Carbon Removal Technologies: Nature vs. Tech

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TUM CARBON REMOVAL INITIATIVE

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URGENT NEED FOR CARBON REMOVAL TECHNOLOGIES

After more than five years, the world seems to be as far out of reach of the Paris Agreement target as ever.

A recent study reported that while 64 countries successfully cut their emissions between 2016 – 2019, 150 countries saw an increase in emissions

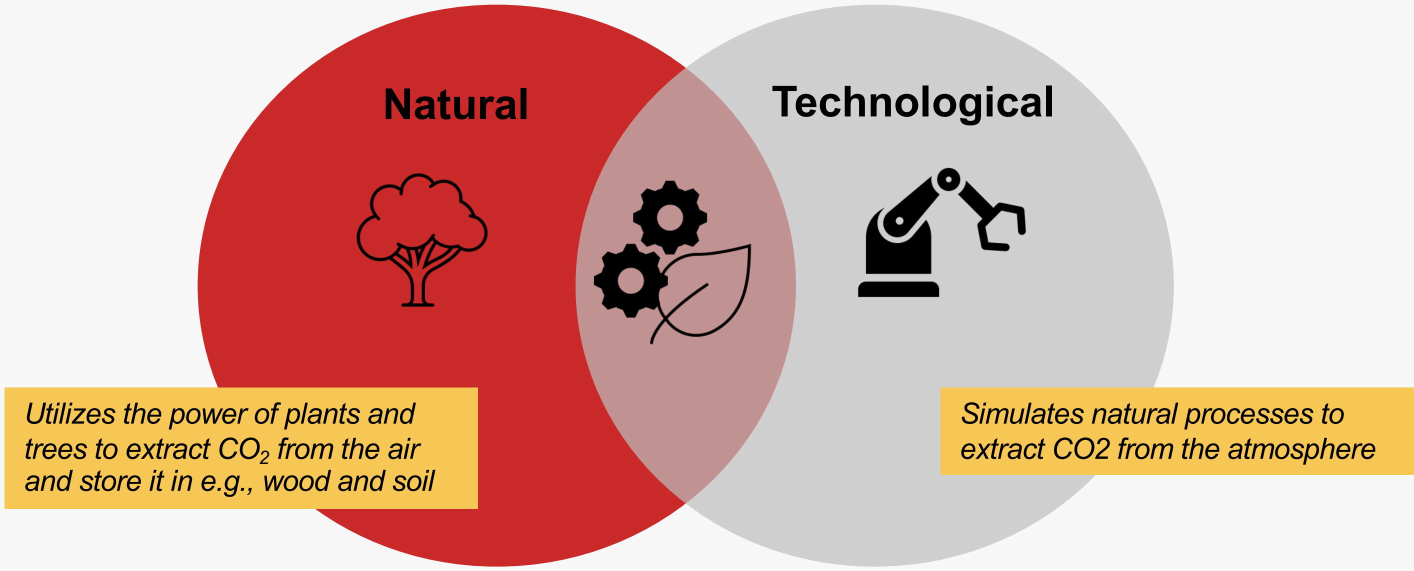
In 2021, the United Nations Secretary-general Antonio Guterres also called for the urgent need of a deep emission cut in order to counter the rebound of fossil emissions, a continuous rise of greenhouse gas concentrations, accelerating climate change and its impacts.

Even though the existing strategies for emission reduction (e.g., energy efficiency and the switch to renewable energy) are important, they have proven to be insufficient on their own to achieve the goals in the Paris Agreement and avert the climate catastrophes.

This gave rise to an increased interest and optimism **in carbon dioxide removal solutions (CDR)** to work alongside carbon emission reduction solutions.

CDR (or negative emissions or carbon drawdown) refers to the removal of carbon dioxide permanently from the atmosphere to be stored in geological, terrestrial or ocean reservoirs, or even in products.

CARBON REMOVAL TECHNOLOGIES



Natural

- Afforestation & Reforestation
- Soil Carbon Sequestration

Technological

- Bioenergy with Carbon Capture and Storage (BECCS)
- Direct Air Capture (DAC)
- Negative Emission Construction

Enhanced Natural Processes

- Biochar
- Ocean Fertilization
- Enhanced Mineralization

Natural:
Afforestation & Reforestation

Definition:

Afforestation: The planting of trees (growing a forest) on locations which have not been forested for quite a while.

Reforestation: The regrowing of trees or forests on land surfaces which have been depleted recently (e.g., deforestation or land use changes)

Carbon Removal:

According to the IPCC, Afforestation and Reforestation together have a potential to remove **0.5 – 10 GtCO2eq per year**. But this rate of carbon removal varies according to the age of trees, species composition, temperature, geology, precipitation, CO2 concentration and site history.

The **photosynthesis** process within forests removes CO_2 from the atmosphere for the time being, with a potential for the carbon to be stored in living biomasses for long periods of time.

Examples:

China's Billion Tree project; a large-scale reforestation effort led by Conservation International in the Amazonian rainforest; the Bonn Challenge aims to restore 350m ha of degraded land by 2030; ECCA30 in Europe; AFR100 in Africa; Initiative 20x20 in Latin America; Salesforce and MasterCard pledged 100m trees; Amazon earmarked US$100m for forests and wetlands; the Ontario Biodiversity Afforestation Project implemented between 2014 – 2016 which was established in 2014 and implemented over 2 years restored forest species on a previously agricultural land

Afforestation & Reforestation: Advantages vs. Disadvantages

Pros

- Promoting biodiversity of flora and fauna
- Improving soil health
- Controlling flood and erosion
- Benefitting Local Economy *(e.g., fuel wood and medicine supply)*
- Improving landholder and farmer profits
- Relatively low-cost

Cons

- Competing with other land uses (e.g., agriculture)
- Reversibility of carbon due to forest disturbance
- Forests reach maturity, unable to extract more carbon
- Albedo Effects: Dark forests absorb more heat (climate change)
- Vulnerability of monoculture plantations to reversal more than natural forests
- Introducing of non-native invasive species
- Faster tree growth, earlier death, and shorter carbon storage.

Natural:
Soil Carbon Sequestration (SCS)

Definition:

The extraction of carbon containing substances from the atmosphere, followed by its storage in soil carbon pools.

Carbon Removal:

The soil carbon pool is approximately 3.1 times larger than the size of the atmospheric pool of **800 Gt.** It has been estimated that soils have the potential to sequester around **2 – 5 $GtCO_2$/year**.

Organic Soil Carbon: Storage of Soil Organic Carbon (SOC) results from the interactions among the dynamic ecological processes of **photosynthesis**, **decomposition**, and **soil respiration**. SCS is primarily facilitated via the photosynthesis process of plants which stores carbon in the form of SOC.

- The higher the amount of organic matter (soil microbes and once-living organisms, e.g., plant and animal tissues) contained in soil, the higher the SOC levels.

Inorganic Soil Carbon: In arid and semi-arid climates, SCS can also be facilitated at a low rate via the conversion of CO2 from air found in soil into inorganic forms such as secondary carbonates.

There are different land management methods, particularly on farmland, to increase the carbon absorbed and stored in the soils.

- Minimization of soil disturbance via the switch to low-till or no-till practices (tilling releases stored carbon)
- Cultivation of perennial crops that do not die off every year, but grow deep roots to store more carbon
- Alteration of planting schedules or rotations, e.g., to plant cover crops or double crops instead of letting the land lie fallow, helping soil to absorb carbon
- Management of livestock grazing
- Adding compost or crop residues on the fields.

Examples:

Living Soils of the Americas (LiSAm) initiative; Carbon Farming landscape project supported by EIT Climate-KIC, 4 Per Thousand (4P1000) initiative, Platform on Climate Action in Americas (PLACA), Adapting African Agriculture (AAA), Mars Petcare collaborating with wheat suppliers to achieve better soil health and reduce farm-level emissions; Aigen employs solar powered robots to get ride of or cultivate plants; the Harnessing Plants Initiative is developing crops that can hold a greater amount of carbon in the ground over a longer time period.

Soil Carbon Sequestration (SCS): Advantages vs. Disadvantages

Improving Soil Health

Increasing Climate Resilience against drought and heavy rainfall

Reducing fertilizer use

Improving crop yields, and hence income for farmers

Saturation: Soils can only hold a finite amount of carbon.

Reversibility of Carbon due to soil disturbance

Forests reach maturity and ceases to absorb more carbon

Difficulty of measuring carbon removal via soil

Big social and economic challenge to bring all farmers on board

Climate change reduces the ability of soil to store carbon naturally

Enhanced Natural Processes: Ocean Fertilization

Definition:

A bio-geoengineering process whereby nutrients are added to the upper layers of the ocean to trigger phytoplankton activities to extract atmospheric CO_2.

Carbon Removal:

Phytoplanktons (e.g., diatoms, dinoflagellates, cyanobacteria and green algae) are tiny marine plants that constitute the foundation of the aquatic food web. They act as primary producers, generating energy through photosynthesis, extracting and storing atmospheric CO_2 and releasing O_2. This process makes up half of the photosynthesis on earth, and relies on nutrients like phosphate, iron, nitrate and calcium. Extra nutrients would stimulate a bloom of the phytoplanktons, taking up extra carbon.

This technology lies on the premise that as the planktons die, they sink to the bottom of the ocean floor, carrying with them the CO_2 that developed into new tissues via photosynthesis. To be sure, a large proportion of the CO_2 will be transported back to the surface via the upwelling process, nonetheless, a small amount remains on the ocean bed and will then be stored as sedimentary rocks in the long run.

There are two methods of adding growth-limiting nutrients into the ocean areas to promote phytoplankton growth:

- **Micronutrient fertilization:** iron etc.
- **Macronutrient fertilization:** nitrogen and phosphorus etc.

Examples:

Ocean Fertilization has generated many negative reactions: the United Nations, the United Nations Convention on Biological Diversity (CBD) and the London Convention on the Prevention of Marine Pollution imposed strict regulations on OF activities, which constitute de facto bans against all forms of commercial deployment.

16 open ocean fertilization experiments were conducted in the last 30 years, but they have all not been able to prove OF as an effective carbon storage solution.

LOHAFEX expedition in 2009; the Ocean Nourishment Corporation Pty Ltd (ONC); the Ocean Nourishment Foundation Ltd (ONF); the Haida Salmon Restoration Corporation (HSRC)

Ocean Fertilization:
Advantages vs. Disadvantages

- Causing unpredictable ecological problems (e.g., disruption of marine food chain or eutrophication)
- Low effectiveness in carbon sequestration
- Producing worse greenhouse gases (e.g., nitrous oxide and methane)
- Affecting livelihood of fishing communities
- Lack of studies

Enhanced Natural Processes: Biochar

Definition: Organic matter (agricultural waste like corn husks, stems, leaves etc.) undergoes Pyrolysis (low-oxygen heating process) to thermochemically break down into biochar, a concentrated carbon skeleton that resists decay. Biochar is a black, fine-grain, pulverised and porous charcoal-like compound. While it looks like charcoal and both are produced in the same way, charcoal is derived from wood, not agricultural wastes.

Carbon Removal: It is estimated that biochar has the potential to remove 1.1 to 3.3 giga tonnes of CO_2 per year by 2030.

At the start, the living crops capture CO_2 during photosynthesis to make biomass. And as the crops turn into waste, they can be utilized as biomass feedstock. Biomass feedstock then undergoes pyrolysis to form biochar. This step is crucial as it avoided the decomposition of wastes, and hence prevented the generation of additional new CO_2 in the atmosphere. Finally, the biochar is added into the soil, CO_2 is sequestered and unable to escape into the surroundings. Therefore, the whole process is carbon negative.

Examples: Ecoera, Biorestorative Ideas, Emergent Waste Solutions, Arti Products. Rogue Biochar, Ekovilla, Novocarbo, etc.

Biochar:
Advantages vs. Disadvantages

Pros

- Improving Soil Health by absorbing more moisture and nutrients, and resisting drought.
- Reducing soil's nitrous oxide emission with a high global warming potential
- Repurposing land for biochar displaces workers and food supplies
- Introducing fauna disrupts the ecosystem
- The simultaneous emission of gas and oil can be further combusted to generate renewable energy
- CH_4 emission from the anaerobic decomposition of organic matter is avoided when pyrolysis takes place instead.

Cons

- The only reasonably priced large-scale solution
- Reversibility of Carbon due to soil disturbance
- Expensive and low availability of pyrolysis facilities.
- Difficulty in verifying and monitoring storage permanence

Enhanced Natural Processes: Enhanced Mineralization

Definition:

Different methods of accelerating the slow natural mineralization processes – i.e. absorption of atmospheric CO2 by different minerals (e.g., olivine or basalt), followed by conversion into rocks and providing long term carbon storage.

Carbon Removal:

Estimated to have a potential of capturing 2 – 4 bn tons of CO2 per year by 2050.

1. In-situ: Injecting carbon-rich liquids underground to react with existing rocks, and transforming into rocks
2. Ex-situ: Reactive rocks are delivered to a CO2 source (e.g., industrial facility) and are being grinded and react with captured or ambient CO2 in high pressure and/or temperature reactors.
3. Surficial: Exposure of the fine grain particles of the rock to CO2 generated by powerplants or direct-air-capture plants. Carried out at places where the rocks are found (e.g., mine tailings or alkaline industrial waste sites) or in distal settings (e.g., scattered along beaches).

Examples:

greenSand Olivine, CarbonCure, Seachange, Future Forest, Blue Planet and Carbon8 Systems, Solidia and CarbonCure, Carbfix

Enhanced Mineralization: Advantages vs. Disadvantages

Pros

Cons

Improving Soil Health via nutrient enhancement from the added minerals

Trapping of CO_2 and de-acidifying the ocean (important for ocean life) due to mineralized carbon traps CO_2 and de-acidifies the ocean

Improving economic viability via creation of products: Job creation, GDP improvement and Innovation enhancement

Does not require its own land, nutrients or freshwater

Extensive mining and processing of raw materials threaten the ecosystem and human health and safety.

Potential threat of heavy metals leakage from the powdered rock into soils or groundwater.

An accelerated and unrestricted change in PH, carbonate saturation state etc. can affect ocean ecosystems

Mining, grinding and transporting of materials are energy intensive processes, which may be emission heavy depending on energy source

Technological: Direct Air Capture (DAC)

Definition:

While CCS captures CO2 from the point sources of CO2, especially those industrial and energy related sources like the chimneys of steel factories, DAC uses mechanical systems to capture CO2 directly from the ambient air,

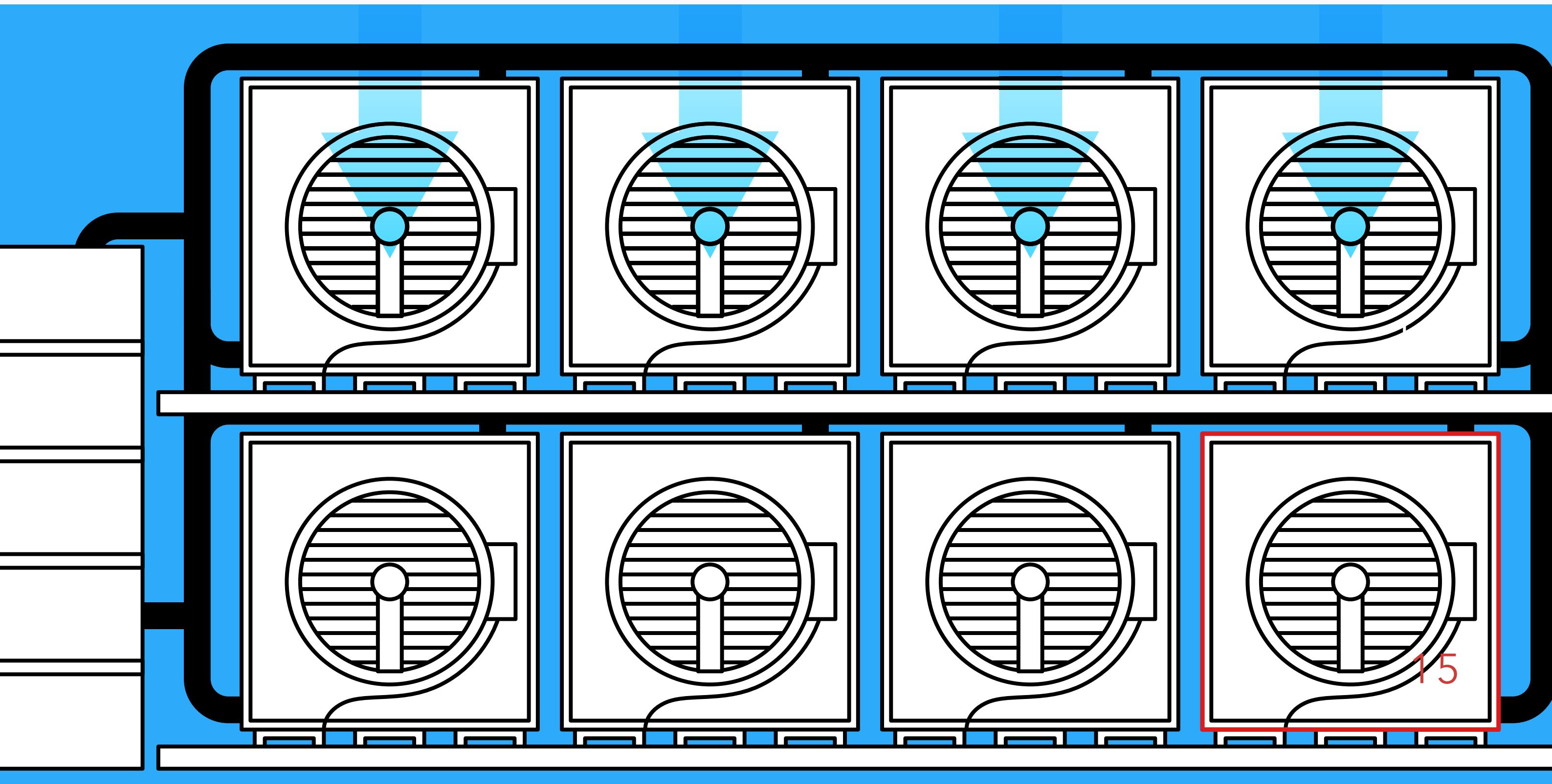
Carbon Removal:

Today, according to the International Energy Forum, 19 DAC plants operate across the world, mostly situated in Canada, Europe and the United States (US), capturing 0.01 MtCO2 annually.

DAC commonly relies on liquid solvent or solid sorbents to extract and trap CO2 from the atmosphere via chemical reactions. In most cases, heat is applied to release the solvent or sorbent for the next cycles of capture. Thereafter, the captured CO2 will be injected deep underground to undergo sequestration in geological formations or to be utilized in different products and purposes.

Examples:

Today, according to the International Energy Forum, 19 DAC plants operate across the world. The industry is dominated by only three companies who own 18 of the 19 existing DAC plants: Climeworks, Global Thermostat and Carbon Engineering



Direct Air Capture (DAC): Advantages vs. Disadvantages

Pros

- The generated CO_2 can be further used to produce long-lasting products (e.g., low-cabon cement)
- Deployable in a large range of locations, reducing infrastructural costs and non-renewable energy production methods
- Low land-use requirement

Cons

- A large amount of energy required for the the material production and the heating of the solvent and sorbent materials for reuse.
- In the case where CO_2 is transported and injected into geologic reservoirs, there are problems of pipelines, CO_2 leakage, water pollution etc.
- Much more expensive as compared to other CDR technologies
- In cases where captured CO_2 is injected into declining oil wells to grow output, it controversially supports the fossil fuel industry

Technological: Bioenergy and Carbon Capture and Storage (BECCS)

Definition:

Biomass (e.g., trees, crops or residues) acts as an energy source. During the process of biomass conversion into energy, CO_2 emissions are captured and stored permanently.

Carbon Removal:

Today, there exists five BECCS facilities worldwide to capture approximately 1.5 million tonnes of CO_2 per year. According to the estimations, BECCS has a potential to sequester 0.5 – 5 billion metric tons of CO_2 per year in 2050.

BECCS removes carbon via 2 methods:

1. **Combustion:** Biomass acts as a fuel source and is transformed into heat, electricity or liquid or gas fuels, to be used in electricity generation or waste incineration etc. The accompanying CO_2 emissions can then be captured from the flue gas stream generated during combustion to be sequestered or stored underground in geological formations.
2. **Conversion** of biomass via either digestion or fermentation processes to generate gaseous or liquid fuels. E.g., bioethanol undergoes fermentation to produce pure CO_2. The CO_2 is subsequently compressed and stored, without capturing. A further combustion of the biofuel or gas can also generate CO_2 for storage.

Examples:

Illinois Industrial Carbon Capture Storage Facility (only large scale BECCS); Tate & Lyle and Archer Daniels Midland (ADM); 200,000 tpa of CO_2 compressed and piped from an ethanol plant in Kansas to Booker and Farnsworth Oil Units in Texas for enhanced oil recovery (EOR); 100,000 tpa of CO_2 compressed and piped from an ethanol plant in Kansas to nearby Stewart Oil field for EOR; CMCL Innovations and Techno-Economic Study of Biomass to CCS conducted the largest and comprehensive techno-economic assessment of BECCS.

Bioenergy and Carbon Capture and Storage (BECCS): Advantages vs. Disadvantages

Pros	Cons
Generating Energy	Threatens food security, causing food prices to rise
Low cost	Displacement of communities for land conversion. Loss of livelihoods, human rights and social identity.
	Biodiversity loss due to the conversion of land for cultivating biomass which disrupts habitats
	Cultivating biomass raises the demand for water
	Increased application of fertilizer for cultivating biomass causes greater stress on nitrogen saturated ecosystems.
	Land conversion for biomass cultivation may cause the leakage of the carbon stored in soils or existing biomass
	Biomass and biofuel combustion causes local air pollution
	In the case where CO2 is injected into geological reservoirs may result in CO2 leakage, seismic activity and water pollution.
	Lower effectiveness as compared to other Carbon Removal Technologies

Technological:
Negative Emissions Construction

Definition:

The construction sector presents an abundance of opportunities for carbon removal via negative emission concrete (made of oxide and carbonate reactions) and potentially negative emissions timber, bamboo or straws etc.

Carbon Removal:

Avoid new emissions: The use of specialized wood products like cross-laminated timber, laminated veneer lumber and glue laminated timber etc. for building construction, e.g., wood panels and beams, helps to replace carbon emission intensive materials like steel, concrete and masonry. As a result, the 'embodied carbon' in buildings is minimized.

Provides CO_2 storage: At the same time, the wood acts as a carbon storage, holding the carbon dioxide which was sequestered during photosynthesis by the plants and trees. To be sure, this is only so when the timbers are produced sustainably. Depending on the lifespan of the product, the carbon storage can be for several decades.

Also, harvesting timber from mature forest gives up new spaces for planting new trees, and hence, increases the uptake of carbon by the forest.

Other approaches to building with wood may be able to sequester carbon, as well, including in low-rise buildings.

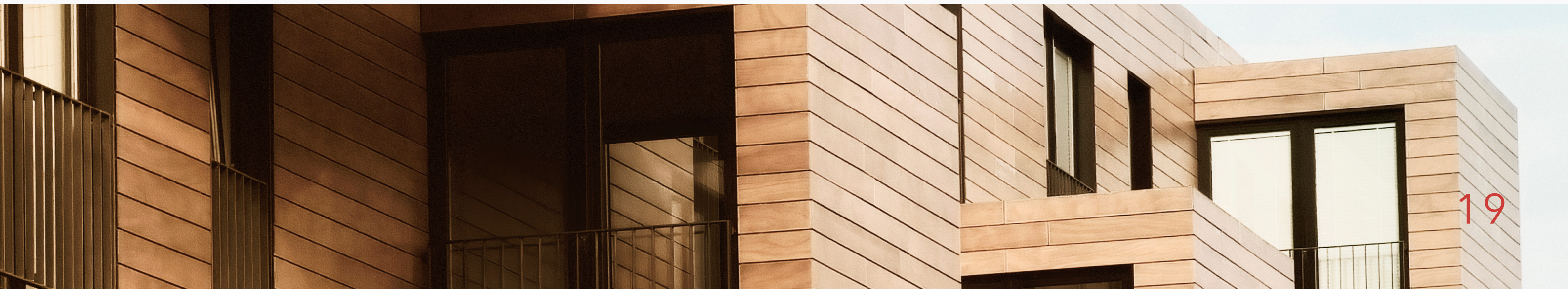
Concretes are produced by mixing large aggregates (stones), small aggregates (e.g., sand) cement and water. The problem is that cement production generates about 5% of the global CO_2 emissions. By changing the constituents, manufacturing or recycling methods of concrete, we can decarbonize concrete and increase the CO_2 storage in the built environment.

1. Replacement of aggregate with mineral carbonation products
2. Carbonation curing: Curing and ageing cement helps to recapture a portion of the CO_2 released during its production. This process can be accelerated with streams of CO_2, strengthening the material at the same time.
3. Alternative cement production: use of magnesium oxide produced from silicate minerals and magnesium carbonates to minimise CO_2 emission. Furthermore, cement can be produced from limestone to sequester CO_2, helping to minimise emissions.

Examples:

There has been an increase in wooden buildings and bridges, e.g., an 18 storey building of the University of British Columbia

Carbon8, Solidia Technologies; Novacem; Origen Power; CarbonCure



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Negative Emissions Construction: Advantages vs. Disadvantages

Pros

Mass timber construction is more cost effective

Mass timber is more energy efficient

Mass timber construction using prefabricated wood panels is faster

Engineered mass timber products are disaster resistant (e.g., fire resistant)

Cons

Increase in demand for timber could drive deforestation

Some timber industries abuse human rights (e.g., child labour and loss of indigenous communities' rights)

Problems of timber durability (e.g., insect and fungal attacks)

Negative environmental impacts and higher energy cost due to the mining, processing, grinding and transport of aggregates for mineral carbonation

Lower Quality of aggregates produced by carbonation

Low acceptance of low carbon cements by customers and producers

Carbon Removal Technologies:

Technology Readiness vs. Cost vs. Global CO2 Removal Potential

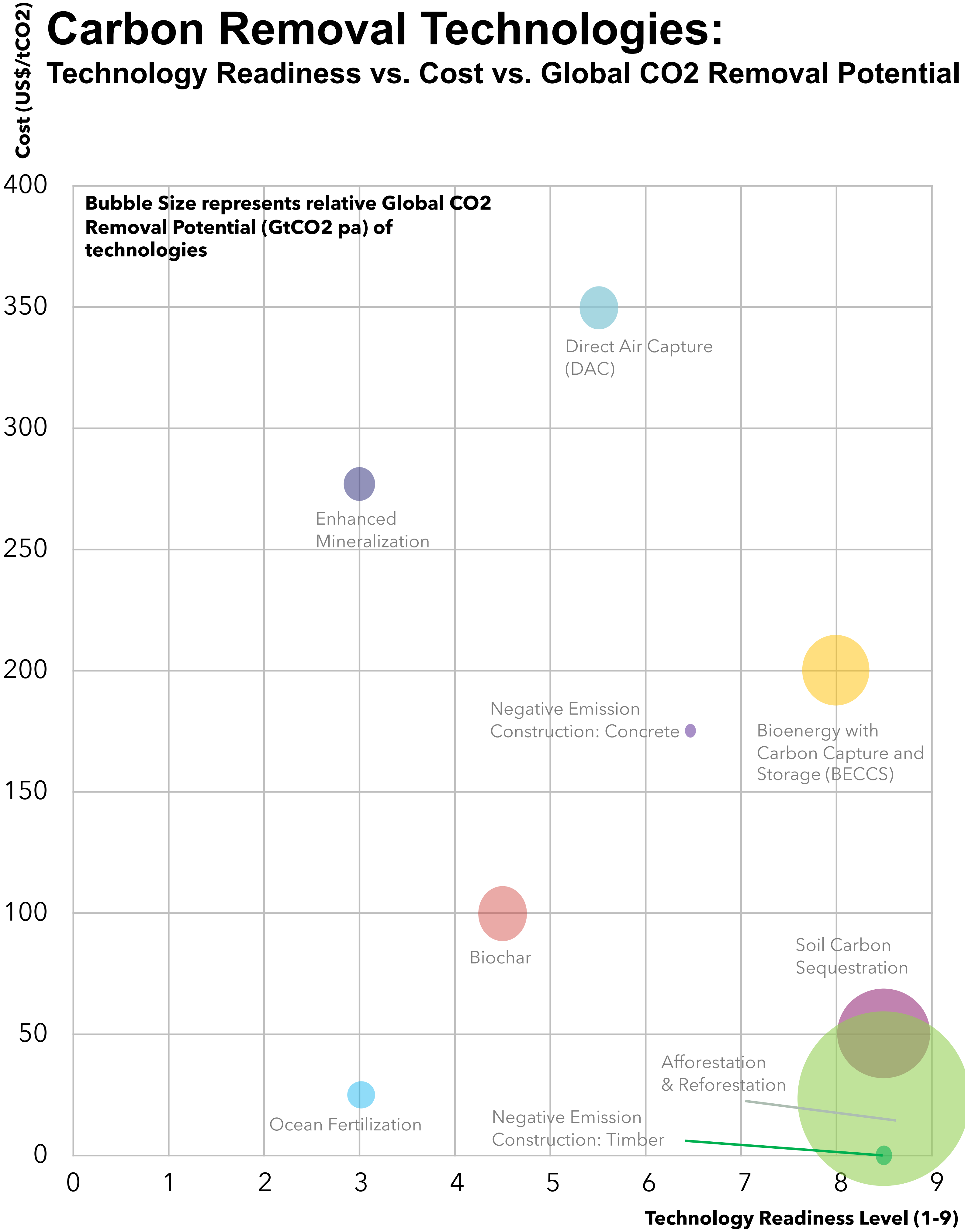
	Technology Readiness Level	Cost (US$/tCO2)	Global CO2 Removal Potential (GtCO2 pa)
Afforestation & Reforestation	8 - 9	3 - 30	3 - 20
Soil Carbon Sequestration	8 - 9	0 - 100	1 - 10
Bioenergy with Carbon Capture and Storage (BECCS)	7 - 9	100 - 300	10
Direct Air Capture (DAC)	4 - 7	100 - 600	0.5 - 5
Biochar	3 - 6	0 - 200	2 - 5
Ocean Fertilization	1 - 5	10 - 500	1 - 3
Enhanced Mineralization	1 - 5	50 - 500	0.5 - 4
Negative Emissions Construction	Timber: 8 - 9 Concrete: 6 - 7	Timber: 0 Concrete: 50 - 300	Timber: 0.5 - 1 Concrete: 0.1

Technology Readiness Level characterizes technology maturity using a 9 point scale, starting from the most basic research (TRL1), invention and research (TRL2), proof of concept (TRL3), bench scale research (TRL4), pilot scale (TRL5), large scale (TRL6), inactive commissioning (TRL7), active commissioning (TRL8), and operations (TRL9) .

Note: This chart is developed with different assumptions and predictions, and hence, may not be directly comparable.

Carbon Removal Technologies:

Technology Readiness vs. Cost vs. Global CO2 Removal Potential



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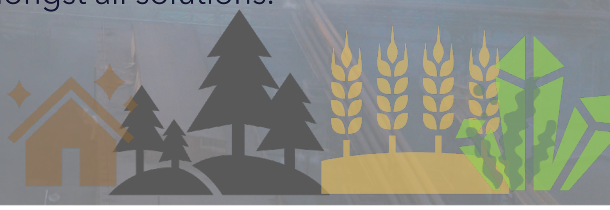
Note: This chart is developed with different assumptions and predictions, and hence, may not be directly comparable.

Conclusion

Amongst all the carbon removal solutions, we can see that **Afforestation and Reforestation is the most competitive** in terms of technology readiness, cost and global CO2 removal potential. The high performance of Afforestation and Reforestation aligns with the general public's preference for natural solutions. And while **Negative Emission Construction Timber** may be competitive in terms of technology readiness and cost, **it does not perform well in terms of global CO2 removal potential**. On the other end, it seems that **DAC** may **not be a competitive solution**, with a low technology readiness between 4-7, below average in terms of global CO2 removal potential, and having the highest cost amongst all solutions.



Nature-based solutions (Afforestation & Reforestation and Soil Carbon Sequestration) are effective solutions to help reduce climate change, and at the same time, they protect biodiversity via the conservation and expansion of ecosystems, preventing the loss of habitat. However, there lies the risk of reversibility, whereby the carbon is stored in biomass which are less permanent, and the captured carbon runs the risk of being released back into the atmosphere via e.g., wildfires, land-use change and land management, or via climate change itself. Furthermore, nature-based solutions are saturable, i.e., each hectare of forest land or soil can only sequester a certain amount of carbon. Worst of all, nature-based solution tend to result in competition for resources amongst one another, and with other priorities like food production.

Therefore, while nature-based solutions can help to ameliorate climate change, they are insufficient to solve climate change alone. They have to work with other technologies, like DAC with the potential of GHG emission rapid cuts, and enhanced natural processes, like ocean fertilization and biochar. These nature-based solutions should be implemented early on, and once it gets saturated after some time, other carbon removal solutions, e.g., DAC, which would have developed to be more competitive in the future, can come into play and take up more important roles.

Another problem is that the implementation of these carbon removal solutions is dependent upon resource availability (raw materials, energy, water etc.), and they may even compete with one another for the limited resources. For instance, BECCS and Biochar rely on biomass feedstock; BECCS and Afforestation and Reforestation require land; Enhanced Mineralization needs minerals - extensive mining and processing of raw materials may threaten the ecosystem; afforestation and reforestation, soil carbon sequestration, BECCS and ocean fertilization rely heavily on fertilizers; enhanced mineralization requires heavy mining and hence, is energy intensive; and DAC requires energy to operate the fans or heat supply to regenerate carbon medium. **In other words, it is important to choose and balance amongst the different carbon removal solutions depending on resource availability.**

Lastly, regardless of the solutions, we must exercise caution to avoid having the perception that we can emit more CO2 today just because we can remove the carbon tomorrow. Large scale carbon removal is challenging and expensive. Hence, **we must continue to work on cutting greenhouse gas emissions or adapting to climate change.**

Many studies have argued for policymakers and governments to develop policy instruments and support frameworks with an emphasis on carbon pricing or other tools, in order to overcome the cost and incentivize carbon removal. At the same time, the financial industry can further offer financial support or market-based mechanisms etc. to drive carbon removal projects. In addition to that, the government should integrate carbon removal into regulatory frameworks and carbon trading systems, e.g., soil carbon sequestration to be embedded into agricultural subsidies.

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