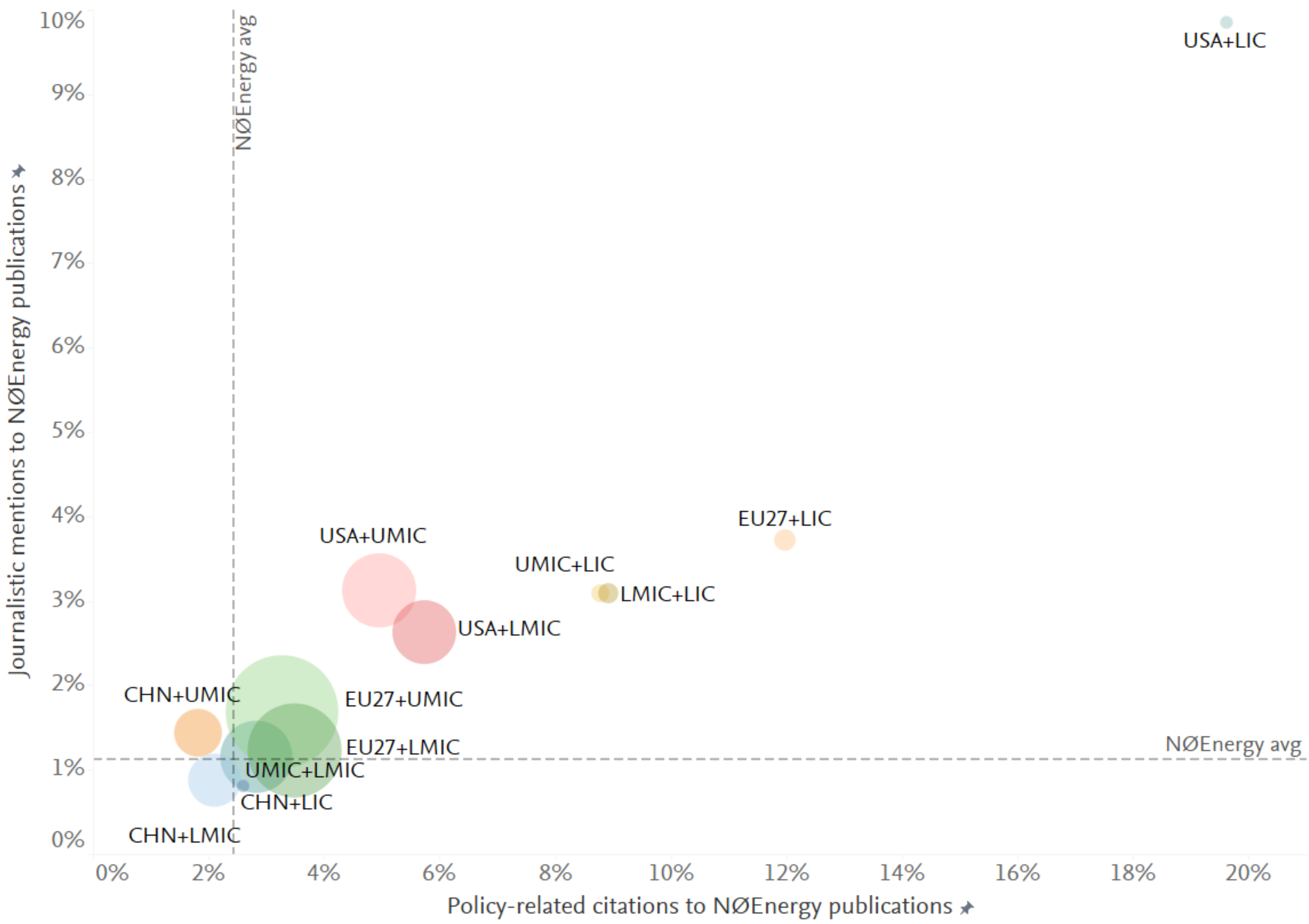


Figure 64
Policy-related and news uptake of NØEnergy North–South collaborations, 2011–2020. Bubble size represents overall output volume. LIC: Low-Income Country. LMIC: Low-Middle-Income Country. UMIC: Upper-Middle-Income Country.

Source: Scopus, PlumX and Overton

These findings on North–South collaborations indicate a high level of uptake of NØEnergy research in the policymaking and news sectors considered here. Nevertheless, it should be noted that these publications amount to a very small fraction of all research in this field (less than 5% overall for the groups presented above; noting that they exclude HIC-South collaborations).

> *"Investment from the Global South will ... be integral in driving climate adaptation in Africa. However, this will have to go hand in hand with policy reforms that provide an enabling environment for clean energy financing and investment. This can look like having proper carbon policies in place that reward companies that reduce their carbon footprint and impose carbon taxes on those that emit the most."*
>
> Kariuki Ngari, Managing Director & CEO, Standard Chartered Bank Kenya

The 25 countries where NØEnergy publications receive the highest numbers of mentions in policy-related documents are shown in Figure 65. Here again, biases in current altmetrics records are expected to favor citations from English-speaking organizations and European countries.

Between 2011 and 2020, the highest proportion of uptake in policy-related reports (10%) was associated with the 17,500 NØEnergy publications produced by Dutch researchers. Switzerland saw the highest uptake of its NØEnergy publications in the news (just under 3.5%; while 6% of 16,000 articles were cited in policy-related literature), followed by the Netherlands (3%). Austria, Belgium, Finland and Sweden, each of which produced moderate volumes of publications (9,000–19,000), also achieved high levels of uptake (7% or more cited in policy-related literature and 3% or more in news articles). As expected, US and UK publications, backed by highly productive scientific sectors, also record high levels of uptake. Of the United Kingdom's 60,000 NØEnergy publications, 7% garnered mentions in policy-related documents and 3% in news reports. Of the United States' 190,000 publications, 4% are mentioned in policy-related documents and 3% in the news. The absence of China, South Korea and Japan from top rankings is potentially related to biases in the altmetrics databases.

Some countries, including the Philippines, Greece, Sri Lanka and Cyprus, scored below average for news mentions of NØEnergy publications but above average for policy-related documents. The Philippines, in particular, has a very high proportion of NØEnergy publications cited in policy-related reports (6% of almost 1,500 publications). It is not clear whether this performance is a result of the nature of publications in terms of policy relevance or the features of the Overton coverage itself.

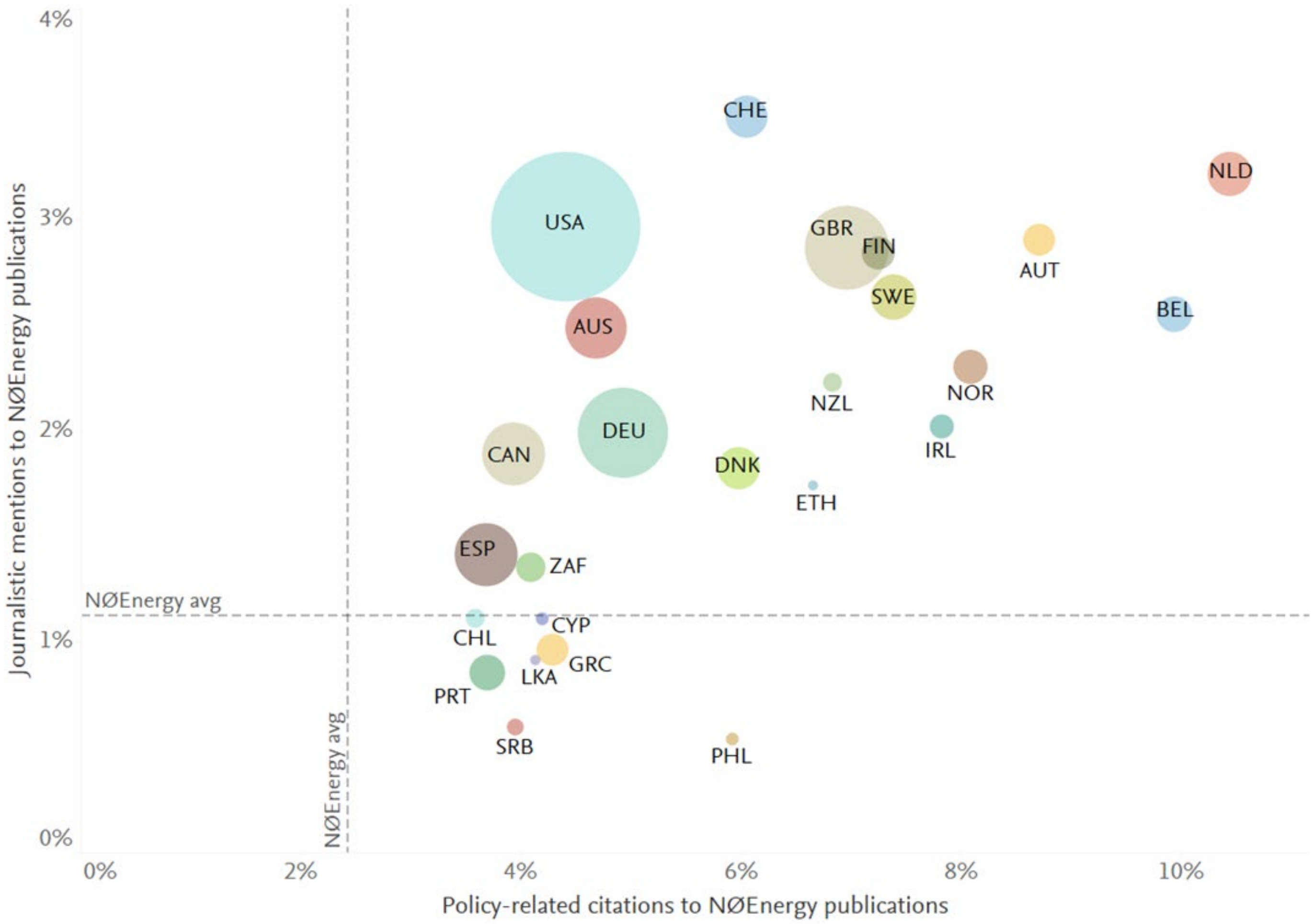


Figure 65
Policy-related and news uptake of NØEnergy research from countries with the most policy-related uptake, 2011–2020.
Bubble size represents overall country output volume.
Source: Scopus, PlumX and Overton

"This process of getting research into a format where it's foremost in the policy discussions in a much more integrated way is extremely important. It has really changed the ability of people to talk about whether we're on the road to 1.5 degrees or not, or to understand how to be on that road and what the important technologies are in support of that."

Leon Clarke, Acting Director and Research Director, Center for Global Sustainability, University of Maryland at College Park

The top 10 largest topic clusters, with 1,500 publications or more, in terms of uptake in policy-related documents are presented in Figure 66. The topics *Air Pollution / Particulate Matter / Air Pollutants*, *Water Resources / Water Management / Water* and *Energy / Economics / Electricity* dominate policy-related reports, with mentions of 19%–20% of all articles. These topics saw uptake in the news of 6%, 5% and 4% of publications, respectively. In *Life Cycle / Sustainability / Sustainable Development*, 14% of 3,000 publications were mentioned in policy-related literature, and 14% of 10,000 publications in *Bioenergy / Biomass / Biofuels* got a mention. Finally, the topic with the second highest score for news uptake, *Model / Climate Models / Rainfall*, scored the lowest for policy-related mentions. Out of 4,500 publications on this topic, only 5% were mentioned in news articles compared with 9% in policy-related material.

It is worth noting that highly cited topic clusters in policy-related documents differ considerably from those with the largest output (see Section 1.1). The full realization of a NØEnergy agenda is therefore likely to benefit from increased efforts and investments in those topics highlighted in Figure 66 with the greatest potential for producing societal outcomes.

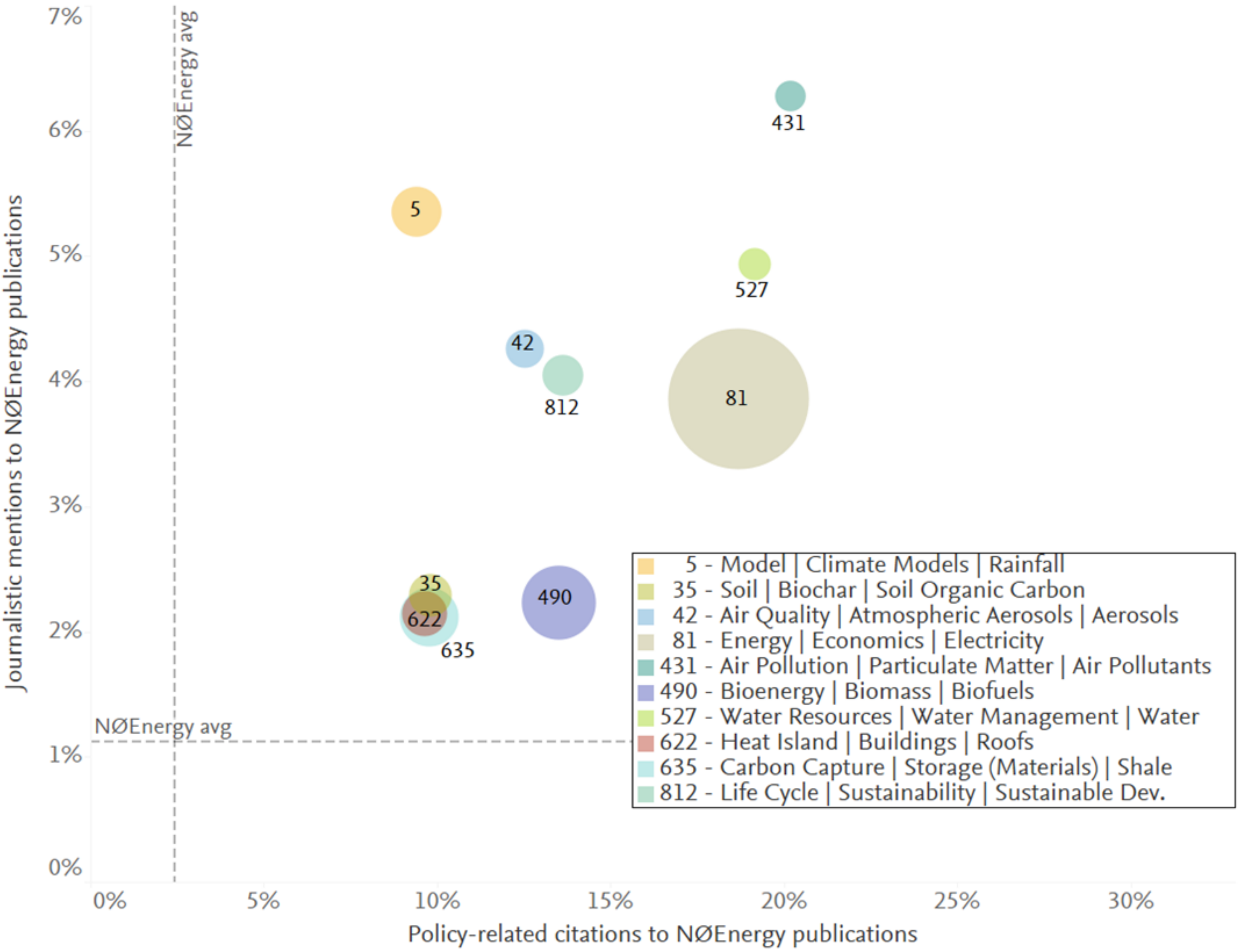
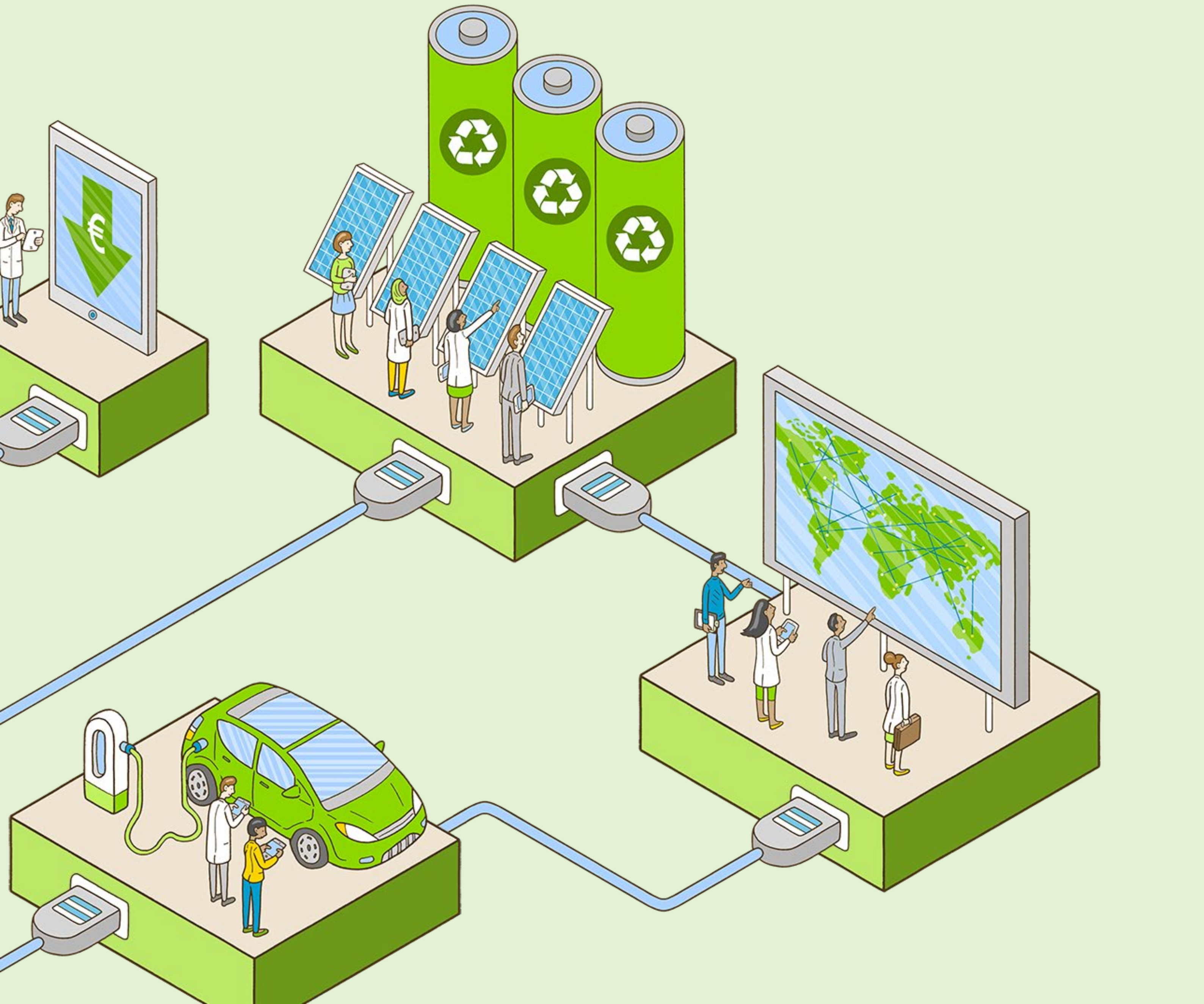


Figure 66
Policy-related and news uptake of NØEnergy publications from selected topic clusters, 2011–2020. Bubble size represents overall topic cluster output volume.
Source: Scopus, PlumX and Overton

Section 2

Interviews with key opinion formers



Prof. Pablo Arboleya

Associate Professor, Electrical Engineering Department, Universidad de Oviedo, Spain
Holder of the Smart Cities Chair at Universidad de Oviedo
Co-founder of LEMUR Research group
Co-founder of Plexigrid

Q: How would you describe the role of research & innovation (R&I) in enabling a clean energy transition?

PA: Crucial! On the one hand, in the development of core technologies, such as those based on energy storage or renewable energy production, basic and applied research are fundamental. On the other hand, we must be able to integrate these new technologies into the energy system, which is a very complex system with a high degree of interdependence between the parts and agents that compose it. Developing engineering solutions that enable this coordinated integration is critical when it comes to achieving a change in the energy paradigm. In this sense, both types of research must be balanced, because falling behind in one of them would cause a bottleneck in the change of energy model. Given that large energy corporations are present in the integration phase, it is also necessary to promote and establish strong cooperative links between research organizations and these corporations so that research does not remain in the academic sphere but is transferred smoothly to the industrial sector.

Q: What initiatives, policy developments or discoveries have emerged in your region/domain over the last 10 years and that you feel have had real impact on a clean energy transition?

PA: In Europe, the last 10 years have seen the take-off of installed renewable energy in the form of large wind and photovoltaic farms connected to high-voltage transmission and distribution systems. This has made it possible for Europe to increase efficiency and reduce energy dependence. Today, and after a decade of unstoppable growth, no one doubts the advantages or the role of this type of generation system. However, the current challenge is to be able to bring these technologies closer to the end consumer, and this entails their massive installation in low-voltage grids. The European Union, in its Clean Energy for all Europeans[37] package published in 2019, has issued clear directives in this regard that will set a similarly clear direction for the next decade. The guidelines mark electrification as a tool for the decarbonization of the energy system and above all the empowerment and protagonism of the end consumer, given that homes and private transport account for a very high percentage of CO_2 emissions. In order to follow these guidelines, it will be necessary to integrate all core technologies into the electricity distribution networks on a massive scale, and this is the challenge that has begun in the last decade and will intensify even more in the period up to 2030.

37 See https://ec.europa.eu/energy/topics/energy-strategy/clean-energy-all-europeans_en

Q: What value do data, such as contained in this report, provide for policymakers, institutional leaders and the research community, and why? Can you identify any other data that would be helpful?

PA: Data such as those presented in this report are of vital importance for analyzing the impact of energy regulatory policies. We cannot forget that there is a very strong correlation between the change in the energy model and research data on enabling technologies. In this sense, reports such as this one can be used as a barometer to measure the impact of regulation. It would be very important to have data that complement those presented in this report in order to evaluate not only publications but also the transfer of knowledge between academic institutions and industry.

Q: What information in this report is most insightful and useful to you, and why?

PA: The part where the levels of research from basic research to applied technologies are evaluated is very interesting. It is of great value in determining the level of maturity of the technologies. In the case of research carried out, for example, in electrical energy transport and distribution systems, this is practically 100% based on applied technology, while in other cases such as energy accumulation systems in electric batteries, the bulk of the research is applied research. The evolution of these percentage levels over time is a very strong indicator of the degree of maturity of the technology. The part where the impact of the evolution of corporates on NØEnergy research is evaluated is also extremely interesting, as this is an indicator of whether industry and academia are aligned in terms of the lines of research to be promoted.

Q: Thinking about the clean energy transition, what R&I priorities do you think should be the focus in the next 10 years?

PA: Technological development is fundamental. Reducing the costs of energy storage systems is critical to the electrification of systems, as storage systems will provide the necessary flexibility to the energy system to be able to massively integrate renewable generation. I believe this message is clear, and it is also clear from the conclusions of this report. However, one issue that concerns me greatly is technological integration in the energy system. In order to achieve this integration with guarantees, it is also necessary to boost the digitalization of the energy system. Digitalization is not a core technology in itself, but it is an extremely important enabling technology that includes the deployment of sensors, communications systems, the use of artificial intelligence and the ability to manage large volumes of data through big data technologies.

Q: What in the report did you find inspiring, insightful or useful? Did it fill a gap?

PA: This report is useful not only for high-level regulatory authorities but also for researchers connected to the fields studied in it. The strategy in selecting the evolution of a particular line of research is of paramount importance. In many cases, researchers in the energy field are driven by personal passions that make us inclined toward the study of one technology or another: the evolution of a line of research at the individual or group level is not always decided by objective criteria. Reports such as this one enable data-driven decisions to be made and also enable researchers to orient and align their research with common interests.

Prof. Franklin Carrero-Martínez

Senior Director, Global Sustainability and Development & Science and Technology for Sustainability, Policy and Global Affairs Division, National Academy of Sciences, Engineering, and Medicine, United States

Q: How would you describe the role of R&I in enabling a clean energy transition?

FCM: R&I are critical in advancing clean energy transitions. The National Academies of Sciences, Engineering, and Medicine's (NASEM) consensus report, *Accelerating Decarbonization of the United States Energy System* (2021), showed that the United States leads the world in research investments in clean energy and in the development of a number of future technologies that are likely to play a significant role in achieving deep decarbonization.[38] However, the United States also currently struggles to leverage its leadership in clean energy R&I into leadership in clean energy markets and supply chains. If the United States can maintain its leadership in the discovery, invention and development of innovative clean energy technologies and leverage its strengths in innovation to create a vibrant clean energy infrastructure, then R&I will serve as a basis for a thriving economy.

Q: What initiatives, policy developments or discoveries have emerged in your region/domain over the last 10 years that you feel have had real impact on a clean energy transition?

FCM: The widespread destruction in California, Houston, Puerto Rico and the Virgin Islands due to extreme events has increased the focus on the potential role of sustainable energy deployment. At NASEM, the key component of our Science and Technology for Sustainability Program is the Roundtable on Science and Technology for Sustainability. The Roundtable provides a high-level forum for sharing views, information and analysis related to harnessing science and technology for sustainability. In 2017–2018, it hosted two workshops focused on clean energy transitions, one of which examined deploying sustainable energy during transition and the implications surrounding recovery, renewal and rebuilding.[39] This workshop examined how cities, regions and nations are building renewable energy into their longer-term planning.

The 2021 NASEM report on accelerating decarbonization also investigated how the United States could best decarbonize its transportation, electricity, building and industrial sectors. To help policymakers, businesses, communities and the public better understand what a net zero transition would mean for the United States, the NASEM report identified the key technological and socioeconomic goals that must be achieved to put the United States on the path to reach net zero carbon emissions by 2050. It presented a policy

[38] National Academies of Sciences, Engineering, and Medicine. (2021). *Accelerating decarbonization of the U.S. energy system*. The National Academies Press. https://doi.org/10.17226/25932

[39] National Academies of Sciences, Engineering, and Medicine. (2018). *Deploying sustainable energy during transitions: Implications of recovery, renewal, and rebuilding: Proceedings of a workshop—in brief.* The National Academies Press. https://doi.org/10.17226/25175

blueprint outlining critical near-term actions for the first decade (2021–2030) of this 30-year effort, including ways to support the communities that will be most impacted by the transition.

As a further initiative, in April 2021, NASEM, in partnership with the Nobel Foundation, Potsdam Institute for Climate Impact Research and the Stockholm Resilience Centre (SRC) / Beijer Institute, hosted the first-ever Nobel Prize Summit. The Summit gathered a powerful network of Nobel Laureates, together with world-leading scientists, business leaders, writers, politicians, artists and young people, to discuss some of the most pressing existential challenges faced by humanity, such as biodiversity loss, climate change, inequality and rapid societal transformation due to emerging and converging technologies.

Q: What value do data, such as contained in Elsevier's NØEnergy research report, provide for policymakers, institutional leaders and the research community, and why? Can you identify any other data that would be helpful?

FCM: Research on complex, multidisciplinary and transdisciplinary issues central to achieving the SDGs increasingly utilizes large data sets to accelerate the generation of knowledge. Understanding the implications of synergies and trade-offs among the goals would require continued monitoring and research to develop better data-driven tools and services for policymakers, institutional leaders and the research community.

The Sustainability Roundtable has been discussing key challenges and opportunities related to increasing awareness of the SDGs in the United States and globally. In July 2021, Ann Gabriel, Senior Vice President for Global Strategic Networks at Elsevier, spoke to the Roundtable on Analytical Perspectives on SDG Research in the United States and noted that increased awareness of the SDGs informs issues of national and regional competitiveness. Elsevier's mapping activity on the landscape of sustainability science, with the focus on SDG 7 on Affordable and Clean Energy and SDG 13 on Climate Action, has been relevant for Roundtable activities.

I also appreciate the comprehensive assessment of clean energy transitions in this report. Measures of assessment and evaluation across research can enhance our ability to influence areas of investment and outcomes. Because the Roundtable focuses on sustainability challenges from local to global scales, and because cities are increasingly driving new policies, an assessment for large or medium-sized cities would be beneficial for developing collaborative actions at the local and global levels.

Q: What information in this report is most insightful and useful to you, and why?

FCM: While all of the assessments and evaluations in this report are highly relevant and important to the Roundtable, the sections on international collaboration, corporate activities on net zero, and Global South participation and South–South collaborations are critical in conducting sustainability activities at the National Academies. The Nobel Prize Summit emphasized issues relating to climate change and increased global inequality, and this report's assessment on the Global South is essential for the scientific community by showing that only a small proportion of NØEnergy research is conducted there. There is a need for coodinated actions.

Q: Thinking about the clean energy transition, what R&I priorities do you think should be the focus in the next 10 years?

FCM: As noted in the 2021 NASEM decarbonization report, achieving net zero carbon emissions in the United States by 2050 is feasible and would not only help address climate change but also build a more competitive economy, increase high-quality jobs and help address social injustice in the energy system. There's a need for immediate action and proactive innovation, as well as for a portfolio of near-term policies, to ensure equitable access to benefits generated as a result of this transition, mitigate harms to vulnerable populations, engage public participation in decision-making and revitalize the US manufacturing sector. To guide policymakers through the transition, in the NASEM decarbonization report we laid out nine technological and socioeconomic goals to reach by 2030: (1) producing carbon-free electricity; (2) electrifying energy services in transportation, buildings and industry; (3) investing in energy efficiency and productivity; (4) planning, permitting and building critical infrastructure; (5) expanding the innovation toolkit; (6) strengthening the US economy; (7) promoting equity and inclusion; (8) supporting communities, businesses and workers; and (9) maximizing cost-effectiveness. The NASEM decarbonization report also emphasizes the need for investing in educational programs for a clean energy workforce.

Elsewhere, the Sustainability Roundtable has been focusing on the importance of attracting the younger generation because young people need to be engaged in seeing these fields as ways to solve the world's problems. A participant at the Nobel Prize Summit urged that scientists must be more thoughtful about data and focus on going from "big data" to "better data" and engaging community members as co-producers of research. And there is also a need to improve scholarly communications by translating science into policymaking.

Prof. Leon Clarke

Acting Director and Research Director, Center for Global Sustainability at University of Maryland at College Park, United States

Q: How would you describe the role of R&I in enabling a clean energy transition?

LC: Good strategies for a clean energy transition need to be based on the best science and the best analysis. If you're not following what the science tells us, what the analysis tells us, what the best strategies tell us, you're going to end up on a path that doesn't make as much sense, and you take a lot more risk when you do that. The role of research is to articulate what matters, what doesn't matter, and to find strong strategies, good openings and potential pitfalls that you need to be aware of as you move forward. So to me, R&I are critical for enabling good progress on the clean energy transition.

Q: You mention risk. Could you expand on that point?

LC: The clean energy transition requires thinking about two things. One of these is which avenues are going to be most successful. What are going to be the investments you want to make, the policies you want to put in place that are going to have the most bang for your buck and would have the biggest effect? And you need research to articulate what those innovative technologies are or which innovative policies work. The second thing, because this is all very uncertain, is to ensure you're not making investments that are going to lock you in to pathways that might not be consistent with a clean energy transition or that will make it difficult for you to follow it. An obvious example is investing in fossil fuel infrastructure. Understanding from research whether you're going to be investing in technologies that may not be on the long-term path or if you're putting in place policies that might get you off that path is really important.

You can think about it from a technology perspective, for instance. Many questions surround the role of the various types of fuels to be used in cars and trucks, and buildings and industry—is it electricity, or hydrogen, or maybe biofuels? As people navigate investing in different infrastructure and putting policies in place to support their choices, they want to have confidence that they're following pathways that aren't going to lock them into one technology, when in fact another may end up being the better solution in the long run. For example, current thinking is that electricity rather than hydrogen will be the way to go for light-duty vehicles. But a country may find that hydrogen makes more sense in their circumstances.

Q: What initiatives, policy developments or discoveries have emerged in either your region or in your subject domain over the last 10 years that you feel have had a real impact on a clean energy transition?

LC: The evolution of batteries, and of solar cells in particular, has been transformative. We wouldn't be considering the types of mitigation actions that countries are considering today, for over the next 10 years, if we hadn't seen those sorts of advances, to the point where photovoltaic cells are frequently competitive with or even cheaper than, say, coal generation. And the innovation in electric cars moved much more quickly than most people anticipated a decade ago. Those developments have really changed the way people see the landscape.

Another innovation has been the "all of society" approach to mitigation. In the United States over the last four years, what we've seen is states, cities and businesses all taking action. With the US Climate Alliance, around half the states have committed to the goals of the Paris Accord, in a bottom-up / "all of society" approach. And it's not just in the United States: you're seeing it increasingly around the world. That's been a really big change in how we're thinking about moving forward.

On the climate policy research side, over the last decade we've really shifted in our understanding of what it means to have these deep decarbonization goals and to have the types of energy transitions we need to reduce emissions and give ourselves the best chance to keep warming to 1.5 or 2 degrees Celsius. Looking back, a number of integrated assessment modeling teams worked in this area, and they were often coordinating among themselves. But that information was not always coordinated and packaged in ways that were as easily accessible for international discussions. Now, you see products like the UN Emissions Gap Report[40] examining how far off we are from being on a 1.5-degree pathway, you see the IPCC report coming out,[41] you see Climate Action Tracker[42] and other groups who are trying to track progress, and they're all building off of this really strong set of research, looking at long-term pathways to limit temperature increase.

This process of getting research into a format where it's foremost in the policy discussions in a much more integrated way is extremely important. It has really changed the ability of people to talk about whether we're on the road to 1.5 degrees or not, or to understand how to be on that road and what the important technologies are in support of that. That's been a really big innovation as well.

Q: What value do data, such as those contained in this report or others, provide for policymakers, institutional leaders and the research community. Can you identify any other data that would be helpful?

LC: Data are the foundation of good strategy. If you don't know where you are and what's going on, you can't develop a good strategy. And that can be the simplest of elements, such as GHG accounting. And it also includes understanding where technology is and how much technology is moving forward, what policies have been used and how effective they are, which are the winners or losers. All of that is absolutely critical for making progress on a clean energy transition.

Consider this in the context of the Global Stocktake of the Paris Agreement, which is coming up in a couple of years. This is an effort to understand where we are on climate and what we need to do going forward. In essence it's three questions: (1) where are we, (2) where do we need to go, and (3) how do we get there? They are all going to be heavily data driven on all of the sorts of issues I just mentioned: what are the emissions, where are the technologies, what's being deployed, what are the costs of technologies? All of that's going to be really important.

We're getting an increasing amount of hard data on where we are and where we need to go. But there remains a really large gap in this context on the social science side. So we know we're increasingly getting a good feel for assessing progress on, for instance, renewables—how much solar has been deployed, how much has been invested, what the emissions are from different countries, what the emissions are from different sectors. We don't have it down perfectly, but we're getting more and more of that information, and we know how those things need to change over time.

But many other issues are relevant to success. What's the public perception? What are some of the vested interests that may be influencing how policies are moving forward for our institutions and countries' structure? To be able to move forward on climate policy, what are the ways in which climate policy's interaction with other priorities, such as energy security, are influencing its ability to go forward? These

[40] See https://www.unep.org/emissions-gap-report-2020
[41] See https://www.ipcc.ch/assessment-report/ar6/
[42] See https://climateactiontracker.org

societal aspects of mitigation aren't as clear as they need to be. It's very difficult because it's not necessarily quantitative information, but it's essential for understanding how we're actually going to move forward on climate. It's a really important research gap, and one that I'm hoping the literature will begin to fill going forward.

Q: Thinking about the clean energy transition, what R&I priorities do you think should be the focus in the next 10 years?

LC: What's going to be critical is understanding these political, economic, capacity, institutional and behavioral issues that I just mentioned—getting a handle on them and navigating it all.

We also need to continue to look at which policies are proving effective and why, and to find ways to make sure that everyone knows about them. For example, some cities have been successful in getting their electric vehicle charging infrastructure in place, in ways that other cities have not. We can learn from those sorts of lessons. A lot of research is also needed on the implementation side: what's been successful and what has not, and what does that tell us for policymaking or investing going forward?

Q: What information in the report do you think is most insightful and useful to you, and why?

LC: I was interested in the notion of where research is being done. A lot of the discussions and a lot of the research has been dominated by the countries with the strongest research capacity. But to address climate change we need everyone involved, and one of the biggest issues that we face consistently is ensuring that all countries have the capacity they need to make progress; where is the research being produced, who's producing the research? That's extremely useful and, frankly, it confirms a lot of what we think. Outside of the big players, how much do the other players really have in terms of capacity to be able to make commitments and to take action on climate and an energy transition? This report doesn't solve that, but it's another lens that highlights the importance of ensuring that this research capacity is really broad based. The capacity to make progress seems too often to be concentrated in particular places. That's a challenge we're all facing, and the report highlights that.

Q: Is there anything else you want to highlight from the report that you found insightful or useful?

LC: When we're talking about getting to net zero, net zero energy systems or net zero emissions, and then net zero economy, we're talking about something that is incredibly broad based. We've known in the mitigation space and the research space for years that there's no silver bullet technology. You can't use solar cells to help airplanes travel, and many countries may not have a lot of sun, so they need other sources of energy. Buildings, industry, transportation, electricity, refining—all these different sectors have a whole bunch of different elements to them, and we have a whole bunch of different countries. So there's no silver bullet technology.

But when you're talking about net zero it really goes much deeper than that. There's no silver bullet technology, there's no silver bullet sector, there's no silver bullet country, there's no silver bullet policy, there's no silver bullet actor. You need to not just have federal governments or national governments engaged, you need to have state or provincial governments and cities, and civil society, businesses.

What's interesting to me about this is that, when we think about net zero, the scope of what's relevant from a research perspective is enormous. It encompasses so much of society that it really makes it hard to think about how to scope that down, because everything that you've got, you have to get down to zero. That means that nothing gets left on the table. It calls for a very broad perspective on what your research is, and it was interesting to see this report grapple with that and try to pull something together that's trying to represent the scope of what's really needed.

Prof. Dabo Guan

Distinguished Professor of Climate Change Economics at the Department of Earth System Science, Tsinghua University, China
Chair at the Bartlett School of Construction and Project Management, University College London, United Kingdom

Q: How would you describe the role of R&D in enabling a clean energy transition?

DG: R&D are crucial to the clean energy transition, although real innovation in science and technology at the R&D stage usually takes place 10–20 years before any commercial application can happen. It's R&D on clean production and sustainable consumption that will determine how we address global climate change, irrespective of any technological innovation or economic mechanisms.

Q: What initiatives, policy developments or discoveries have emerged in your region/domain/area of specialism over the last 10 years that you feel have had real impact on a clean energy transition?

DG: This report shows that China contributes to a significant proportion of publications on the clean energy transition and has become a leading powerhouse on clean energy research and technological innovations. This is to do with systematic policy implementations and huge funding investment in this field over a period of time. This is not going to stop. The transition to clean energy will increasingly be seen as a key area of productivity for China.

Q: What information in this report is most insightful and useful to you, and why?

DG: In my view, the most impressive finding from the report is the small but growing participation of the Global South in the clean energy transition. In the past, most climate change-related work done in the Global South was around climate adaptation. They had only a small voice when it came to mitigation and, consequently, to global climate negotiations. This was partially due to a lack of research being done in those regions. Global climate change mitigation is very much in the hands of the Global South countries, however. Apart from the major emitters such as China and India, other developing countries in South Asia and Africa have grown their economies and emissions dramatically over the past 10 years. It's vital for them to find a way to leapfrog to a transition to clean energy. Research on data and methods are the key elements before any application studies.

Q: Thinking about the clean energy transition, what R&I priorities do you think should be the focus in the next 10 years?

DG: There definitely needs to be more research on clean energy transitions in the countries of the Global South. Taken individually, no single nation in the Global South contributes significantly to global emissions, with the exceptions of China and India. However, collectively, they are among the top emitters in the world. Future climate change mitigation patterns show us transitioning from an emission-heavy country focus to a more scattered focus. In future, more work will need to focus on international cooperation among the Global South.

Q: What in the report did you find inspiring, insightful, useful? Did it fill a gap?

This was my first time seeing an R&D analysis on the subject of the clean energy transition, which is such a multidisciplinary research area. The role of the Global South was of particular importance and is worthy of further analysis.

Prof. Hiroshi Komiyama

Chairman of the Institute, Mitsubishi Research Institute, Inc.
President, Platinum Society Network[43]
The 28th President, The University of Tokyo, Japan

Q: How would you describe the role of R&I in enabling a clean energy transition?

HK: That's a very broad question! The role ranges from basic research on materials, through the technological aspects, to user-friendly processes. For example, materials are very important: the magnets in wind turbines and vehicle powertrains often use rare earth materials such as dysprosium. The supply of this material is limited, and more research is needed to replace it with other materials.

In Japan solar power is an efficient electricity source, yet uptake of renewables in general is only now gathering pace. Some parts of society do not necessarily desire rapid change, and companies prefer to initiate it themselves rather than being told to change. As researchers, we need to consider how we navigate our societal systems to be able to effect change.

Q: How important is the work done by the Platinum Society Network—which you founded to enable this societal transition—to corporates, regional governments and academia?

HK: Japanese regional areas are losing young people. It's a common issue around the world—urbanization and regional depopulation. Renewable energy has the potential to revitalize local economies. It's impossible for Tokyo to be self-sufficient using renewable energy only. But it is possible for regional areas. Once people in regional areas realize this, many become confident of their own sustainability. For example, Mayor Takenaka of Kamishihoro, which is a town in the north of Japan, once said self-sufficiency was their aim. I told him that not only could they be self-sufficient, but they could also sell 10 times the energy they consume. He checked the numbers and came back to me saying, "You're right! We're already self-sufficient."

Q: What has had the most impact in the last 10 years in terms of the clean energy transition? In Japan or globally.

HK: Cost reduction has played a big part. In these 10 years, the average cost of electricity produced by solar panels has reduced to a ninth or a tenth of what it was originally. If we were building a new power system—using nuclear, fossil fuels or renewable energy sources—10 years ago the most expensive option would have been solar power, followed by wind power. Now, though, solar power is the cheapest. After the Fukushima disaster, the cost of nuclear increased, too. For 2021, the IEA estimates that 70% of global investment in building new power systems will be for renewable energy sources.[44] Even with our present

43 See https://www.platinum-network.jp/en/
44 See https://www.iea.org/reports/world-energy-investment-2021/executive-summary

technology, we can increase renewable energy use. But global warming is much more critical than we expected 30 years ago, so we need to accelerate our progress.

Q: The report looks at the research outputs around net zero and clean energy technologies. What value does this type of data provide for you as well as for policymakers and the wider research community?

HK: Looking at these data, I'm not surprised by China's research volume. In a sense, they have what might be an advantage: they have to increase the country's power supply and electricity production, and renewables are the cheapest option. One of the global leaders in photovoltaics research, and winner of the Japan Prize in 2021, is Martin Green (Scientia Professor, UNSW, Australia[45]). His team made key achievements, increasing the power conversion efficiency in silicon photovoltaics as well as integrating them into practical devices. Many of his post-docs returned to China and founded companies.[46] Thanks to excellent technology and an ability to mass produce, China is in a strong position in photovoltaics and is making solar power a key renewable energy source globally.

Of course, being able to see which countries are excelling in certain fields is good to know. But there are so many subcategories within renewable energy and net zero technologies, so the details are also important. I'd like to see more detailed data, down to the article level!

Q: You've already mentioned what's important to accelerate the clean energy transition. What, in your opinion, will be the most important thing in the next 10 years?

HK: Efficiency remains important. If you think about the cost of solar panels, the most expensive part is not the active layer (which produces electricity) but the surrounding frame, for example, or the glass panel that covers the active layer, or the steel that supports the panel. In short, the installation materials are very costly. So, if the energy efficiency doubles, you get double the power per installation, halving costs.

In Japan, we need to think about how we mount these panels on different types of buildings (and therefore roofs). This requires planning and design, which in turn requires human resources. Implementing AI for these kinds of processes would speed things up, I think. This also links back to societal issues. It doesn't matter if we develop an amazing solar panel if we get no uptake from society more broadly.

Q: The Tokyo Olympics was the first-ever "zero-emission Games". As the Chair of the Tokyo Olympics Sustainability Committee, how do you see the net zero legacy of these Games?

HK: With the Olympic Games, we created a showcase for a sustainable zero-emissions society, and we've relayed this to the Paris Games. I'm sure they will do even more. Everything was powered by renewable energy at the Tokyo Olympics. The Olympic flame burned hydrogen for the first time ever, and the hydrogen was produced in Fukushima Prefecture (via the electrolysis of water using solar power). Electric vehicles were used for transportation during the Games. I guess the most talked-about aspect was the urban mining we did for the Olympic medals. All medals were created using recycled metals from used small electronic devices including smartphones. It showed that we can replace traditional mining with urban mining. The medal project symbolized the possibility of a circular economy.

[45] See http://en.people.cn/n3/2018/1107/c90000-9516132.html
[46] See https://www.abc.net.au/news/science/2021-09-19/solar-panels-why-australia-stopped-making-them-china/100466342

Q: In your 2018 book, *New Vision 2050*, you envisioned moving toward teleworking. Given that this has now been enforced upon many of us due to the pandemic, how can this opportunity be leveraged to facilitate more change—for example, in energy usage?

HK: Again, the issue is how to speed things up, particularly in Japan. Japan is a good country—people are kind, and people are not so greedy. But they don't want to move or change, because it's good already—it's comfortable. This is what we are trying to challenge. This "good" that many people experience here may not necessarily be sustainable.

To me, the most important way to address this is by having people interact. Right now, much of the knowledge is concentrated in Tokyo. Almost too much. So, we're encouraging people from Tokyo to travel to regional areas. Some people may even choose to relocate there, especially with remote-working capabilities. This interaction then facilitates knowledge being shared and communicated more widely.

Regional area revitalization is key to solving social issues, including achieving net zero. The Platinum Society Network is making good progress—but we're still at early stages. It's a vision for me, but I think it will happen.

Joan MacNaughton

CB HonFEI (Lady Jeffrey), Chair, Climate Group (United Kingdom); Non-Executive Director En+Group plc (Chair, Health, Safety and Environment Committee); and HAHL plc; Chair, International Advisory Board, New Energy Coalition of Europe; Member of Advisory Boards for Equans UK plc, the Grantham Institute (at LSE/Imperial College), and the Joint Institute for Strategic Energy Analysis (at the National Renewable Energy Lab, United States)

Q: How important, in your view, is the role of R&D in the transition to clean energy?

JM: R&D are absolutely vital.

We've got a lot of the technologies that we need to get to net zero, but they're not necessarily at the stage that we need them to be to contribute effectively to the net zero transition. About half the technologies are already maturing in the market, but the other half still need developing. The initial research phase is the start of it all: it's the genesis of everything. But then you need development and demonstration, and then deployment.

All four of these phases must occur for the technologies to play their part in enabling us to get to net zero with decent living standards for all. We've seen this in the cost reductions that have occurred over the last decade or so. The figures are dramatic—an over 80%–90% reduction in cost for solar or batteries—and this in turn means that deployment becomes more feasible and progress can accelerate. That's an important part of the next era of transition—because we don't have unlimited time.

We can also see clear evidence of a shift in the balance of effort in clean energy technologies infrastructure, compared to what you might call the polluting technologies. The IEA published a report earlier this year that showed that the growth in international patent families has been more than double for clean technologies generally, compared with those for fossil fuel technologies.[47] That's quite a shift. And in the latest year for which they quote a figure, 2019, it's probably not far short of three times the gross. We have to bear in mind that it's starting from a lower base, but it shows an important trend in the significance of these technologies and the significance of R&D in them—that is then feeding through to the register of the patents that have been applied for. The IEA report also noted that countries are tending to specialize in a family of technologies or a few families of technologies. That gives real depth for those families of technologies, but it also means that we've got to have international collaboration.

Q: How important is international collaboration in achieving a transition to clean energy by 2050?

JM: Countries will tend to specialize in areas that are important to them, or where they already have the basis for expertise—for example, if they've got a university or research institution that has strengths and history in a particular area. This does underscore the need for international collaboration though, because otherwise gaps might not be addressed. It's not enough that each country will bring to the table what it's quite good at, or experienced in, or willing to fund. We have to take a broader view and see where the gaps are and how they can be filled.

[47] IEA. (2021). *Patents and the energy transition.* https://www.iea.org/reports/patents-and-the-energy-transition

One very good survey of this is the IEA annual report called Energy Technology Perspectives,[48] which looks across the different technologies that are crucial for the energy transition and gives them a report card on how well they're developing and what more needs to be done. It's a very good tool for gap analysis.

One mechanism that uses that to advantage is the Clean Energy Ministerial.[49] This is a group of countries—originally about 20 of the biggest energy users, although now it's grown beyond that, but it's still not huge—and they come together once a year. They're supported by a secretariat, and countries will raise an issue they think needs to be addressed and where leadership by an individual country or a group of countries working together can make progress.

One of the earliest initiatives of the Clean Energy Ministerial was called the 21st Century Power Partnership. It was focused on getting to zero or very low carbon power generation and looked at things such as what policies and incentives actually drive decarbonization of the power sector most effectively and what else needs to happen in the power sector to enable that to happen, all while preserving security of supply and promoting affordability and access to electricity, which is still a huge issue in the Global South. Out of that group, others have emerged to include smart grids and the flexibility that sophisticated approaches to a grid can bring. This can be absolutely crucial in supporting significant penetration of a power grid by renewables without risking instability, because most renewables tend to be intermittent.

One of the interesting features about the Clean Energy Ministerial, and I think a secret of its success, is that not every member of the group has to agree to every initiative. It requires a core group to take leadership and run the initiative. The object is to make sure that it's not just one or two countries and that it is truly global, but you don't need everybody to sign up. You just need a few people with the will and who are prepared to resource it to make progress. And that's a huge strength because that helps with pace, and one of the challenges in the net zero transition is to get velocity into taking initiatives and making them happen, and then getting the results to be able to apply them in the real world. It's a great example of what can happen when you collaborate internationally.

Analysis has shown that the costs of getting to net zero are far, far lower if there is international collaboration than if each country goes down its own chosen path. The collaboration needs to be around policy coordination, deployment and research because some research issues are too big for an individual country to resource. The classic example of that is nuclear fusion.

International collaboration is important for another reason: we're not going to get to net zero unless we have public buy-in. If the public in a country think that they are making strides in this area, perhaps making sacrifices in spending, they're not going to commit to that and support it if they think that other countries are not pulling their weight. So international collaboration, whether on research or more broadly, is really important for securing and sustaining public acceptance.

In a world where there are many, many forces pulling countries apart, collaboration on such a clear and obvious existential threat can help be a counterweight. Because when people work together, it's much more difficult to demonize everything else that other countries do, and it keeps the channels of communication open.

Q: COP 26 is being held in the United Kingdom this year. What are your thoughts on the United Kingdom's position in relation to the clean energy transition and to international collaboration?

JM: In some respects our policy framework has been world leading. Our decision to set up the framework of rolling five-year carbon budgets has been a terrific innovation in policymaking. And it gives parliament a

[48] See https://www.iea.org/topics/energy-technology-perspectives
[49] See https://www.cleanenergyministerial.org/

much better handle on holding the government to account here, which I think doesn't exist to the same degree in other policy areas in this country.

There are some real challenges to meeting our targets for 2030 and beyond. There are also some very good policies, such as the phase-out of sales of new internal combustion engines, and the hydrogen strategy. But the evidence is that the strategies are not at the moment fully underpinned by the necessary plans. If you look at the electric vehicle strategy, that's terrific because it's a very solid bit of regulation, and it's sent a signal to the car manufacturers that they are definitely responding to. However, without some work from the government on things like common standards, does somebody really want to go electric if they've got to get a separate app on a separate account for different types of charger?

There's been a huge amount of investment into charging stations and some companies are really stepping up. But, again, is anybody looking at overall deployment and whether it's going into all the right places? If we're going to meet the 2030 target of everyone who wants to buy a new vehicle being able to buy electric and be confident they can charge these vehicles, then there are some gaps in the policy. That said, the research side is doing excellent work on innovative automotive approaches, and there's a wonderful facility at Warwick University, the National Automotive Innovation Centre, that the government has supported and that has really contributed to the things that need to happen for electric vehicles to become the car of choice for the consumer.

Q: Why do corporates and academia need to collaborate in this sort of area?

JM: Academia brings some of the best blue-sky ideas. It doesn't have a monopoly on them, as there's some great work going on in companies, but the work done in companies is often based on some ground-breaking research from a few years before that came from academia. But one of the things that corporates have, and that academia often doesn't, is an understanding of what the challenges are in the market. And so they can help academia to think about where the next priorities lie. They can shape the focus of the academic work, and then they can help to get it through into the market.

But the clock is ticking, and the faster we can get meaningful collaboration between companies and academia on problems that they're both going to have to help solve, then the faster we will get the solutions to reducing emissions. We need every hand to the pump, because a lot of this has taken off but not as quickly as science suggests it needs to.

Dr. Chukwuka Monyei

Research Fellow in Energy Justice and Transitions (SPRU – Science Policy Research Unit), University of Sussex Business School, United Kingdom

Q: How would you describe the role of R&I in enabling a clean energy transition?

CM: You can't overemphasize it: it is very important for the clean energy transition. The only problem is the political will. So, while R&I is important for achieving clean energy transition, political will in terms of government activities and, of course, support is equally critical.

The products of R&I are also very important. On its own, R&I is not enough to actually fast track humanity's progress in this transition.

Q: Can you tell me a bit more about that relationship between political will and R&I?

CM: If you look at the issue of electric vehicles, you discover that there's a tipping point on price for consumers. In terms of recharging electric vehicles, you have various standards—Tesla has come up with its own standards in terms of fast charging, Nissan has its own standard, etc.—and this creates disconnects in the system. What is needed is for governments in, for instance, the United States to come up with a policy that ensures that if I have a Nissan Leaf, I can use a Tesla charging station and get the same result irrespective of the make and model. Then I can access the available fast-charging stations. What that does is accelerate adoption because I don't have the added burden of identifying which charging stations can give me the same utility. Across Europe, you have some harmony in terms of similarities and standards, but you have a dissonance among the various players in markets such as the United States.

That's just one aspect where political will is needed. In Africa—for instance, Nigeria—you also have a lot of disconnect. Governments are aware of the utility benefits of, say, promoting renewable energies, but you have disconnects among various government agencies in terms of policies. For instance, the Minister of Finance might come up with taxes on, let's say, imports of inputs related to renewable energy products, and then you have another government agency promoting a subsidy for renewable energy products. Such disconnects could simply be resolved by all these agencies coming together to achieve harmony, but you need the political will to actually start that process. So R&I is very important, but then you also need government, for government support and political will, to be able to deploy innovations, much like what you have in Germany.

Q: What initiatives, policy developments or discoveries have merged in your region or subject domain over the last 10 years, and what do you feel had a real impact on a clean energy transition?

CM: I would say there are two big ones.

One is improved battery technology storage. You have radical improvements in the amount of energy we can store by unit area. And that has also been met with a decrease in the cost of batteries, which was very important, because budget plays a key role in the promotion of clean energy technologies, especially in developing countries like in Africa. A lot of people are adopting solar home systems, etc., first because of the reduced cost of lithium-ion batteries, per kilowatt hour, but also because the density of what we can store has been increasing. Over the last 10 years that's one aspect of innovation that's been important.

Another aspect increasing in significance in the Global North is the increasing handshake between the government and society in promoting technology. This is a human-centered approach to driving clean energy technology, so it's not just a top-down approach—now we have some coherence between governments and people. Having that buy-in from society, from people, into government policies is very important, because if you can achieve that buy-in now that means that people will be comfortable with the outcomes of the projects.

Q: What value do data, such as contained in this report, provide for policymakers, institutional leaders and the research community, and can you identify any other data that will be helpful?

CM: The research you've conducted, what you've been able to do, is an aggregate of what is scattered out there. You've been able to bring it into one place and, in so doing, you have actually given us an idea, especially policymakers, about the jobs of the future. The idea of net zero is actually not just about energy, but also about the infrastructure needed to achieve that, and that's what this particular report has been able to identify. It allows people in government to think about how we can enable our workforce to play a critical role for the future, and identify aspects that will be critical for the success of achieving net zero. Areas such as cyber security, IT networks, all the supporting infrastructure, not just energy itself but all the disciplines, so that governments in different countries can begin to build up capacity in certain niche areas and be able to lead research in those particular areas. I don't think there's any report on this scale, or one that's been able to highlight this, because this is massive.

Q: You highlighted this interesting point about future jobs. Can you say a bit more about what those other kinds of jobs would be in the future, either that we need to increase now or new ones that we don't really have?

CM: The fourth industrial revolution is going to rely heavily on the Internet, and this means that Internet-enabled or Internet-related jobs are going to be critical for the future. We are looking for people versed in cryptology, in hacking, in the cyber security space, in different roles that we are not even aware of.

This opens up another conflict, though: privacy and the ethics of the Internet of the future. How are we going to be able to balance issues of privacy, how much information should the government know? How can we encrypt this information? How can it be used, without giving governments too much access to such information, and what it can be used for and to what purposes...?

Your report highlights the obvious roles—for instance, expertise in battery technology, chemical process engineering, IT (things like encryption, cryptology, like cyber security, blockchain technology)—as well as roles that we are not familiar with. It also provides the benchmark, a platform, to build upon, because as we continue to grapple with new problems, we will begin to rethink new roles, and new expertise, and begin to get creative so we can address the problems that will come up in the future.

Q: Thinking about the clean energy transition, what R&I priorities do you think should be the focus in the next 10 years?

CM: We have to focus on humans because the big beneficiaries of the transition are definitely going to be humans! Figure 22 in the report shows that there isn't a very good connection between research in the core sciences and research in the humanities, in the arts and all those particular areas. That's already exposing a potential failure of the current trend, and if we continue with this current research trend, we're definitely going to have failure. There would be a lot of opposition to the outcomes because you won't have a lot of buy-in. So the majority of research should focus on having buy-in from people. Our research must be human-centered. I think that's a better way to put it: the clean energy transition—in terms of the design of how I want to achieve this net zero goal—must be done with a lot of buy-in from humans. But then, too, there needs to be a deliberate attempt by governments to provide education for people, as that's fundamental to having buy-in from the population. What's happening, what's this all about, what are the potential benefits, what are the potential consequences, how does the government intend to mitigate this, what options are on the table, what will the government provide? If they know these things, then people are able to make informed decisions, as communities, as groups, as individuals, and this will encourage buy-in to the clean energy transition.

Q: Is there anything else you want to highlight from the report that you found either insightful or useful?

CM: The success of the clean energy transition will depend largely on buy-in from the Global South, and we need a concerted effort by policymakers across the globe to ensure this. This is because the Global South has the potential to negate any possible benefits that would be gained from achieving the objectives of a clean energy transition to net zero emissions. As we make progress toward a clean energy transition to net zero, we must have significant plans in place to ensure that the Global South is able to buy into this particular part. And that would depend largely on what has been offered to them in terms of capacity development and, of course, in terms of knowledge transfer. These are very important aspects that must be considered, otherwise the whole idea of the transition will be wasted. Because the projected increase in energy usage is going to come from the Global South, having them buy-in early enough benefits our ability to sustain the whole energy transition.

Kariuki Ngari

Managing Director & CEO
Standard Chartered Bank Kenya

Globally, nearly every nation has endorsed the Paris Agreement, setting net zero carbon emission targets to limit global warming. Of those, 190 have solidified their support with formal approval. Africa has not been left behind. Over 90% of its countries have endorsed the Paris Agreement and committed to transitioning to green energy within a relatively short time frame. Clean energy and agriculture are prioritized in over 70% of African Nationally Determined Contributions.

Although Africa produces less than 4% of global emissions,[50] it is the most-exposed region to the adverse effects of climate change. We are already seeing disproportionate impacts related to a changing climate in the continent. Madagascar is on the brink of experiencing the world's first "climate change famine" after going four years without rain. In 2018, devastating cyclones affected 3 million people in Mozambique, Malawi and Zimbabwe. In Kenya, optimal and medium tea-growing conditions are predicted to shrink by about 25% and 40% respectively by 2050. Furthermore, GDP exposure in African nations vulnerable to extreme climate patterns is estimated to hit USD 1.4 trillion in 2023.

On the other hand, the global commitment to net zero emissions by 2050 is growing, across governments, businesses, investors, cities, regions and civil society. However, COVID-19 is forcing many governments and businesses in the African region to focus on immediate survival. In addition, with limited resource and budget allocations, the majority of African countries are focused on improving productivity and accelerating economic growth, further delaying the net zero transition.

Many African countries simply lack the incentive to adopt climate mitigation frameworks. It becomes difficult for a country like Nigeria to prioritize adoption of clean energy when oil is a major income-generating source. It therefore becomes crucial for net zero champions to show how the adoption of clean energy will contribute to local job creation or economic growth in the long term.

The operational and commercial costs also cannot be downplayed. Substantial investment is needed to adopt alternative energy solutions, be it shifting from electrical power to hydropower or shifting from fossil fuel.

This is also true for players in the private sector. Standard Chartered's 2020 *Zeronomics* report[51] shows 85% of companies require medium or high levels of investment to transition to net zero, rising to 91% of carbon-intensive companies. On the investor side, emerging markets remain a blind spot for many investment funds, and transition finance is deemed too risky by many, despite the billions of dollars now aligned with environmental, social and governance (ESG) objectives.

[50] See https://unfccc.int/files/press/backgrounders/application/pdf/factsheet_africa.pdf
[51] See https://www.sc.com/en/insights/zeronomics/

Investment from the Global South will therefore be integral in driving climate adaptation in Africa. However, this will have to go hand in hand with policy reforms that provide an enabling environment for clean energy financing and investment. This can look like having proper carbon policies in place that reward companies that reduce their carbon footprint and impose carbon taxes on those that emit the most.

The financial sector could also help by providing incentives in the form of margin discounts on loans and bonds linked to the net zero transition. As mentioned, financing is a key impediment and proper financial solutions will help individuals and companies adopt sustainable solutions, technologies and infrastructure.

Africa has a vast number of investment opportunities aligned to clean energy. The biggest investment opportunities can be found in renewable energy projects in emerging markets, where growing demand for new sources of reliable, clean and affordable electricity is greatest.[52] With an estimated USD 4.226 trillion investment needed in the generation and transmission of electricity in all emerging markets by 2030, the private sector should explore this and other clean energy investment opportunities.

African countries should also be encouraged to adopt technology to support the transition. Technology can be a key enabler as it provides an opportunity for hard-to-abate sectors to cut their carbon emissions through processes such as carbon capture and storage. Data and technology can also be applied in monitoring the impacts of climate change, accelerating the use of renewables and directing capital due to smarter ESG reporting, ratings and investments. This will have both short-term and long-term benefits and will also reduce transition costs.

Standard Chartered acknowledges climate change as one of the greatest challenges facing the world today, given its widespread and proven impact on the physical environment and human health and its potential to adversely impact economic growth. This gives us the opportunity to support the net zero transition by engaging with a wide range of stakeholders including clients, governments, civil society and academics on the impact of climate change and how these can be mitigated. Successful partnerships between finance institutions, development banks, international financial institutions and governments to finance both mitigation and adaptation needs will be critical, particularly in developing countries. COVID-19 recovery plans also offer the opportunity to build back greener and cleaner. Decision-makers must now walk the talk.

[52] See https://av.sc.com/corp-en/content/docs/Standard-Chartered-Opportunity-2030.pdf

Prof. Yutao Wang

Professor, Department of Environmental Science and Engineering,
Fudan University, China

Q: How would you describe the role of R&I in enabling a clean energy transition?

YW: R&I are the most important drivers of the clean energy transition. Research on the current state of this transition adds to and strengthens public understanding and awareness of the climate crisis and thereby accelerates the public response to the situation. R&I output also provides a variety of ways to deal with the climate crisis by presenting clean energy technologies based on research from many regions and fields. Decision-makers can select technologies that suit their needs from among many options. The emergence of the clean energy transition to address climate and environmental issues is advancing the overall research, updating the scope and breadth of research, and promoting timely, global and socially relevant discussions and debates on clean energy technology.

Q: What initiatives, policy developments or discoveries have emerged in your region/domain over the last 10 years that you feel have had real impact on a clean energy transition?

YW: In China, the most highly relevant policy to the topic of net zero is the carbon-neutral policy proposed in 2020. China commits to scale up its Intended Nationally Determined Contributions by adopting more vigorous policies and measures. It aims to have CO_2 emissions peak by 2030 and to achieve carbon neutrality by 2060. To achieve carbon neutrality, China has developed detailed energy transition plans and provided substantial funding for research related to the energy transition. More and more research has emerged to try to apply the outputs of previous research to real-life situations. The commitment to carbon neutrality was only made a short time ago, but it's already having a significant impact on the clean energy transition. Everyone, from government to individuals, from the scientific community to industry, has risen to the occasion and got involved in this massive initiative. From my perspective, our research group has received quite a few consulting requests from traditionally high energy-consuming enterprises as they formulate their own carbon neutrality roadmaps. Enterprises are keen to learn more about net zero R&I and to seize the opportunity to integrate with the latest research outputs and national policies.

Q: What value do data, such as those in this report, provide for policymakers, institutional leaders and the research community, and why? Can you identify any other data that would be helpful?

YW: The data contained in this report can help policymakers, institutional leaders and researchers make informed decisions in their respective fields and identify their positioning, challenges and opportunities. They can clarify the hot spots in and prospects for current R&I for audiences and provide new research directions. Policymakers and institutional leaders, for their part, can adjust the focus of program support and make those adjustments promptly. All the data in the report will be useful to the audience. For example, the academic–corporate collaboration data show that such collaborations have been increasing in clean energy research over the last 20 years, but the data on corporate publications show that their share in the field has been declining since 2010. In short, corporates are publishing less, but they are collaborating more with academia when they do so. Nonetheless, cooperation between corporates and academia is very helpful for achieving net zero and making the research useful and practical.

Q: What information in this report is most insightful and useful to you, and why?

YW: To me, the most inspired part of this report is that related to adopting a systemic innovation approach to increase support "for innovation across the innovation chain (research, development and demonstration)".[53] Previous studies have focused on a link in the innovation chain, but any research in the environmental field needs to consider a systematic approach. A net zero plan, in particular, involves all aspects of the system and needs to coordinate the interests of all parties. When research, technology development and innovation are combined with policy and market design, targeted to the actual needs of society and corporates, then innovative systems approaches can truly achieve net zero programs.

Q: Thinking about the clean energy transition, what R&I priorities do you think should be the focus in the next 10 years?

YW: In the future, the clean energy transition needs to focus on two aspects. One is the development of technologies that are truly applicable and accessible. This is not just for a few developed countries but for the wider world, so that different countries and regions can choose the appropriate clean energy technology for their situation. Second, the time cost and implementation effect of these technologies should be fully considered. At present, many countries have committed to carbon neutrality plans, but the time frames for each country to reach carbon neutrality will differ. Therefore, the time costs and implementation effects of R&I for new technologies are the important factors for a country or region to consider in choosing this clean technology.

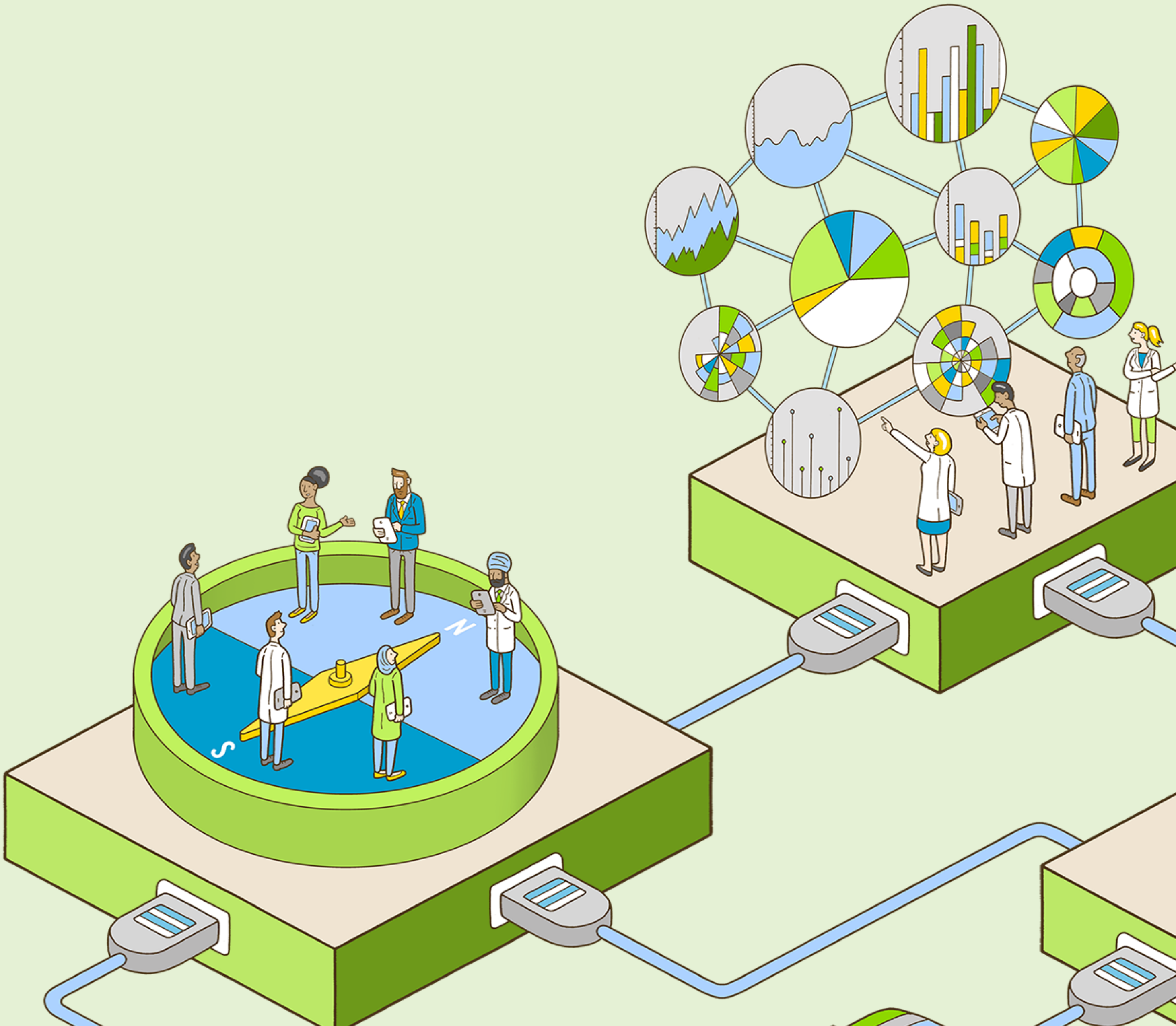
Q: What in the report did you find inspiring, insightful, useful? Did it fill a gap?

YW: I think the segment in the report about the Global South's participation in clean energy research is very insightful. We've rarely paid attention to these situations in the past. Researchers are more willing to follow hot issues and hot areas because of easier access to data, more financial support, greater ease in collaborating and easier field surveys. This reminds us that we need to give more visibility to research on "South international publications" and "South focus" topics and call on all researchers to pay more attention to the Global South's research.

[53] As per the discussion related to the International Renewable Energy Agency's *Global Renewables Outlook* report at the beginning of Section 1.11. To access the report, see https://irena.org/publications/2020/Apr/Global-Renewables-Outlook-2020

Section 3

Conclusion and future outlook



Conclusion and future outlook

NØEnergy is a broad, multifaceted and fast-growing area of research. This report provides an overview of the evolution of the field over the last two decades and a snapshot of the current research landscape. It also indicates where future efforts could be directed.

This report presents data and analyses of clean energy research and innovation as a pathway to achieving net zero. We analyzed scholarly output and patents to identify the trends in research underlying the field, from both a geographic and a disciplinary perspective. The report examines the funding of NØEnergy research, whether there is sufficient conceptual and collaborative diversity in the field, and the extent of collaboration between different countries and regions and between the Global North and South. Considering the crucial importance of transforming research and innovation into deployable technologies, we also focus on the transition from basic science to applied technology, the scale of academic–corporate relations, the role of corporates in NØEnergy research, and the patents landscape. Finally, we investigate the connections between research, policy and the wider media.

We believe the report makes a valuable contribution to discussions on the relevance of research and innovation to achieving net zero. Our analysis of over 1.6 million publications and 800,000 patents in NØEnergy research identifies some positive signs and some points of concern. However, we see this report as a beginning rather than an end—a springboard for further discussions. Our analyses have generated a number of additional questions that we believe warrant further exploration.

What constitutes NØEnergy research?

One of the first challenges we faced in this report was specifying the problem space: how can clean energy research for net zero be defined? We started with the foundations of research associated with SDG 7 – Affordable and Clean Energy. While SDG 7 captures a very broad domain of research related to emissions, it does not capture research on carbon removal, so we included part of the research associated with SDG 13 – Climate Action. The sheer diversity of research topics relevant to NØEnergy research is astonishing. Going forward, there will be merit in further discussion of the extent of this domain, whether it should be expanded and how.

Is NØEnergy research focused in the right areas?

Data show that research output on bioenergy and carbon capture and storage is fluctuating or declining, yet these topics feature prominently in many national and intergovernmental pathways, including those of the IPCC and IEA, to net zero by 2050. A deeper analysis of research trends in topic clusters allied to net zero policy strategies could reveal further examples, which will help illuminate crucial gaps in current and future research programs developed to support policy. Many experts interviewed for the report mentioned the comparative scarcity of NØEnergy-oriented social science and humanities research, and of cross-disciplinary exchanges between these areas and science- and engineering-based areas of the field.

Are the big emitter countries and corporates funding NØEnergy research proportionately?

Understanding of the funding landscape of NØEnergy research, as presented in this report, is constrained by how well researchers acknowledge their funding sources in publications. Obtaining data on the funding of NØEnergy research at source opens the possibility of analyzing the contributions of countries and regions to clean energy research as a proportion of all funding, per head of capita, per GDP or by emissions, among other factors. These comparators could serve to support more detailed discussions about carbon equality and climate justice. And while corporates may wish to keep the details of their funded NØEnergy research in-house for competitive purposes, transparency on the amount they are spending would contribute to the debate about equitable contribution to mitigating climate change.

Is there sufficient conceptual and collaborative diversity within NØEnergy research to tackle the grand challenges of climate change?

Our report suggests that NØEnergy research tends to focus on a few disciplines (although these subfields may themselves encompass a broad swathe of research topics), which could limit its ability to produce the broad-reaching societal outcomes needed to combat climate change. While cross-disciplinarity in research is often cited by research leaders and policymakers as an important approach to tackle grand challenges, our data indicate that there is room for improvement. In future work, it would be relevant to consider how expertise in social sciences and humanities could be integrated more effectively with the physical or biological sciences to inform questions around behavioral changes or societal transitions. Cross-disciplinarity is seldom fostered or achieved at the level of whole funding agencies, institutions, or countries and regions, so analyzing the expansion of interdisciplinary and multidisciplinary practices is arguably to be best conducted at the level of individual research programs. It is worthwhile repeating here the need for a better understanding of the contributions of NØEnergy-adjacent social science and humanities.

“We’ve known in the mitigation space and the research space for years that there’s no silver bullet technology. You can’t use solar cells to help airplanes travel, and many countries may not have a lot of sun, so they need other sources of energy. Buildings, industry, transportation, electricity, refining—all these different sectors have a whole bunch of different elements to them, and we have a whole bunch of different countries. So there’s no silver bullet technology.

“But when you’re talking about net zero it really goes much deeper than that. There’s no silver bullet technology, there’s no silver bullet sector, there’s no silver bullet country, there’s no silver bullet policy, there’s no silver bullet actor. You need to not just have federal governments or national governments engaged, you need to have state or provincial governments and cities, and civil society, businesses.”

Leon Clarke, Acting Director and Research Director, Center for Global Sustainability at University of Maryland at College Park

Is there enough NØEnergy research in and for the Global South?

Our report reveals that while overall trends in international collaboration, levels of participation by local researchers and research focused on regional issues are positive for the Global South, these increases have been modest. This could make the implementation of NØEnergy research outcomes problematic in the future. Increasing the frequency of Global North–South collaboration should be a priority for NØEnergy research policies.

Is the NØEnergy field sufficiently diverse?

Equality, diversity and inclusion are key to making impactful progress in the research and development of solutions that will affect whole societies. How well clean energy research and its associated evidence-based policy decisions address these areas will surely affect the sustainable application of solutions to meeting net zero targets. Investigating the equality, diversity and inclusion levels in NØEnergy research would be a useful area for future analysis, mirroring funding already earmarked for investigation of these issues.[54] Going forward, we will examine the participation of women in NØEnergy research, both geographically and by topic, based on methodologies developed in our recent gender report.[55]

How effective are academic–corporate collaboration and corporate research in NØEnergy?

"Analysis has shown that the costs of getting to net zero are far, far lower if there is international collaboration than if each country goes down its own chosen path. The collaboration needs to be around policy coordination, deployment and research because some research issues are too big for an individual country to resource."

Joan MacNaughton, CB HonFEI (Lady Jeffrey), Chair, Climate Group

NØEnergy research must transition successfully and rapidly to commercial, real-world applications if we are to benefit fully from its potential to tackle climate change and mitigate against its effects. This will require the full engagement of corporates, as well as researchers and policymakers. However, we observe in our analyses that the output from corporates has not retained the same level of activity as the research overall, and few of the largest corporate emitters produce any significant research in this area at all.

We also observe that while patents related to GHG emissions reduction are growing exponentially, other vital areas such as solar, wind, biomass energy, biofuels, energy from waste and energy efficiency are increasing more modestly. Although patents are not representative of the entirety of industry's activities, our findings may indicate that more corporate involvement is needed in the development and deployment of clean energy technologies in some of these areas.

How can interactions between NØEnergy research and policy be increased?

Alternative metrics are now helping us track the outcomes of research relevant to policymaking and media coverage. In addition to looking at news mentions and social media data from PlumX, this report is the first of its kind from Elsevier to incorporate Overton's policy (or policy-related) citation data, which will also be available in SciVal in late 2021. Our analysis indicates that only 2.5% of NØEnergy publications are cited in policy-related literature, which is lower than the estimated 3.2% average for all Scopus publications. Further avenues of research could detail case studies of concrete achievements of NØEnergy research leading to

[54] See https://www.ukri.org/opportunity/equality-diversity-and-inclusion-in-the-energy-research-community/
[55] See https://www.elsevier.com/connect/gender-report

policy-driven social change. They might also identify features of certain programs or projects that facilitate the policy-related uptake of research findings.

Which areas of NØEnergy research should we analyze in more depth?

Elsevier is planning a limited but focused follow-up analysis in a number of areas considered in this report. We plan to look in more detail at electric vehicles, photovoltaics, energy efficiency and carbon capture and storage. Elsevier is open to collaborating with interested parties in these areas. In the meantime, we are making the NØEnergy data set available via the ICSR Lab,[56] and welcome the development of new and deeper analyses by interested research groups.

Final words

The above are just a few suggestions for future analyses that could inform and support the pathway to net zero. We note that—as mentioned by Kariuki Ngari, Standard Chartered Bank Kenya, in his interview—redirection of climate change and clean energy research and development funding to support work on COVID-19 and public health systems hit by the pandemic has been reported in Global South countries.[57] If not effectively mitigated, this will have knock-on effects, not only on research but also on the speed and comprehensiveness of the development and deployment of clean and affordable technologies addressing energy needs and carbon equality, as well as achieving net zero targets.

We hope that this report will serve as a useful resource for research leaders, funders, policymakers and researchers. NØEnergy research is doing well, but as the report has shown, there is room for improvement to capitalize fully on the innovation and knowledge potential of this field and so tackle the single most significant challenge we face: climate change.

> *"R&I are the most important drivers of the clean energy transition. Research on the current state of this transition adds to and strengthens public understanding and awareness of the climate crisis and thereby accelerates the public response to the situation."*
>
> Yutao Wang, Professor, Department of Environmental Science and Engineering, Fudan University

[56] See https://www.icsr.net/icsrlab/

[57] See also Van Bodegom, A. J., & Koopmanschap, E. (2020). *The COVID-19 pandemic and climate change adaptation*. Wageningen Centre for Development Innovation. https://www.wur.nl/en/show/The-COVID-19-pandemic-and-climate-change-adaptation.htm; and Quevedo, A., Peters, K., & Cao, Y. (2020). *The impact of Covid-19 on climate change and disaster resilience funding* [Briefing note]. ODI. https://cdn.odi.org/media/documents/The_impact_of_Covid-19_on_climate_change_and_disaster_resilience_funding_trends.pdf

Appendix A

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The following organizations provided data or additional visibility for the report.

Ban Ki-moon Centre for Global Citizens

Overton

Times Higher Education

Appendix B

Glossary of terms

Altmetrics

Altmetrics is composed of a set of methods to measure the visibility of peer-reviewed scientific publications in traditional news outlets and policy documents and on social media. These mentions are usually tracked through document identifiers such as DOI, PMID and the URL of the article.

This report presents findings on citations and mentions of NØEnergy publications outside of Scopus—for example, in repositories of policy-related literature (such as the UK Parliamentary Office of Science and Technology), online news portals (such as *The Conversation* or the *New York Times*), or social media platforms (e.g., Wikipedia). Our analysis captures discussion of NØEnergy findings outside of the academic community, among policymakers or government scientists, scientific educators, and a broad audience of the science-news-reading public.

When we refer to *news* or *journalistic mentions*, we define this as content generated by journalists, or scientific news aggregators with editorial oversight. Policy-related documents made up of technical advice and evidence syntheses are known as *synoptic science documents*.

We use the PlumX and Overton databases (see Appendix C for details) to produce our altmetrics indicators. Both databases mix automated coding and parsing methods with some manual curation to link peer-reviewed publication records to those from selected online repositories and aggregators.

Bibliometrics

The quantitative data used in this report are analyzed using bibliometric techniques. Bibliometrics is a set of methods that use data from databases indexing records of scientific publications and patents, as well as other R&I outputs of growing interest such as designs and trademarks, to derive new insights into these outputs' corresponding funding and performance. Within bibliometrics, the branch of scientometrics examines the records of research publications to measure scientific activity. It is also increasingly looking at related types of outputs such as research data sets and protocols. The branch of technometrics focuses on patent records as a proxy measure for innovation. It is being actively expanded to cover other forms of innovation that are not well captured by patents, such as those covered by designs and trademarks.

Competitive impact

Competitive impact is a composite indicator, used to assess the value of individual patent families. This indicator is the product of the patent-related indicators known as market coverage and technology relevance (see below).

Compound annual growth rate

The compound annual growth rate (CAGR) is defined as the year-over-year constant growth rate over a specified period of time. Starting with the first value in any series and applying this rate for each of the time intervals yields the amount in the final value of the series.

Collaboration

Research collaboration is measured by counting publications resulting from the efforts of two or more authors. Such publications are referred to as co-publications throughout the report. Collaboration can be categorized into various types; in this report, we focus on the following three:

- International collaboration—where the affiliations listed by the authors of a publication include institutions from two or more countries or regions
- South international collaboration—where the affiliations listed by the authors of an international co-publication include at least one author from a Global South country; this category includes both North–South and South–South co-publications
- Academic–corporate collaboration—where the affiliations listed by the authors of a publication include institutions or organizations from both academia and the corporate sector; this is a type of intersectoral collaboration

Field-weighted citation impact

Field-weighted citation impact (FWCI) is an indicator of the citation impact of a publication. It is calculated by comparing the number of citations actually received by a publication with the number of citations expected for a publication of the same document type, publication year and subject. An FWCI of more than 1.00 indicates that the entity's publications have been cited more than would be expected based on the global average for similar publications; for example, a score of 2.11 means the entity's publications have been cited 111% more than the world average. An FWCI of less than 1.00 indicates that the entity's publications have been cited less than would be expected based on the global average for similar publications; for example, an FWCI score of 0.87 means the publications have been cited 13% less than the world average.

The FWCI is always defined with reference to a global baseline of 1.0 and intrinsically accounts for differences in citation accrual over time, differences in citation rates for different document ages (e.g., older documents are expected to have accrued more citations than more recently published documents), document types (e.g., reviews typically attract more citations than research articles), as well as subjects (e.g., publications in Medicine accrue citations more quickly than publications in Mathematics).

The FWCI uses an unweighted variable 5-year window. The mean FWCI value for 2012 publications, for example, is calculated for documents published in 2012 using their citations from 2012 to 2017. For recent output with less than five years since publication, all citations available at the date of data extraction are used in the calculation. For instance, if an article is published in 2016, and the data are extracted in 2018, the article's FWCI is calculated using the article's 2016–2018 citations.

Global South and Global North

The term *Global South* refers to three groups of countries: Upper-Middle-Income Countries (UMICs), Lower-Middle-Income Countries (LMICs) and Low-Income Countries (LICs), in line with World Bank definitions.[58] In this report, the Global South category excludes China, which is normally considered a UMIC country. This is because although China is a recipient of some development aid, it is also a scientific powerhouse. China collaborates routinely because of its high academic status rather than as a result of development-oriented scientific collaboration.

[58] See https://datahelpdesk.worldbank.org/knowledgebase/articles/906519

Global North countries are divided into four categories: China, EU-27 countries (including Bulgaria), the United States and an aggregate of the remaining High-Income Countries (HICs), as defined by the World Bank, which includes Australia, Canada, Israel, Japan, Saudi Arabia, South Korea, Switzerland and the United Kingdom.

Interdisciplinarity / conceptual diversity

The interdisciplinarity indicator captures diversity in the disciplines associated with the prior findings on which a research publication is based and that are cited within the publication (i.e., the thematic subfields associated with the references). This indicator captures the conceptual underpinnings of research. In this report, we refer to this as "conceptual diversity".

Scores for this indicator are 1.00 at the global level (for a given subfield): a field will score above 1.00 if it is more diverse than the global average or less than 1.00 if it is below the global average.

It is also possible to measure the percentage share of a publication set that achieves exceptionally high levels of interdisciplinarity. In this report, we discuss publications that are within the top 10% most interdisciplinary within their field. For this indicator, a score of more than 10% is above average and a score of less than 10% is below average.

Inventor country or region

While technically a country or region is not an inventor, it can be helpful to infer the country or region of origin of a patent from the address of the inventor. The term "inventor country or region" is shorthand for all the patents originating from a specific country or region.

Market coverage

Market coverage is a measure of the total size of the worldwide markets in which patent protection exists. The more patents a patentee (e.g., an institution or a country or region the patent owners are affiliated with) owns in important markets, the more valuable the patents are estimated to be. This is because innovators spend more effort and resources on protection in multiple (global) markets via patents if they believe an invention is more valuable.

Market coverage is calculated based on granted and pending patents, hence valid patents per country are adjusted for each market's size, as opposed to simple country counts. The size of each market is estimated using the sum of countries' and regions' gross national income (GNI) relative to the US GNI (as the largest global economy). A market coverage of 2 means that the protected markets are in total twice as large as the US market alone.

Multidisciplinarity / collaborative diversity

The multidisciplinarity indicator captures the diversity arising from collaboration between co-authors from different disciplines (i.e., the topics associated with the prior publications of the authors). This indicator captures the collaborative underpinning and team composition of research. In this report, we refer to this as "collaborative diversity".

The score for this indicator is 1.00 at the global level (for a given subfield): a field will score above 1.00 if it is more diverse than the global average or less than 1.00 if it is below the global average.

It is also possible to measure the percentage share of a publication set that achieves exceptionally high levels of multidisciplinarity. In this report, we discuss publications that are within the top 10% most multidisciplinary within their field. For this indicator, a score of more than 10% is above average and a score of less than 10% is below average.

NØEnergy publication set

For this report, capturing clean energy research related to net zero required the use of a diverse set of publications in the Scopus database. These publications focus on different methods and technologies for reducing emissions and removing carbon from the atmosphere. The analyses conducted in the report required the creation of a publication set that could capture all facets of this broad research field. We therefore based our publication set on two existing Scopus publication sets relating to the United Nations' Sustainable Development Goals (SDGs): the set for SDG 7 – Affordable and Clean Energy and the set for SDG 13 – Climate Action.

SDG 7 and SDG 13 are the SDGs most relevant to clean energy research as a pathway to net zero. While the SDG 7 publication set captures most research relating to curbing emissions, an important body of work associated with carbon removal, particularly carbon capture and storage, is acquired by the SDG 13 set. Our overall publication set therefore encompasses all the publications related to SDG 7, as well as those from SDG 13 that are relevant to clean energy. We refer to this publication set as "NØEnergy research".

Patent asset index

The patent asset index (PAI) indicates the value of a country or region's patent portfolio. The PAI is a composite indicator, taking into account portfolio size, technology relevance (the number of citations from other patents referring to the patent) and market coverage (the bigger the market, the more value it has).

Patent family

A patent family is a set of related patents that are filed at multiple patent authorities to protect the same invention in more than one country. This has implications when analyzing patent output because counting the number of individual patents would mean capturing the same patent multiple times, leading to errors in assessing the value of the individual invention. Working with patent families therefore accounts for all patents covering the same invention and enables analysis of the value of the invention.

Portfolio size

Portfolio size indicates the number of patent families attributable to an entity—for example, a country or region, or a topic cluster, or the overall total. When calculated for a country or region, it is attributed based on the affiliation addresses of patents' listed inventors.

Published patent

Patent applications must be filed with a patent office, which then "publishes" the patent sometime later. The average time taken from filing to publishing varies from patent office to patent office. Once a patent has been published it must still be "granted", but the granting of a patent usually takes several years. In this report, we count patents that have reached the point of publication.

Relative activity index

In this report, the relative activity index (RAI) indicator is defined as the share of a country's article output in a topic cluster relative to the global share of articles in the same topic cluster. A value of 1.0 indicates that a country or region's research activity in a field corresponds exactly with the global activity in that field; a value higher than 1.0 implies a greater emphasis; and a value lower than 1.0 suggests a lesser focus.

Scholarly output

In this report the terms output, articles and publications refer to peer-reviewed articles, reviews and conference papers published in journals and conference proceedings and indexed in the Scopus database.

South focus

South focus refers to publications with mentions of Global South locations (cities, countries or regions) in titles, abstracts or keywords. These locations are likely to be associated with fieldwork, local prototyping or research associated with regional issues.

Sustainable Development Goals

The Sustainable Development Goals (SDGs), which were launched by the United Nations in 2015,[59] are defined as “the blueprint to achieve a better and more sustainable future for all”,[60] by addressing the global challenges we face. Since their launch, Elsevier has worked with the research community to map the landscape of sustainability science, starting with the *Sustainability Science in the Global Research Landscape* report (2015),[61] developed with SciDev.net. Since then, we have mapped publications in Scopus to 16 of the 17 SDGs, combining expert-led search queries with machine learning models.

The methods and queries for the SDG publication sets are available here: https://elsevier.digitalcommonsdata.com/datasets/9sxdykm8s4/1

Technology relevance

Patent citations are divided into two main classes: backward citations and forward citations. Backward citations are those made to earlier patents (or publications) cited by a focal patent; they are often used as measures of knowledge transfer. In contrast, forward citations are those linked to a focal patent by patents filed after it and that list the focal patent as a backward citation. The number of forward citations a patent receives accumulates over time and appears to be correlated to the patent’s (i.e., its underlying invention’s) technological impact. Forward citations indicate the existence of downstream research efforts, suggesting that money is being invested in the development of the technology. Also, the fact that a given patent has been cited by subsequent patent applications suggests that it has been used by patent examiners to limit the scope of protection claimed by a subsequent patentee, to the benefit of society. In this sense, forward citations indicate both the private and the social value of inventions. Forward citations are commonly used to measure the technological impact of innovation.[62]

Technology relevance is based on forward citations. Technology relevance measures whether a patent has been cited more often than other patents from the same technology field and year. The total number of patent citations received not only depends on the technology field of the patented invention but also on the time that has passed since the patent was published. Patents only recently published tend to have received much fewer citations than older patents. The time-dependency of citations is corrected by dividing the number of citations received by a patent by the average number of citations received by all patents published in the same year.

Technology relevance also considers that international patent offices follow different citation rules. Therefore, the number of patent citations is corrected for age, patent office citation practice and technology

[59] See https://sdgs.un.org/
[60] See https://www.un.org/sustainabledevelopment/sustainable-development-goals/
[61] See https://www.elsevier.com/research-intelligence/resource-library/sustainability-2015
[62] Aristodemou, L., & Tietze, F. (2018). Citations as a measure of technological impact: A review of forward citation-based measures. *World Patent Information, 53*, 39–44. doi: 10.1016/j.wpi.2018.05.001

field. It is a relative measure comparing one patent to other patents. A value of 2 means that the patent is twice as relevant for subsequent developments as an average patent in the same technology field and of the same age.

Topics and topic clusters

Topics (or Topics of Prominence) refer to nearly 96,000 research topics created using the citation patterns of Scopus-indexed publications. The methodology for using citation patterns to define research topics was developed through an Elsevier collaboration with research partners.[63] The advantage of taking a citation-based approach to identify research topics is that one need not rely on identifying all the relevant keywords to define a research area. Rather, the research area is delineated by citation patterns in the topic, whereby research that appears in the same citation network is clustered together in the same topic. This approach provides a more nuanced definition of the research topic.

Topic clusters are a higher-level aggregation of these research topics and are based on the same direct citation algorithm that creates the topics. While topics are easy for subject experts to understand, they are more difficult for subject generalists to comprehend. To help in the discovery and understanding of the topics, Elsevier has aggregated them into around 1,500 topic clusters. When the strength of the citation links between topics reaches a threshold, a topic cluster is formed. Topic clusters are named by the three most relevant key phrases within the cluster—for example, *Wind Power / Electric Power Transmission Networks / Electric Power Distribution* or *Deforestation / Forest / Conservation*.

Both topics and topic clusters are mutually exclusive: a publication belongs to only one topic and only one topic cluster. More information on topics is available at https://www.elsevier.com/solutions/scival/releases/topic-prominence-in-science and https://service.elsevier.com/app/answers/detail/a_id/28428/

[63] Klavans, R., & Boyack, K. W. (2017). Research portfolio analysis and topic prominence. *Journal of Informetrics, 11*(4), 1158–1174. https://doi.org/10.1016/j.joi.2017.10.002

Appendix C

Data sources and analytical platforms

Elsevier Fingerprint Engine®

Based on state-of-the-art Natural Language Processing (NLP) techniques, the Elsevier Fingerprint Engine is a back-end software system that extracts information from the unstructured text of scientific documents. It applies a domain-relevant thesaurus to each scientific publication to map text to semantic "fingerprints" or collections of weighted key concepts. By identifying and extracting new concepts, the Elsevier Fingerprint Engine can enrich each thesaurus and generate new vocabularies, so it continuously improves the insights it delivers to researchers and funding bodies. It can be used as a back-office processing component of applications or as a stand-alone service. See https://www.elsevier.com/solutions/elsevier-fingerprint-engine

Overton

Overton is the world's largest searchable index of policy documents, guidelines, think tank publications and working papers. Its database consists of more than 1.65 million policy documents, with data collected from 182 countries and over a thousand sources worldwide. These policy documents include white papers from international multilateral organizations, as well as guidelines from city councils, parliamentary transcripts and other classes of the so called "gray literature". Around half of these documents make citations to academic or scholarly publications. More than 2 million distinct journal-based publications are cited by at least one policy document in the database. See https://www.overton.io/

PatentSight

LexisNexis PatentSight is a powerful and easy-to-use analysis platform that provides quick answers that are accessible to both top management and intellectual property experts, as well as data experts in a wide array of application areas. The software and its underlying data enable the evaluation of companies and technologies, comprehensive analysis for strategic decision-making, as well as searching and viewing individual patents and all important patent details. PatentSight BI is praised for its intuitive usability, flexibility and powerful visualizations. PatentSight compiles bibliographic patent data from over 95 authorities worldwide (utilizing DOCDBN, the European Patent Office's master documentation database with worldwide coverage) and has the most comprehensive full-text patent data, with over 100 million patent documents in English, approximately 700 million drawings and illustrations of inventions, and nearly 100 million PDFs that are searchable (via OCR) and quickly downloadable. See https://www.patentsight.com/en/

PlumX

PlumX Metrics provide insights into the ways people interact with individual pieces of research output in the online environment. Examples include research being mentioned in the news or tweeted about. These metrics are divided into five categories (citations, usage, captures, mentions, social media) to help make sense of the huge amounts of data involved and to enable analysis by comparing like with like. See https://plumanalytics.com/learn/about-metrics/

SciVal

SciVal is a web-based analytics solution with unparalleled flexibility that provides access to the research performance of over 20,000 academic, industry and government research institutions and their associated researchers, output and metrics. SciVal allows you to visualize your research performance, benchmark relative to peers, develop strategic partnerships, identify and analyze emerging research trends, and create uniquely tailored reports. See www.scival.com

Scopus

Scopus is Elsevier's expertly curated abstract and citation database with content from over 7,000 publishers to help track and enhance researcher and institutional data and discover global research in all fields. Scopus covers over 84 million items from more than 26,000 serial titles, 240,000+ books and 10.4 million+ conference papers connected through a robust data model including over 94,000 affiliation and 17 million author profiles. Scopus coverage is multilingual and global: approximately 46% of the titles in Scopus are published in languages other than English (or published in both English and another language). In addition, more than half of Scopus content originates from outside North America, representing countries across Europe, Latin America, Africa and the Asia-Pacific region. See www.scopus.com

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