Scaling Carbon Removal

A Climate Technology White Paper

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Carbon removal: an introduction

Introduction

Scaling long-term carbon removal

In this paper, we outline the key strategies for scaling long-term carbon removal. Specifically, we analyze technology innovations and the early-stage companies developing them. The paper contains the following sections:

1. **Synthetic carbon removal:** How can we develop totally novel carbon capture mechanisms to reduce levels of atmospheric carbon? (Pages 9-18)
2. **Land-based carbon removal:** How can we leverage the earth's soil and vegetation to reduce levels of atmospheric carbon? (Pages 19-27)
3. **Ocean-based carbon removal:** How can we leverage the earth's water cycle and oceans to reduce levels of atmospheric carbon? (Pages 28-37)

This paper provides data and context on each type of carbon removal, evaluates proposed innovation in the field and suggests ways to overcome potential challenges. In the introduction, we explain why the challenge of carbon removal is important and unsolved, and what makes a good technology. We then highlight 5 startups that are leading the charge in these areas.

BNEF Pioneers: hunting for innovation

This is one of three reports to be published following the 2022 BNEF Pioneers awards.

BloombergNEF's annual Pioneers competition identifies and recognizes innovators developing new technologies to tackle some of the most important challenges in the fight against climate change.

Each year, the Pioneers competition focuses on three innovation challenges.

For the 2022 program the challenges were:

1. Providing round-the-clock zero-emissions power (research note available here)
2. **Scaling long-term carbon removal (the focus of this research note)**
3. Decarbonizing aviation (research note available here)

For more information about the Pioneers competition, please visit https://about.bnef.com/bnefpioneers/

Why did BNEF choose carbon removal as a challenge for this year's Pioneers?

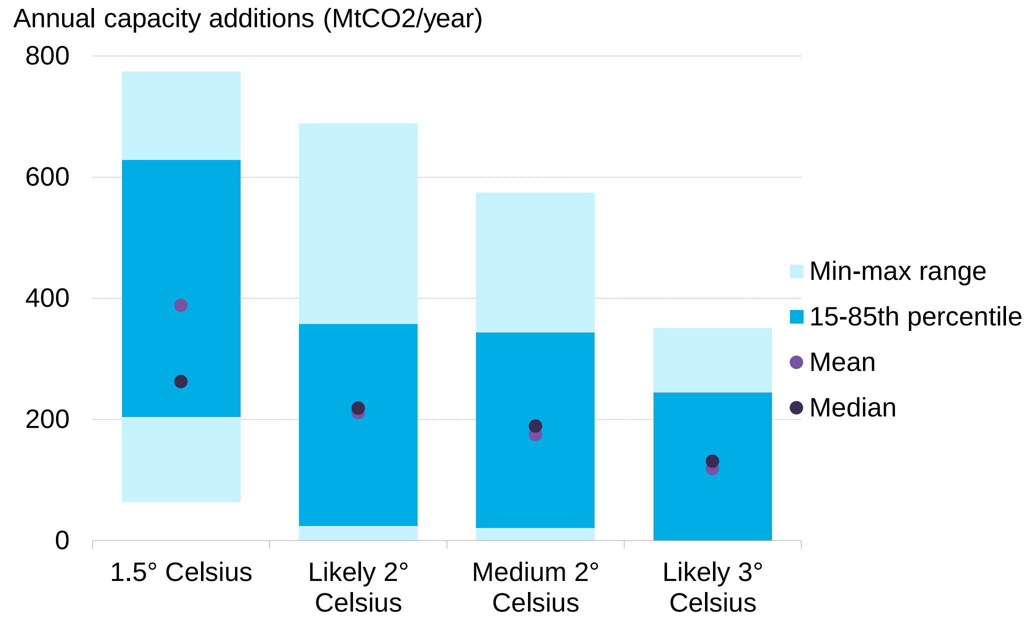
Meeting net-zero targets will first and foremost require rapid and deep emissions reductions. But it is becoming increasingly clear that removing carbon dioxide from the atmosphere will also be needed to avoid global warming above 1.5°C.

Calculations of how much removal is required vary dramatically. Integrated assessment models estimate that anywhere from 1.5-15.5 gigatons of CO_2 ($GtCO_2$) in additional removal capacity could be deployed between 2030-2050 in order to meet 1.5°C warming targets.

BNEF estimates that demand for carbon offsets could reach 3.4-5.2 $GtCO_2$ equivalent per annum by 2050. At an estimated cost of $47-120 paid per metric ton, this translates to a market size of $160-624 billion annually. This market would be equivalent in value to the GDP of Austria, or 0.5% of the global economy. Former Bank of England Governor Mark Carney has called for a $100 billion per year voluntary offset market.

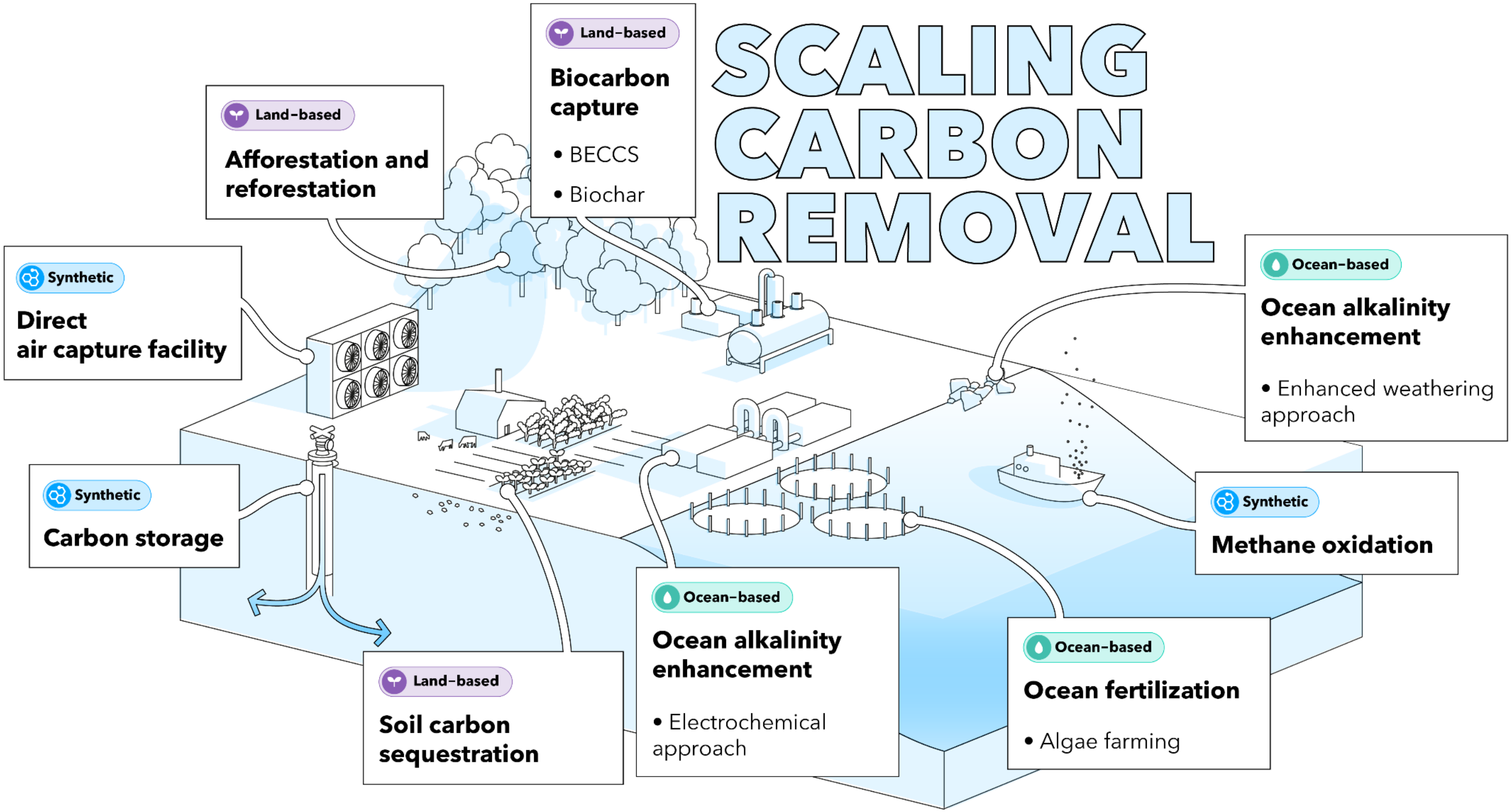
While it is clear carbon removal is necessary, there are many technologies that could potentially serve this demand, all with various advantages and disadvantages. This report highlights key technology routes for scaling long-term carbon removal and a collection of the most important technology developers working on them. Because of the sheer scale of carbon removal that will be needed, which technologies emerge as leaders will have important implications for both the environment and the economy.

Estimated annual deployment of additional BECCS capacity, 2030-2050



Source: BloombergNEF, Negative emissions – Part 3: Innovation and upscaling. Note: 'BECCS' refers to bioenergy with carbon capture and storage. The above estimates come from a variety of integrated assessment models (IAMs). IAMs have historically tended to use BECCS as the main carbon removal technology as it was until recently considered the most scalable source of negative emissions. 'Likely' means that there is a 66% chance of meeting the warming target described. 'Medium' translates to a 50% chance.

Overview of technologies covered in this note



Source: BloombergNEF

Innovation map of carbon removal technologies

Synthetic carbon removal

Direct air capture

Liquid solvent
- Mission Zero Technologies
- Carbon Engineering

Solid adsorption
- climeworks
- CarbonCapture
- noya
- Global Thermostat
- Sustaera

Other
- RedoxNRG
- INFINITREE
- VERDOX
- Heirloom
- REPAIR CO₂ CAPTURE
- carbyon
- Calcite Carbon Removal

Carbon storage
- Carbfix
- 44.01

Methane oxidation
- Blue Dot Change – Helping nature repair the climate
- zelp

Land-based carbon removal

Afforestation and reforestation

Robotics
- AirForestry
- drone seed
- dendra systems

Photosynthetic enhancement
- RIPE
- Living Carbon

Soil carbon sequestration
- CarbonCount
- YARD STICK Soil Carbon Revealed
- Grassroots Carbon
- Nori
- loam
- HONE CARBON
- Perennial
- indigo

Biocarbon sequestration

Pyrolysis
- CARBOFEX
- Climate Robotics
- CHARM Industrial
- carbo culture
- Standard Gas
- TAKACHAR
- ECOERA
- net zero

BECCS
- Biorecro
- drax
- mote

- Inter Earth
- Carbon Sequestration Inc

Ocean-based carbon removal

Ocean fertilization
- Brilliant Planet
- RUNNING TIDE

Enhanced weathering

Coastal
- PROJECT VESTA
- Cquestr8

Terrestrial
- Eion
- the future forest company
- greenSand
- CO2-ZERO
- RockFarm

Electrochemical

Electrochemical ocean alkalinity enhancement
- PLANETARY
- HEIMDAL
- ebb carbon

Direct ocean capture
- SEACHANGE

Source: BloombergNEF

What makes a good carbon removal technology?

The table below scores the carbon removal solutions described in this note across the following metrics:

Maturity: Technologies covered in this note go all the way from laboratory-scale projects (such as methane oxidation) to multi-billion dollar industries (such as forestry offsets)

Scalability: As mentioned previously, the enormous scale that will likely be required means carbon removal solutions will be constrained by limited resources – for example, land availability.

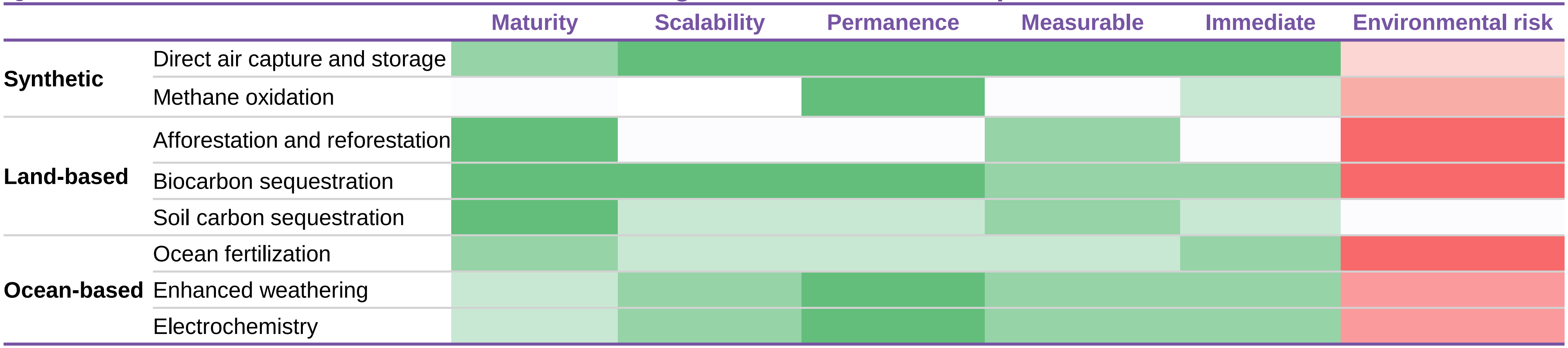
Permanence: Some carbon removal solutions, notably soil and forestry projects, only store carbon for decades. If the carbon stored now re-enters the atmosphere within decades it will continue to warm the planet. Carbon needs to be stored for at least a century, and preferably longer.

Measurable: In order to ensure that society is removing the correct amount of carbon, removal should be measurable. Some solutions produce 99% pure streams of CO_2, so are easy to measure. Others (mostly nature-based) will require complex monitoring systems that rely on new sensing and computational technology.

Immediate: Not all carbon removal credits are created equal. A ton of carbon stored in a forestry credit will take years to be absorbed into the forest. In the meantime, the carbon that has yet to be absorbed will continue to warm the planet. A direct air capture plant, on the other hand, removes carbon from the atmosphere instantly.

Environmental risk: Beyond just land use, all carbon removal strategies carry some level of environmental risk. These industries could produce their own pollutants, disrupt food webs, or more.

Qualitative evaluation of carbon removal technologies described in this report



Source: BloombergNEF. Note: Darker green indicate the solution performs better on this metric. Darker red indicates the solution carries greater environmental risk. Ratings are qualitative relative to others. Direct air capture does carry environmental risk, but less than the other solutions described in this table.

BNEF Pioneers 2022 winners

Challenge 2: Scaling long-term carbon removal technologies

Carbfix

Carbfix captures CO_2 and turns it into stone underground in less than two years.

Climate Robotics

Climate Robotics develops agricultural implements to produce biochar – a soil amendment that improves soil health while sequestering carbon.

VERDOX

Verdox's technology removes CO2 from industrial emissions and the air, and the company says its process uses 70% less energy than conventional approaches.

For more information on this year's winners, please see *Climate-Tech Startups to Watch in 2022: BNEF Pioneers Winners*

Synthetic carbon removal

Synthetic carbon removal

Direct air capture has the least risk associated with any carbon removal strategy because it is immediate, measurable, allows for permanent storage and has minimal ecosystem impacts. Investors have funnelled $1.2 billion into the technology since 2018 in the hopes of driving costs below $100 per ton of CO_2. Innovation in carbon storage and utilization technologies is less active but a vital component in scaling the industry.

What is it?

Synthetic carbon removal strategies are those where the carbon removal process does not involve the disruption of the 'fast carbon cycle' – the natural carbon flow into or out of the soil, vegetation or oceans. Synthetic carbon removal technologies include direct air capture, carbon utilization* and storage, and very early-stage methane oxidation – the conversion of methane to CO_2, which has a lower warming impact.

What should we tackle first?

The most important technology category in synthetic carbon removal by far is direct air capture (DAC). It is the least risky of all carbon removal technologies because it is immediate, measurable, allows for permanent storage and, compared with land- and ocean-based solutions, has minimal ecosystem impacts. If costs can be brought down to below $100/tCO_2$, DAC will likely be the carbon removal solution of choice. This fact is not lost on investors, who have ploughed more than $813 million of funding into DAC startups since the beginning of 2022. Reducing the energy intensity of DAC and improving the durability and performance of sorbents are the key priorities for lowering the cost of DAC.

Carbon storage costs at most $30/tCO_2$, only a fraction of the hundreds of dollars that carbon capture costs. Innovation in storage, therefore, mostly relates to improving the security of storage to avoid the risk of leaks and reducing long-term monitoring requirements.

**Note: Carbon utilization will likely be a vital store of carbon and could provide an important revenue stream for direct air capture projects. It is not covered in this report because BNEF has already examined it here: Advancing Sustainable Materials: A Climate Technology White Paper.*

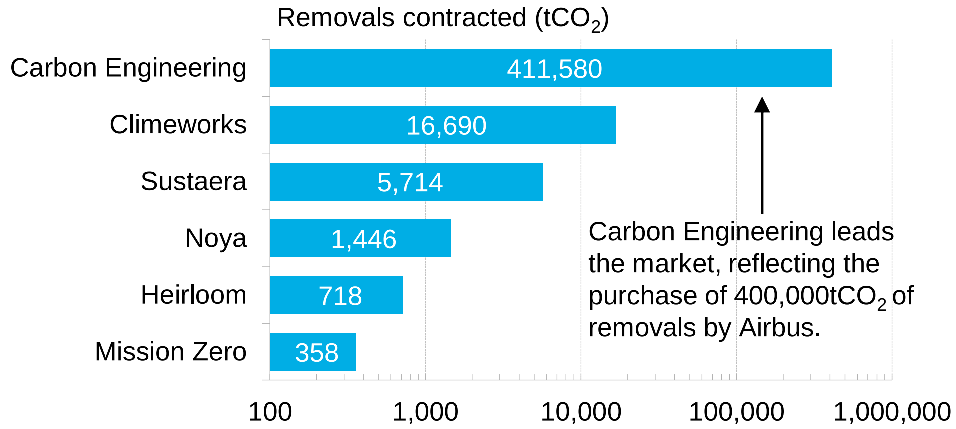
This section also discusses the nascent field of methane oxidation, which could grow in significance as mitigation efforts focus on the rising importance of methane as a greenhouse gas – particularly in the short run.

What is difficult about synthetic removal?

Synthetic carbon removal is currently difficult because it is very expensive, especially compared with the low-quality forestry and renewable energy offsets that dominate voluntary markets. Today's cheapest DAC offsets cost in the order of $250-600/tCO_2$.

The operational costs of DAC are dominated by the energy that is required to strip CO_2 from the materials that absorb it from the atmosphere. Capital costs are also high, particularly as the industry is so early stage. A lot of the equipment must be custom built for pilot projects, and many of the vital materials are not yet produced at industrial scale.

Confirmed DAC removals agreed for purchase



Source: BloombergNEF, Marginalcarbon.com

Direct air capture

Direct air capture (DAC) works by bringing air into contact with a sorbent, a material that filters CO_2 from the air. Sorbents are 'regenerated' rather than being disposed of once they are saturated with CO_2. Regeneration involves exposing the sorbent to what is known as a 'swing cycle', where the temperature, pressure, moisture and/or electrical voltage on the sorbent is shifted, causing the CO_2 to be stripped from it. DAC technologies can be classed by the type of sorbent and associated swing cycle. DAC could be the carbon removal strategy of choice if costs can dip below $100/t$CO_2$, because it is immediate, permanent and measurable. But it currently carries a cost premium. Investments in more energy efficient, cheaper sorbents would drive down system costs. Totally novel swing cycles could also disrupt the industry.

New approaches and technologies

Two DAC approaches have been deployed, and dominate funding and research:

Liquid solvent absorption (L-DAC): These systems use alkaline solvents (such as sodium hydroxide, potassium hydroxide, or calcium hydroxide) to absorb CO_2. The most mature companies using liquid solvents have high-temperature requirements for regeneration, meaning natural gas must be burned during capture. New solvents are coming to market that address this.

Solid adsorption (S-DAC): These systems generally use amines (compounds derived from ammonia) as sorbents. Rather than being absorbed by a solution, CO_2 adsorbs (clings to the surface) of the solid material. S-DAC systems have lower temperature requirements (80-100°C) and so are easier to electrify. However, they are more energy intensive.

Novel technologies using electrochemistry and passive contactors are also being explored.

Limitations

Currently expensive: Carbon removal via DAC costs at least $600/t$CO_2$, among the most expensive carbon credits available.

Energy intensive: A huge share of DAC's cost is the energy required to regenerate sorbents. At current levels of energy intensity, if DAC were used to capture 1GtCO_2/year, it would account for around 1% of the world's final energy demand.

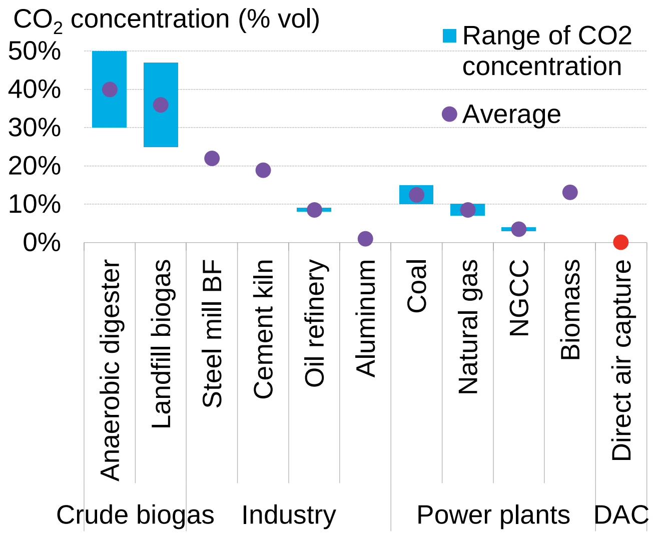
Environmental considerations: While potentially less damaging than nature-based solutions, any activity has externalities. L-DAC can consume a lot of water, while S-DAC can produce potentially harmful waste from its amine-based sorbents.

Potential solutions

Increase surface area per unit mass of sorbent: Increasing the surface area of materials reduces the amount of sorbent that must be purchased. It also improves the energy density of regeneration, as there is less non-surface area sorbent that acts as a heat sink during regeneration.

New sorbents: Lower cost sorbents with less energy-intensive regeneration processes would reduce the cost of DAC. Metal-organic frameworks have been proposed as one example of materials that could be useful as solid sorbents in DAC.

CO_2 concentration of gas sources



Source: BloombergNEF, Porous materials for carbon dioxide separations. Notes: NGCC = natural gas combined cycle, BF = blast furnace

Direct air capture

Liquid solvent (L-DAC)

How does it work?

Maturity

Carbon Engineering

Carbon Engineering's technology is referred to as calcium-oxide looping. The process uses a potassium hydroxide (KOH) solution to absorb CO_2 from the air, using fans to draw air into contact with the solution. The resulting potassium carbonate (K_2CO_3) is then reacted with a separate process loop involving calcium oxide, to transfer the CO_2. This regenerates the potassium hydroxide so it can absorb more CO_2. The calcium oxide loop produces calcium carbonate ($CaCO_3$) as an output, which can be heated up in a calciner unit (needing temperatures above 900°C) to strip the CO_2 and produce a pure stream of CO_2 and fresh calcium oxide. Carbon Engineering's process is distinguished by its use of natural gas and the high level of water consumption relative to other leading DAC providers.

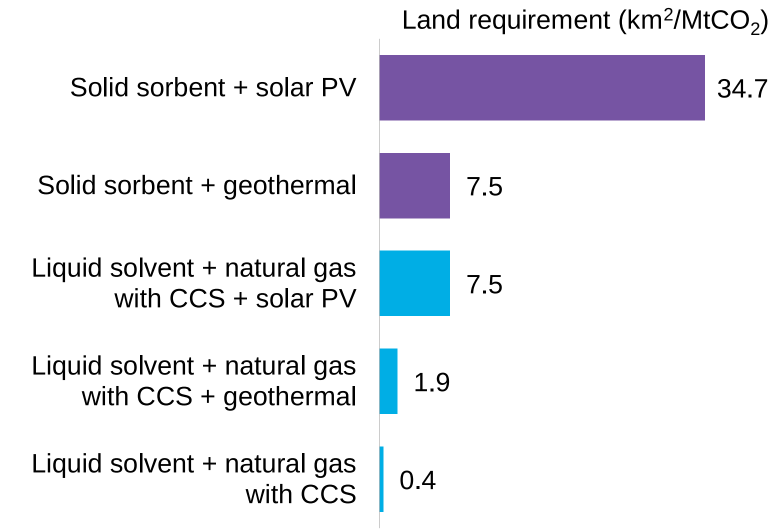
Carbon Engineering is a Canadian company. Founded in 2009, the startup commissioned its demonstration plant in 2015 with a capacity of 1tCO_2/day. In 2019, Carbon Engineering announced a partnership with Oxy Low Carbon Ventures to construct a capture plant. It was initially set to have a capacity of 0.5MtCO_2/year, but has since increased to 1MtCO_2/year. The project should be by the largest DAC plant by several orders of magnitude once it is commissioned in 2024 and aims to deliver carbon removal at a price of $200-250/t$CO_2$. In March 2022, Oxy Low Carbon Ventures announced it would sell 0.4MtCO_2 of offset credits over four years to Airbus using Carbon Engineering's technology. The company has raised a total of $102 million.

Mission Zero Technologies

Mission Zero Technologies' process uses an unnamed liquid solvent to capture CO_2 in a process that is similar to that of Carbon Engineering. Instead of using heat to regenerate the solvent, Mission Zero uses an electrochemical separation technology that it says is currently used at scale to produce clean drinking water. The process uses less than 1.8 gigajoules/tCO_2, making it less energy intensive than both Climeworks and Carbon Engineering's DAC processes, and it is fully electrified.

Mission Zero Technologies was founded in 2020 out of Deep Science Ventures – an accelerator group based in Imperial College London that recruits founder teams to address specific scientific challenges. The company has two major partners: O.C.O Technology (carbon utilization in aggregate) and 44.01 (a carbon storage developer). Mission Zero was chosen by Stripe as part of its carbon removal purchase program and offered its offsets at a price of $319/t$CO_2$. Mission Zero aims to build a plant with an annual capture capacity of more than 1,000tCO_2 by 3Q 2023. In May 2022, it announced it had raised $5 million from Breakthrough Energy Ventures and Anglo American.

Land area requirements of S-DAC versus L-DAC (by energy source)



Source: BloombergNEF, WRI. 'CCS' refers to carbon capture and storage.

Direct air capture

Solid adsorption (S-DAC)

How does it work?

Maturity

climeworks

Climeworks uses solid adsorption. First, air is drawn into collectors using fans, and the CO_2 is chemically bound to the sorbent, which is a solid amine housed in a cellulose fiber filter. Once the sorbent is saturated, the collector is closed and the temperature is increased to a range of 80-100ºC using low-grade heat and a temperature-vacuum swing cycle. Climeworks collectors are modular.

Climeworks is a Swiss company spun-out of ETH Zurich in 2009. It is the DAC market leader, alongside Carbon Engineering. Climeworks has commissioned at least three DAC plants with a cumulative capacity of 5,050tCO_2/year. Its largest plant, Orca, was commissioned in 2021. Orca is a 4,000tCO_2/year plant in Iceland that cost an estimated $10-15 million. In April 2022, Climeworks announced it had raised $650 million in unattributed venture capital, bringing its total funding to $793 million. It will use some of this funding to construct a 40,000tCO_2/year facility.

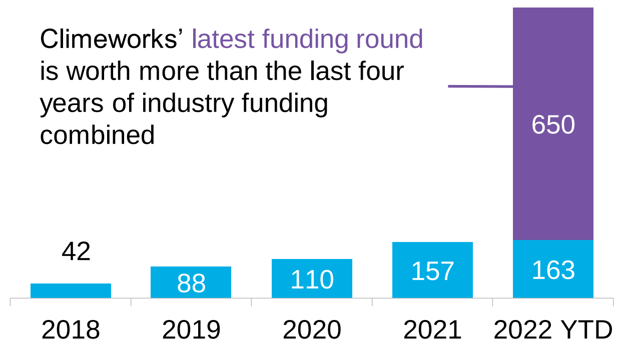
Global Thermostat

Global Thermostat has developed a proprietary amine-based adsorbent that is bonded to porous, honeycomb ceramic ‘monoliths’, acting as carbon sponges or filters. The sorbent regeneration process differs to Climeworks. The filters are moved and then regenerated with low-temperature steam.

Global Thermostat was founded in 2006, and the company says it has raised $70 million and has built two facilities so far. The first is a demonstration plant with a capture capacity of 1,000tCO_2/year. In 2018, it built a 4,000tCO_2/year plant. To date, the company has focused on selling its captured carbon for utilization. In April 2021, Bloomberg profiled the company, suggesting it had been paralyzed by mismanagement and had made little progress in the last decade. It also reported that Global Thermostat’s 4,000tCO_2/year facility was not running and that the contractor that constructed it had sued the company for $600,000 in unpaid bills.

Investment in DAC technologies

$ million



Source: BloombergNEF

CarbonCapture

CarbonCapture uses ‘molecular sieves’ to perform a solid adsorption capture process. The company has not published much publicly on its process. However, it did fund a research paper highlighting the suitability of “zinc-containing chabazite zeolites” as sorbents for low-concentration CO_2 capture processes, suggesting this is likely the technology route it is exploring. Zeolites are microporous aluminosilicate materials that are commonly used as commercial sorbents and catalysts.

Carbon Capture was founded in 2019 and has raised $35 million to date in a Series A round. Its team is experienced in building well-funded climate startups. Bill Gross co-founded the company. Two of his most high-profile past ventures include Energy Vault and Heliogen, both of which went public at billion-dollar valuations on less than $10 million of revenue. Adrian Corless – the former chief executive officer of Carbon Engineering – is the chief executive officer and chief technology officer of Carbon Capture. Energy Vault’s Chief Technology Officer Andrea Pedretti is also a co-founder of Carbon Capture.

Direct air capture

How does it work?

Maturity

Passive contactors

Heirloom

Heirloom's technology is similar to that of Carbon Engineering, in that it uses calcium oxide looping. It has two main distinctions: it has removed the potassium hydroxide solvent (KOH) and does not use fans to direct air flow, which account for 6.3% of energy demand in Carbon Engineering's process. Instead of reacting the calcium oxide loop with the potassium hydroxide solvent, Heirloom sets thin deposits of calcium hydroxide ($Ca(OH)_2$) out in trays where they are exposed to air. The $Ca(OH)_2$ captures the CO_2 in the air and forms calcium carbonate, which can then be calcinated in a high temperature reactor to strip the CO_2 from it, and regenerate fresh $Ca(OH)_2$ powder. The trays containing powder are modular and can be vertically stacked to reduce the footprint of plants. Heirloom's intellectual property (IP) is related to how it has accelerated the rate at which CO_2 reacts with the $Ca(OH)_2$ powder. It says that 86% of the powder turns to carbonate within three days of exposure.

Heirloom was founded in 2020 and has gained Stripe, Shopify and Klarna as customers for its future credits. It says its first commercial plant will aim to capture 100,000tCO_2. In March 2022, the company raised $53 million in a Series A round. In its purchase application to Stripe, Heirloom said it would commission its initial pilot plant in June 2021. However, after its series A, the company stated the funding would be used to build a pilot plant.

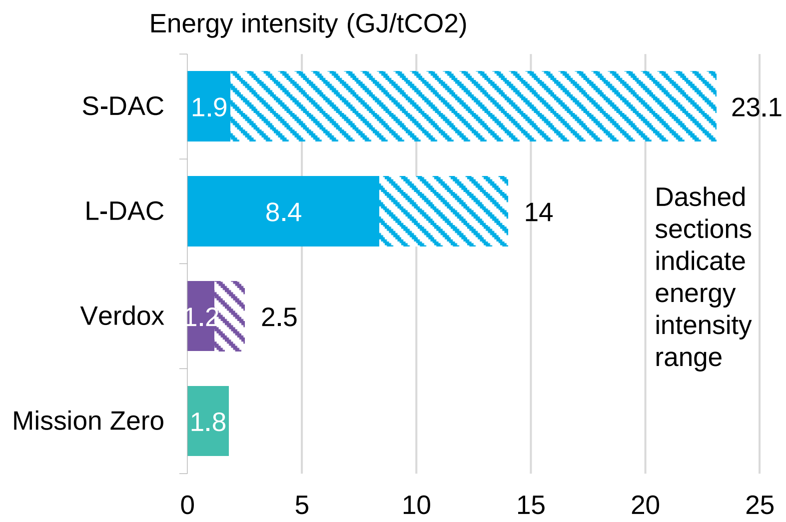
Electrochemical

VERDOX

Verdox is trying to reduce the energy intensity of carbon capture by relying on an 'electro-swing' cycle, rather than one based on temperature and pressure. Verdox has created an electrochemical cell where, by altering the voltage across the electrodes, one side of the cell gains an affinity for CO_2, causing CO_2 to cling to the electrode. It can then similarly discharge the CO_2 once the electrode is saturated. As well as being up to 70% less energy intensive than the most mature DAC processes, it is fully electrified. The process can also be used to capture CO_2 from low-concentration flue gases, such as aluminum.

The journal article upon which Verdox's process is based was published in October 2019 and the company was founded shortly thereafter. Momentum is gathering fast, with the announcement of an $80 million round of financing in 2021. Investors include Breakthrough Energy Ventures, Prelude Ventures and Lowercarbon Capital. It has also in the past been awarded grants from the US Advanced Research Projects Agency–Energy (ARPA-E). Some $20 million of its funding was provided by Norsk Hydro, which aims to apply the technology for point-source capture in its aluminium smelters.

Energy intensity of select DAC technologies



Source: BloombergNEF, Negative Emissions Technologies and Reliable Sequestration: A Research Agenda. Note: Verdox and Mission Zero claims taken from company presentations.

BNEF pioneers

Carbon storage

Carbon storage technologies are a critical enabler of direct air capture. Current practices rely on storing supercritical CO_2 in porous sedimentary rock formations beneath an impermeable caprock. While this is cheap, it requires monitoring to prevent leaks. In-situ carbon mineralization is a process where CO_2 is mixed with water to form a weak acid and then injected underground. This causes it to react with stray minerals and then carbonate (turn to stone). Carbon mineralization is more expensive than supercritical storage but eliminates virtually all risk of CO_2 leakage. Basalt and peridotite rock formations are the best candidates for mineralization. Studies show these two minerals could provide thousands of gigatons of carbon storage, enough capacity to meet demand.

New approaches and technologies

Storing supercritical CO_2 in porous sedimentary rock (saline aquifers or old oil and gas reservoirs), sealed by a non-porous caprock, is the most mature CO_2 storage practice, accounting for 99% of capacity.

In-situ mineralization: Carbon mineralization is the process of CO_2 reacting with stray cations in rocks (such as Ca^{2+}, Mg^{2+} and Fe^{2}) to form solid carbonate – in other words, stone. In-situ mineralization refers to the process where it happens in the subsurface. It is achieved by mixing CO_2 with water to form a weak carbonic acid. The acid is then injected into the subsurface where it reacts with the rock. Basalt and peridotite formations are the two main candidates for use in carbon mineralization. Mineralization eliminates the risk of any carbon leaking over time, as it has turned to stone. Carbon mineralization on surface rocks is referred to as ex-situ mineralization.

While the reaction is the same, ex-situ mineralization is often classified as carbon utilization rather than storage, because the carbon is used as feedstock for construction materials. This was covered in Pioneers 2021: Advancing Sustainable Materials.

Limitations

More expensive: Carbon mineralization currently costs two to three times more than supercritical storage ($10/t$CO_2$ versus $20-30/t$CO_2$). Costs, however, are hugely dependent on transport, so this will evolve as the industry matures.

Subsurface risk: Any kind of subsurface infrastructure project carries development risk. Storage in peridotite rock formations, for example, has the potential to reduce permeability by clogging pores with mineralized carbon, preventing further storage at that site. Similar risks, however, exist with supercritical storage.

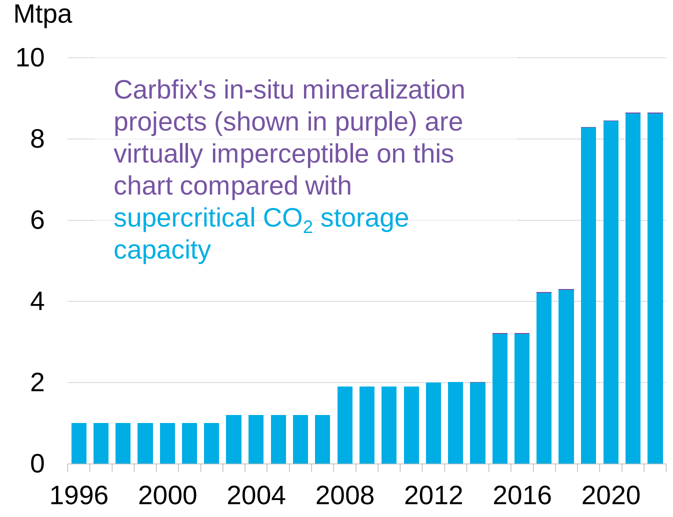
Supercritical head start: Storing supercritical CO_2 has a two-decade head start on carbon mineralization as a process.

Potential solutions

Remove regulatory hurdles: Carbon storage projects can take years to permit. This process must be expedited so the industry can scale at the rapid pace that is necessary.

Project scale up: Building large-scale storage projects that can store CO_2 from multiple point sources, as well as collocated direct air capture plants, will generate economies of scale and reduce the cost of permanent carbon sequestration.

CO_2 geological storage capacity by project type



Source: BloombergNEF

Carbon storage

How does it work?

Maturity

Basalt

Carbfix

Carbfix injects CO_2 into basaltic rock formations and has demonstrated that 95% of the CO_2 is mineralized within two years. The basaltic rocks that Carbfix's process relies on are conveniently located where geothermal energy – a low-carbon baseload source of power and heat that can be used to power direct air capture plants – can be plentifully found. This means Carbfix's storage sites could be located relatively close to sources of zero-carbon baseload, and therefore low-carbon direct air capture plants.

Carbfix is founded on an academic collaboration dating back to 2007. Its pilot injection site was launched in January 2012. Since 2014, the company has stored 80,000tCO_2 (mostly from point source capture) and has signed partnerships with Aker Carbon Capture, Rio Tinto and Climeworks to co-develop services and projects. Carbfix won the XPRIZE twice this year for two separate projects, in partnership with Verdox and Heirloom, both also profiled in this note. Carbfix's next major project is the development of its Coda Terminal, a shipping terminal in south-west Iceland that will act as a major carbon storage hub for northern European industry. It aims to have a capacity of 5,000 tCO_2/year from 2026, scaling up to 3MtCO_2/year by 2031. Carbfix is a wholly-owned subsidiary of Reykjavik Energy.

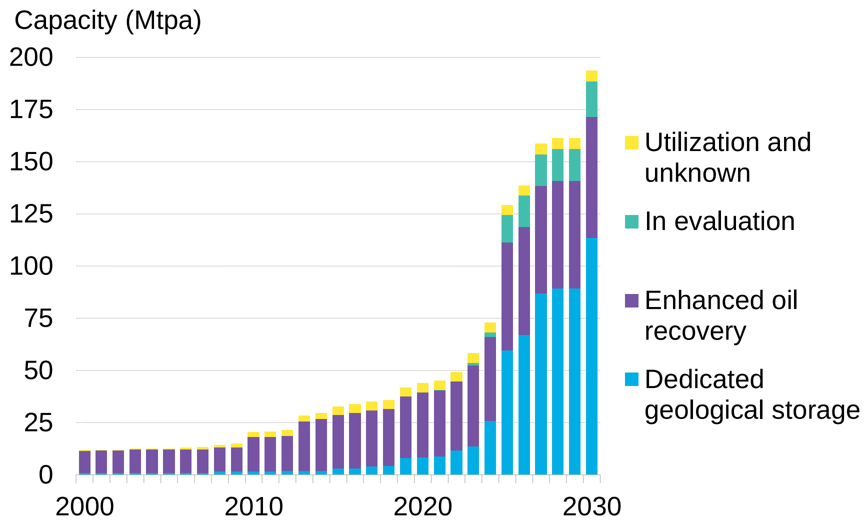
Peridotite

44.01

44.01's process is similar to that of Carbfix, but it uses peridotite as a storage medium for carbon, rather than basalt. Peridotite has more abundant minerals that induce the mineralization reaction than basalt, but it is also less abundant, further from population centers and less porous (making it more prone to clogging).

44.01 is newer to the carbon mineralization game than Carbfix, having been founded in 2020. 44.01 has a similarly impressive list of partners as Carbfix, including Stripe, Shopify and Climeworks. 44.01 won the Carbon XPRIZE in 2022 in partnership with Mission Zero Technologies to build Project Hajar. The first phase of Project Hajar will commission in 2024 and aims to sequester 1,000 tCO_2/year. 44.01 has raised $5 million in seed funding and counts Breakthrough Energy Ventures as an investor.

CO_2 storage outlook



Source: BloombergNEF

Methane oxidation

Methane's warming impact amounts to 16% of total greenhouse gas emissions and is the second-largest cause of radiative forcing. As this warming impact is felt in the near term, it is worth addressing methane emissions. Because methane exists at about 0.4% the concentration of CO_2 in the atmosphere, it is likely going to be too energy intensive to suck it out of the air in a DAC plant. Research has focused on reducing the warming impact of atmospheric methane through oxidation (inducing the breakdown of methane into CO_2) rather than capture. While this does not eliminate the warming impact, it dramatically reduces it. Research into atmospheric methane oxidation is very early stage, more so than any other carbon removal strategy addressed in this note.

New approaches and technologies

Iron salt aerosol (ISA): Spraying ISA in the lower atmosphere would increase the level of chlorine radicals, which would accelerate the breakdown of methane into CO_2. ISA has numerous impacts on the climate – including on biological activity in the ocean – but it is distinct from ocean iron fertilization strategies, which capture carbon by increasing biomass growth in the ocean.

Microbial: Methanotrophs are microbes that metabolize methane, turning it into CO_2. Accelerating the natural oxidation process of existing methanotrophs, or genetically editing microbes with faster metabolisms, could reduce methane emissions.

Photocatalysts: Some materials act as photocatalysts for methane oxidation, meaning when they are exposed to UV light, they induce a methane oxidation reaction. Candidate materials include titanium oxide and silver-coated zinc oxide.

Limitations

Does not eliminate warming effect: While methane is a more potent greenhouse gas than CO_2, its warming effect is short-lived as the methane will ultimately naturally oxidize into CO_2. Methane oxidation is therefore only reducing the near-term warming impact of methane, rather than eliminating the emissions.

Early stage: While all the technologies discussed in this note are early stage, methane oxidation is more so than most. These technologies have not evolved past lab stage and have yet to receive the large amount of funding that other carbon removal companies have. The potential negative externalities of methane oxidation processes are also, therefore, less explored.

May need higher concentrations: It is too early to tell whether the oxidation of methane at atmospheric concentrations will be cost effective, or whether oxidation will only work in areas with high methane concentrations.

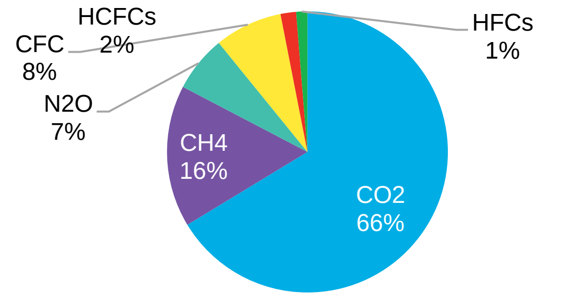
Potential solutions

Demonstrate lack of negative externalities: The early stage of many processes means there are multiple risks to methane oxidation. ISA injection could disrupt ecosystems, and microbial methane oxidation has, in some cases, been demonstrated to produce nitrous oxide (N_2O), another potent greenhouse gas with a long lifetime.

Co-removal with other gases: A huge amount of air would need to be processed to meaningfully impact methane concentrations (0.04% of the world's atmosphere to remove the equivalent of $1GtCO_2e$). The co-removal of other greenhouse gasses in the same air handling process could make it more energy and cost efficient.

More robust catalysts: Experiments using photocatalysts to oxidize methane on dairy farms showed they degraded too quickly to mitigate emissions cost effectively.

Global warming impact of GHGs, 2020

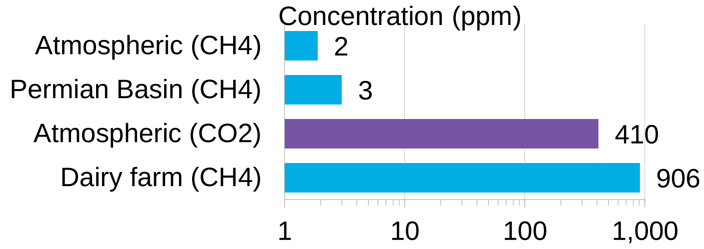


Source: BloombergNEF, NOAA. Note: Warming impact treated as equivalent to radiative forcing. CFCs = Chlorofluorocarbons, HCFCs = Hydrochlorofluorocarbons, HFCs = Hydrofluorocarbons

Methane oxidation

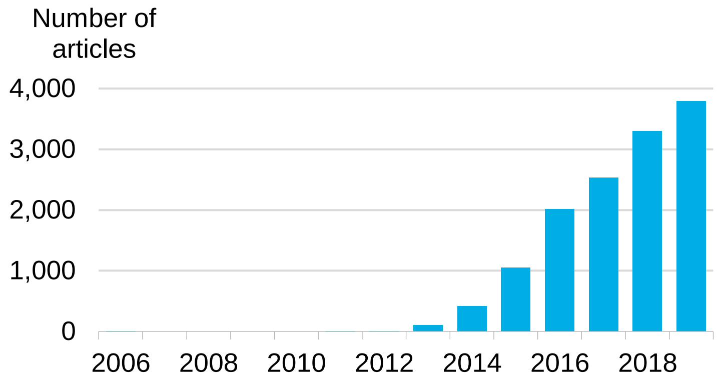
		How does it work?	Maturity
Iron Salt Aerosol	Blue Dot Change (Helping nature repair the climate)	Blue Dot Change aims to use the iron-salt-aerosol method to oxidate methane. Its process works by injecting iron dust into the atmosphere from the back of large ships. This iron spray reacts with ultraviolet rays in sunlight and sea salt in the water to generate free chlorine radicals. The chlorine radicals then react with the methane, eventually turning it into CO_2.	Blue Dot Change was founded in December 2020. The company has not publicly announced any funding. It has an ambitious scale-up timeline, saying in its Stripe carbon removal funding application that it hopes to achieve full scale by December 2023, and oxidate 300 million tons of methane per annum.
Microbial	**The Banfield Lab**	The Banfield Lab at the University of California, Berkeley, is running basic science research projects to better understand methanotrophs. The lab discovered a new class of novel DNA structures called ‘Borgs’ in July 2021 that assimilate various genes from microorganisms in their surroundings. Borgs’ DNA structures are large, so require a lot of energy to support. This, coupled with the fact that many of the Borgs contain genes involving the metabolic processes for consuming methane, suggest they could be a vital new tool in engineering more effective methanotrophs.	Borgs were only discovered in July 2021 from a basic science project, and their existence is still up for debate. They might perhaps be an already-discovered DNA structure presenting itself in a new manner. Professor Jill Banfield, however, who leads The Banfield Lab, said she had not been as excited about a discovery since Crispr – the DNA sequence that enabled gene editing methods. While this could be viewed as hyperbole, Jennifer Doudna is also an author on the paper outlining the discovery of Borgs. Doudna shared the 2020 Nobel Prize in Chemistry for her role in the discovery of the method for genome editing, known as Crispr-Cas-9.

Concentrations of various greenhouse gases



Source: BloombergNEF, Atmospheric Methane Removal: A Research Agenda

Crispr-Cas-9 published journal articles



Source: BloombergNEF, Lens.org.

Crispr was a relatively obscure concept until 2012, when a discovery highlighted the potential use cases of the technology. Investment and research in the topic has been growing at a rapid pace since. If Borgs do result in similar scientific advances for engineering methanotrophs, they are unlikely to occur any more quickly than the timeline depicted above.

Land-based carbon removal

Land-based carbon removal

The land carbon sink, which consists of the earth's soil and vegetation, has absorbed 31% of anthropogenic emissions. Cheap land-based carbon offsets (in the form of forestry projects) currently dominate voluntary carbon removal markets, but it is difficult to verify the carbon stored in these projects, and the carbon storage is not durable. Land-based solutions such as biochar, or bioenergy with carbon capture and storage (BECCS), that store carbon durably will boost the long-term potential of land-based removal strategies.

What is it?

Land-based carbon removal strategies reduce the level of atmospheric carbon, either by strengthening the flows of carbon into vegetation and soil, or weakening flows of carbon out of vegetation and soil. The earth's soil and vegetation are known together as the land-carbon sink. The land sink has great potential as a resource for carbon removal. It exchanges around 440GtCO_2e with the atmosphere each year, equivalent to approximately 11GtCO_2e on net. The land sink has absorbed 31% of anthropogenic emissions.

Removal strategies that focus on strengthening the land sink are currently the world's largest source of carbon removal offsets – in other words, forestry and agricultural projects. Regenerative farming, which encourages the drawdown of carbon into the soil through different farming practices, is also gaining momentum as farmers seek to bring in new revenue from burgeoning offset markets. Removal strategies that weaken carbon flows out of the carbon sink (such as biochar production and bioenergy with carbon capture and storage) have less developed markets, but would make a more durable and scalable carbon removal solution in the long term.

What should we tackle first?

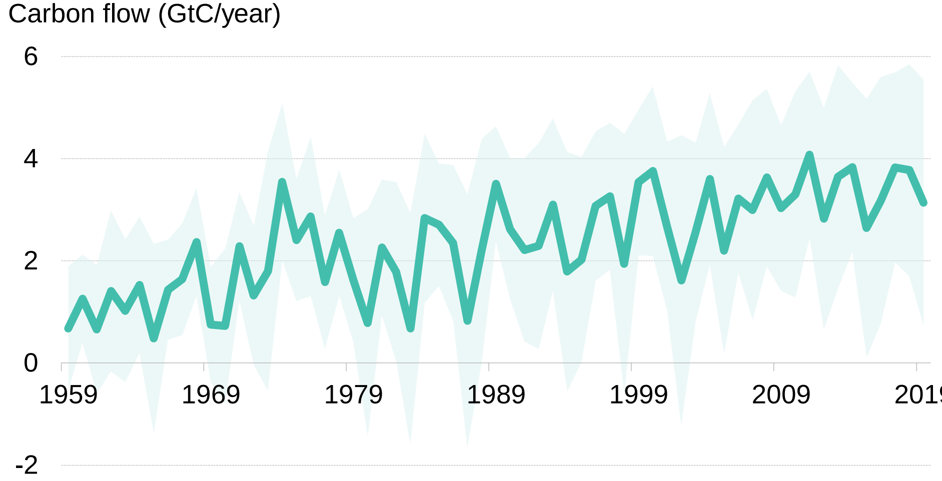
Permanently sequestering biogenic carbon – carbon stored in biological material – is the best form of land-based carbon removal. Lowering the cost of point source capture for use in bioenergy plants, and reducing the cost of biochar production, are the key routes to doing this. On the other hand, improving the quality of forestry projects will also enhance the land efficiency of biocarbon sequestration, and can be applied to an already very large offset market. Regenerative agriculture will likely scale quickly as it offers a new, sustainable revenue stream to many agricultural stakeholders.

What is difficult about land-based removal?

Strategies that rely on growing biomass to capture carbon inevitably run into issues regarding land use, because capturing gigatons of carbon annually in this way will take a significant share of the world's arable land. This will have negative impacts on biodiversity, as land-based forestry projects are often monocrops. It will also have implications for food security, as land used for carbon removal could potentially compete for farmland, driving up food costs.

Land-based strategies are also difficult to scale quickly because they require a certain level of control over land, and this means engaging with a huge number of decentralized stakeholders.

Net annual carbon flow into land sink



Source: BloombergNEF, The Global Carbon Project. Note: Lines indicate the average of climate models. Lighter shaded areas indicate 95% confidence intervals based on the same set of models. Human emissions amount to around 10GtC (GtCO_2e) annually.

Afforestation and reforestation

Afforestation and reforestation (A&R) offsets have been criticized as some of the lowest quality carbon removal credits available. They do not act as permanent storage, they are difficult to measure and there are significant concerns about their impact on land use and biodiversity. A&R offsets supply a significant share of the removals market and this is unlikely to change until at least the middle of the next decade. Improving land-use efficiency and A&R verification will significantly enhance the effectiveness of the offsets market. Efforts to increase the photosynthetic efficiency of vegetation and automate forestry management with intelligent drones are some of the main technology routes to achieving this.

New approaches and technologies

Photosynthetic enhancement: One strategy to improve A&R projects is genetically engineering plants to enhance the rate at which they absorb CO_2 through photosynthesis. Current efforts are focused on reducing the rate of photorespiration in plants – through inserting C_4 plant genes into C_3 plants. Other strategies include improving the energy efficiency of CO_2 conversion in plants and making plants grow to maximize the light capture of the whole canopy rather than individually competing for light.

Robotics: Aerial drones equipped with sensing, weed management and planting technology are being used to improve forest management practices. This makes projects easier to verify and more effective.

Measurement and verification technologies like satellites are essential in incorporating forestry projects into any net-zero strategy. This is covered in last year's note, *Understanding Our Planet*, and so is not discussed here.

Limitations

Not permanent storage: Carbon stored in vegetation will likely return to the atmosphere in decades, slowing rather than preventing or reversing climate change

Land-use and biodiversity implications: A&R projects are often criticized because they are monocultures. The large-scale removal of carbon through forestry projects would consume a massive amount of land and hence reduce biodiversity. A&R could also compete with land used to grow food, driving up prices and creating food insecurity.

Limited biotech capabilities: A review of photosynthetic enhancement strategies found they are "limited by our ability to introduce, position, and regulate inserted genes" in plants. Many genetic enhancement concepts are also at the lab stage, and it is currently difficult to tell how the perceived benefits would translate into real-world environments.

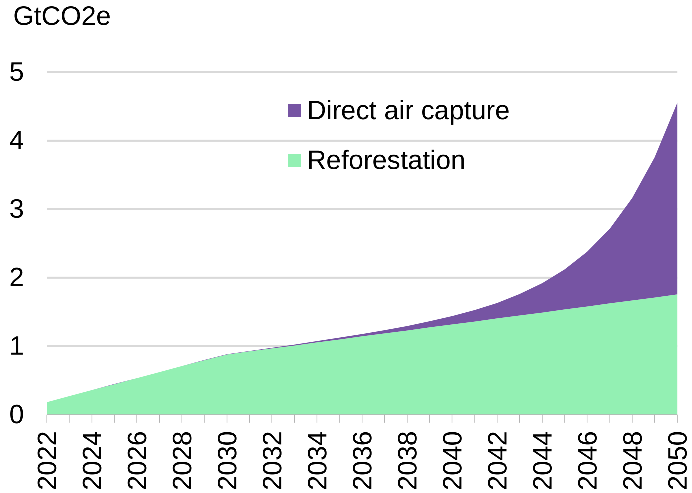
Opposition to genetic engineering: In the US, trees classified as genetically modified organisms (GMOs) cannot be included in forestry projects certified by the Forest Stewardship Council as being responsibly managed.

Potential solutions

Pair with biocarbon sequestration technologies: A&R projects could be paired with technologies – likely pyrolysis – for converting biomass for permanent geological or soil sequestration.

Relax regulation on genetic engineering: Allowing plants that have been genetically engineered to be included in forestry projects would let companies developing novel plant breeds generate revenue.

Carbon removal supply by sector



Source: BloombergNEF, SBTi

Afforestation and reforestation

		How does it work?		Maturity
Photosynthetic enhancement	RIPE	The RIPE project (realizing increased photosynthetic efficiency) is an international research effort between institutions in the US, UK, Germany, China and Australia to enhance photosynthesis. It has nine main areas of research. Its focus is predominantly on improving food security through raising crop yields, rather than carbon removal.		The RIPE project was founded in 2012 and funded by a five-year $25 million grant from the Bill and Melinda Gates Foundation. It has since received a further $58 million from past funders, as well as the UK government and the Foundation for Food and Agriculture Research.
	Living Carbon	Living Carbon has developed a hybrid poplar tree with photosynthetic enhancement traits. Lab results have shown that its trees grew 53% more biomass compared with a control group after 21 weeks. Living Carbon is also attempting to incorporate genes that slow the rate of decay of biomass, in order to trap carbon for longer than typical forestry projects, and genes to help plants leach metal from soils.	Living Carbon took part in the Summer 2021 Y-Combinator cohort – a startup accelerator. In February the following year, it raised $15 million in a Series A round. To date, the company has only demonstrated the improved efficiency of its plant in the lab. It is currently running a field trial with Oregon State University and has chosen 3,200 acres of land for its pilot projects. Living Carbon is developing a research and development platform for synthetic biology related to plant science. Its enhanced poplar is just the first product it has publicly announced.	**C_3 versus C_4 plants: reducing photorespiration** Photorespiration is a process that occurs during photosynthesis when rubisco – the enzyme whose main purpose is consuming CO_2 to produce useful carbohydrates – reacts with oxygen instead of CO_2. When rubisco reacts with oxygen, this uses energy but does not produce sugars. The most common photosynthesis process in plants – C_3 carbon fixation – is estimated to be around 25% less efficient due to photorespiration. Around 15% of plants use a different photosynthesis process called C_4 carbon fixation, which combats photorespiration. This makes C_4 plants much more energy efficient in their use of sunlight. Examples of C_4 plants include corn, sorghum and sugarcane. Living Carbon's photosynthetic enhancement relies on incorporating genetic traits from C_4 plants into a C_3 plant. The reason it is useful to add C_4 traits to a C_3 plant is because C_4 plants do not grow to be as large as forests and so store less carbon per acre.
Robotics	drone seed	DroneSeed has developed 55-pound+ drones that are equipped with sensors, herbicide sprayers and seed planting instruments. The drones are able to create maps of their environment to centimeter-level accuracy, decide where is the optimal location to plant a seed and then plant it. DroneSeed is focused on reforesting areas affected by wildfires.		DroneSeed was founded in 2015. It raised a $5 million seed round in 2017 and a $36 million Series A round in September 2021. The following month it acquired Silvaseed, a 130-year-old seed provider, to be more vertically integrated in the reforesting business. DroneSeed announced its largest carbon removal purchase to date in March 2022: some 50,000tCO_2 from Shopify.

Biocarbon sequestration

Vegetation is the largest annual sink of atmospheric carbon. Unfortunately, vegetation decays as it reaches the end of its lifecycle, releasing almost as much carbon back into the atmosphere. Biocarbon sequestration strategies seek to stop this natural source of emissions by processing biomass into a form that cannot decay. While this is technically not carbon removal, it is functionally the same. Popular processing techniques include pyrolyzing the biomass to convert it to biochar for use in agriculture, or burning biomass in power plants equipped with point source carbon capture. Biocarbon sequestration has huge potential as a durable form of carbon storage, but challenges remain around land use and creating the complex supply chains for processing decentralized sources of biomass.

New approaches and technologies

Pyrolysis: Pyrolyzing biomass – heating it in the absence of oxygen – converts the carbon stored in biomass into a more stable form that will not decay into the atmosphere. Biochar – a charcoal-like substance – is one popular product. Biochar can be deposited in soil where it stores carbon for hundreds of years, while simultaneously enhancing soil health. Pyrolysis can also produce bio-oils that can be injected underground, where they solidify, storing carbon permanently.

Bioenergy with carbon capture and storage (BECCS): BECCS is the process of creating energy with biomass (power or fuels) and then using point source carbon capture to make the process carbon negative. Climate models have relied on BECCS to drive most of their negative emissions scenarios. Biomass-to-power is the most land-efficient type of BECCS from a carbon removal perspective.

Limitations

Sourcing biomass: Biomass is produced at a decentralized level, from both a geographic and organizational perspective, making it difficult to build supply chains. Companies seeking to process biomass also often assume that they can take the material, usually waste, at very low cost. Once waste producers realize value is being generated, they can hike prices.

Land use: BECCS has been particularly criticized for the large amount of land it would need to use to achieve any meaningful impact on emissions – some 1GtCO_2 would require about 4% of today's cropland.

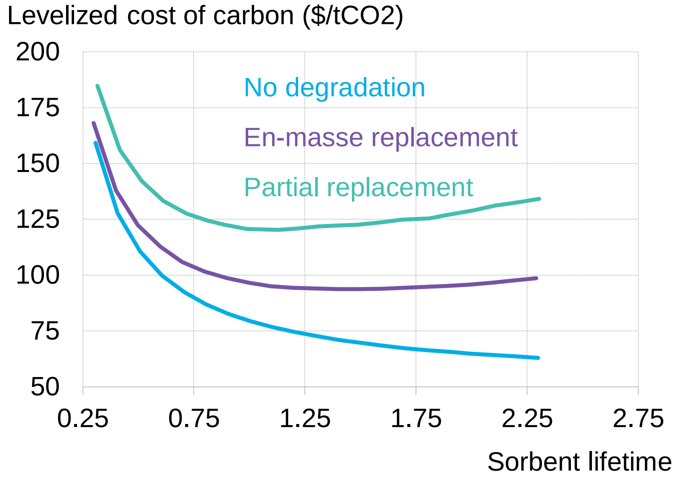
Scarce resources: Biomass products are a useful tool in decarbonizing other hard-to-abate industries such as aviation, shipping and petrochemicals. It may not be the best allocation of resources (or highest value option) to use biomass pyrolysis or BECCs carbon removal.

Potential solutions

Pair with more land-efficient vegetation: Pairing biocarbon sequestration with technologies discussed in the afforestation section could improve the land-use efficiency of biocarbon sequestration

Decentralized plants: Smaller plants or in-field processing would dramatically reduce feedstock costs for biomass, because transport is such a large component of feedstock costs. This is, however, somewhat at odds with the use of point source capture in BECCS, which relies on centralization to benefit from economies of scale for transporting and storing carbon.

Cost of carbon removal using BECCS under different sorbent performances



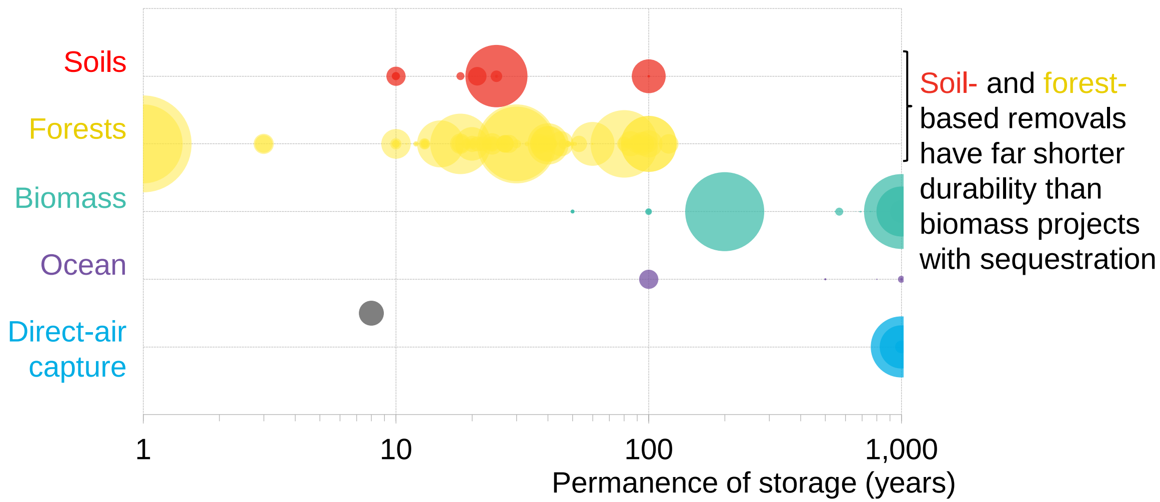
Source: BloombergNEF, *Defining Targets for Adsorbent Material Performance to Enable Viable BECCS Processes.*

Biocarbon sequestration

BNEF pioneers

Biochar	How does it work?	Maturity
carbo culture	Carbo Culture is developing a new generation of large-scale pyrolysis reactors to produce biochar from waste biomass. Its pyrolysis process produces biochar, as well as syngas that can be used to generate renewable heat.	Carbo Culture was founded in 2017 and built a demonstration reactor in 2019. It raised a $6.2 million seed round in 2021. Zendesk has purchased carbon removal credits from Carbo Culture. Carbo Culture hopes to commission 14,000tCO_2 worth of capture capacity in 2024 and scale to more than 100,000tCO_2 post-2025.
Climate Robotics	Climate Robotics is developing a system that collects agricultural waste and pyrolyzes it to produce biochar in the field. This decentralized process eliminates a huge limitation of biomass processing: the cost of transporting it to central locations for processing. BNEF research estimates that harvesting and transport costs account for about 80% of waste biomass feedstock costs.	Climate Robotics was founded in 2020 and has raised $4.7 million to date, most of which was from a $4.4 million seed round. The company also received an undisclosed investment from Exelon as part of the latter's Climate Change Investment Initiative. Climate Robotics' only publicly announced project is a contract with Microsoft to remove 1,000tCO_2 at a contracted durability of 200 years. The project will operate in Texas and sequester 2.2tCO_2 per acre annually.

Permanence of carbon removal applications submitted to Microsoft and Stripe procurement programs



Source: BloombergNEF, Carbonplan.org

A small number of projects have emerged that are seeking to sequester biocarbon in an even more simple way than pyrolysis: burying it. These companies are developing processes to permanently store biomass in either the earth, or saline water bodies to prevent the decay and emissions of biogenic carbon. The practice has yet to attract funding or offset purchases from major players in the industry.

Biocarbon sequestration

How does it work? / Maturity

Bio-oil (not fuel)

CHARM INDUSTRIAL

How does it work? Charm Industrial has developed mobile pyrolysis units that are used to convert waste agricultural and forestry residues into low-grade bio-oil. It then injects this bio-oil underground where it solidifies via autopolymerization. Charm is similar to Climate Robotics in the sense they have both created decentralized pyrolysis units. However, Charm is different in that it produces a liquid that is stored, rather than biochar, which is a soil additive.

Maturity: Charm is relatively old for a carbon-removal startup, having been founded in 2018. It was also one of the inaugural pre-purchases made through Stripe's pioneering carbon removal program. Charm sold its first offsets to Stripe at a price of $600/tCO_2$, which it hopes to bring down to $175/tCO_2$ in five years, and to $50/tCO_2$ in 20 years. The company has raised $25.5 million according to PitchBook. Charm says it has removed more carbon from the atmosphere than DAC leader Climeworks.

BECCS

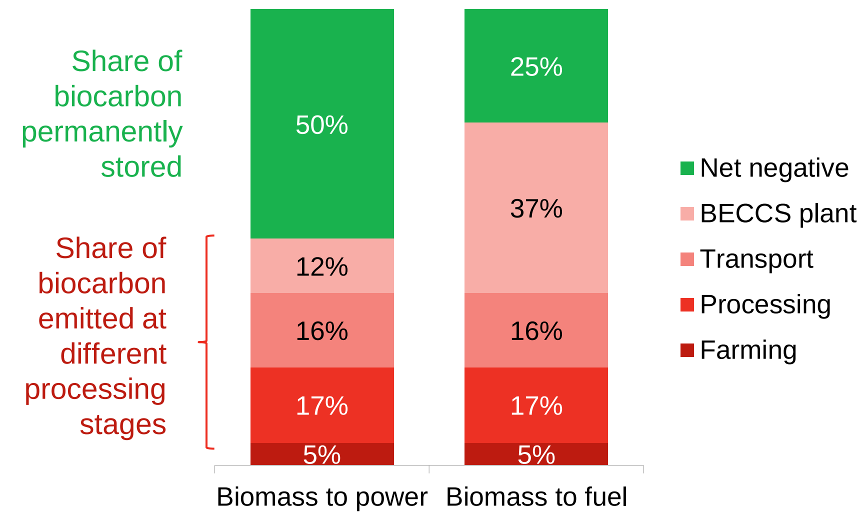
drax

Drax has run two pilots for implementing CCS on biomass-fired power units. The first was with C-Capture in early 2019, and the second with Mitsubishi Heavy Industries (MHI) in late 2020. In June 2021, Drax signed a long-term partnership to implement MHI's solvent-based capture process (KM CDR) at its power plants.

Drax operates 2.6 gigawatts (GW) of biomass-fired power generation, with a further 1.3GW in coal that could, in the future, be transitioned to biomass. Drax plans to be a carbon-negative company by 2030 through the use of BECCS, installing carbon capture technology on one of the units by 2027 and adding another by 2030, each with the capacity to capture 4 $MtCO_2$ per annum.

In 2015, Drax pulled out of similarly ambitious plans to construct a coal-fired CCS power plant due to dwindling government support for clean energy, suggesting the construction of its BECCS capacity is not a certainty.

Carbon efficiency of different BECCS processes



Source: BloombergNEF, Grantham Institute.

Biomass-to-power is a much more carbon-efficient (and thus land-efficient) way to generate negative-emissions energy than biomass-to-fuels.

Soil-carbon sequestration

Regenerative farming could remove gigatons of atmospheric carbon by increasing the carbon content of soils. While there are no technical barriers to regenerative farming, there are limited incentives for farmers. A whole crop of marketplaces has sprung up to help farmers monetize the practices through the sale of offsets. Technical innovation in the field is focused on measuring soil carbon content to improve offsets credibility. Adoption of regenerative farming could take years, as farmers must test new growing practices in annual cycles. The potential scale of soil carbon sequestration is limited, as the carbon sink will eventually saturate, and concerns remain around the durability of carbon stored in this manner. Green premiums for goods made with regenerative practices would accelerate the industry.

New approaches and technologies

Regenerative farming practices are the best strategy for sequestering carbon in soil. They include minimal soil disturbance and cover cropping to boost soil carbon levels. While there are no technical barriers to using regenerative farming practices, there are still innovations that will be necessary to commercialize the practice at scale.

Measurement: Better technology is needed for analyzing the amount of carbon stored via soil carbon sequestration. Innovation is focused on making soil sampling quick and simple, avoiding the need to send samples to labs, and making it easier to verify offsets.

Biologicals: The term biologicals refers to soil microbes that are used as crop inputs to boost performance. Biologicals development has focused on reducing the use of nitrogen fertilizer – itself an important climate challenge – but they are also being used to encourage soil carbon sequestration.

Limitations

Monitoring expensive, new tech adoption could be slow: Monitoring soil carbon levels involves taking soil samples, conducting analysis and making a soil management plan. New sensing and analytics technologies can automate a lot of this work, but adoption may be slow. Farmers can take years to implement new practices, as they need to test out new management practices with crop cycles. The success of these practices can only be determined at the end of a growth season.

Permanence and scalability: No matter how efficient and effective soil carbon sequestration gets, it will only ever be a partial solution. Soils will saturate with carbon if they are absorbing hundreds of millions of tons of carbon annually. There are also concerns around the durability of soil carbon sequestration. This does not make the practice pointless, it is simply a limitation.

Potential solutions

Generate green premiums: Regenerative farming practices can be economic, but the case is not always clear. Certification schemes that verify that goods come from farms using regenerative practices – akin to Fairtrade coffee – could generate green premiums for products, accelerating adoption.

Remove regulatory hurdles: Agricultural policy can often discourage regenerative farming practices. The US government's Federal Crop Insurance Program, which covers around a third of American farmers' income, has provisions that discourage soil health practices.

Marketplaces for selling carbon offsets generated through regenerative farming

CarbonCount Measurement and Certification

indigo™

Nori

GRASSROOTS CARBON

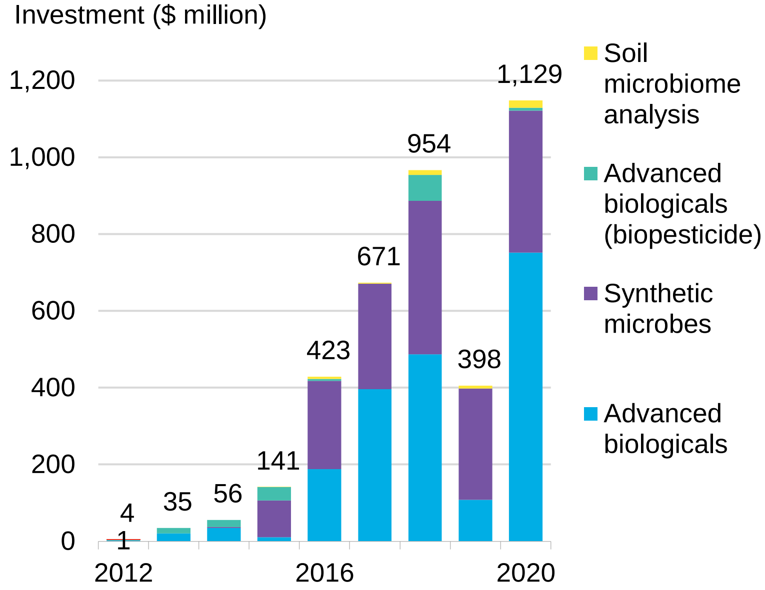
SOIL VALUE EXCHANGE

Source: BloombergNEF, company websites.

Soil-carbon sequestration

		How does it work?	Maturity
Biologicals	loam	Loam Bio has developed a microbial seed coating that enhances a plant's ability to store carbon in the surrounding soil. The microbe helps store carbon in what are known as micro-aggregates. The aims of Loam's products are to boost yields and allow farmers to sell offsets. Loam claims that its microbes generate an increase of 7-17% in soil-carbon content over a season. If this estimate was applied to 1.8 million hectares (approximately the total addressable market), it would capture about 8GtCO_2. It is unclear how quickly this carbon sink would saturate.	Loam was founded in 2019 and has raised a total of $37 million. The company has received funding from Shopify's carbon removal fund.
Soil carbon measurement	YARD STICK Soil Carbon Revealed	Yard Stick has developed a project management platform to monitor, report and verify soil carbon content levels. Its software creates automated soil sampling plans and it has developed a handheld spectral hardware device that allows farmers to conduct soil analysis onsite, without expertise. This negates the need to take soil samples and send them to a lab.	Yard Stick was founded in 2020. The company has not publicly disclosed any fundraising, but it is included in Lowercarbon Capital's portfolio page. It currently has 13 employees on LinkedIn.
Soil carbon measurement	HONE CARBON	Hone has developed a handheld measurement device that can analyze soil and crop characteristics onsite. The device relies on spectral imaging technology. Hone claims that its soil analysis process is five times cheaper than conventional soil sampling techniques.	Hone was founded in 2016. In late 2021, it raised $4.7 million in a Series A round and $1.9 million in a secondary round in February 2022. Hone has recently shifted its focus to soil carbon analysis, creating a subsidiary, Hone Carbon, focused on the market. Hone currently has 10 customers, including Loam Bio and Australia's national R&D agency. Hone's sensors meet the requirements set out by the Australian government for generating Australian Carbon Credit Units.

Venture capital and private equity funding for startups in the advanced agricultural biologicals industry



Source: BloombergNEF, Crunch Base, CB Insights, company websites, news. Note: This chart is based on only disclosed investments. 'Advanced biologicals' refers to those who develop biofertilizers or biostimulants, and some develop biopesticides as well. 'Advanced biologicals (biopesticides)' focus on only biopesticides.

Ocean-based carbon removal

Ocean-based carbon removal

The ocean naturally absorbs almost 9.5GtCO_2, on net, from the atmosphere every year. Novel solutions are emerging that strengthen this natural sink by reducing the acidity of the ocean and encouraging the growth of biogenic carbon. Ocean-based removal strategies eliminate concerns around land use, but any removal strategy done at a gigaton scale could severely disrupt ocean ecosystems.

What is it?

Ocean-based carbon removal strategies are those where atmospheric carbon is drawn from the atmosphere and into the ocean. These strategies rely on strengthening the natural ocean carbon sink, which absorbs around 9.5GtCO_2, on net, each year. The ocean is also a huge store of carbon. It stores 45 times more carbon* than the atmosphere and 12 times more carbon than the land. Removing all anthropogenic carbon from the atmosphere and adding it the ocean would only increase its carbon content by 1%. The ocean absorbs carbon in two main ways: via biomass growth in the ocean, and when CO_2 dissolves in water due to contact with the ocean surface (known as the solubility pump).

What should we tackle first?

Stimulating the growth of biomass by depositing nutrients in certain regions of the ocean is, to date, the most well-researched ocean removal strategy, but pilot projects have run into concerns around destabilizing food webs. There is also uncertainty regarding the durability of carbon stored in this manner. Cultivating macroalgae (seaweed), and then sinking it deep into the ocean, is a new path being explored.

A more novel route that has gained momentum in the last year is to strengthen the solubility pump by enhancing the alkalinity levels of the ocean. There are several pathways being explored to achieve this. Some involve simple depositing of minerals on the coast, while others involve the construction of complex new electrochemical processes. Scientists have high confidence that strengthening the solubility pump would effectively and durably reduce atmospheric carbon levels. There is little real-world evidence, however, on how this would impact ecosystems.

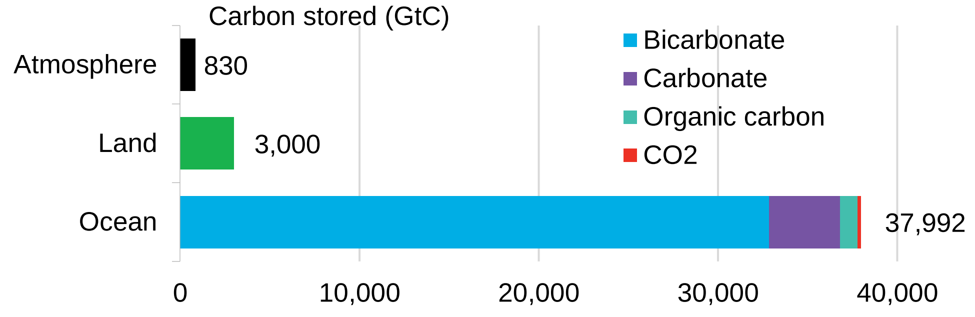
What is difficult about ocean-based removal?

Like all high-quality removal offsets, ocean-based offsets remain expensive because projects are small and so there are no economies of scale.

While ocean-based removal strategies do not have the same land-use concerns as land-based strategies, because they need to be carried out at such a large scale, there are challenges relating to dealing with the unintended consequences of strengthening the ocean carbon pump.

The biggest concern is the effect ocean-based removal strategies would have on ecosystems. This relates to how shifting nutrient and carbon availability could disrupt food webs, or the potential introduction of toxic minerals when attempting to boost the ocean carbon sink. Some electrochemical strategies also produce byproducts, such as hydrochloric acid or chlorine, which would require scaled waste management systems.

Carbon storage in the atmosphere, land and ocean



*Source: BloombergNEF, *Note: These statistics relate to the amount of **carbon** stored in the ocean not CO_2. Only 0.05% of oceanic carbon exists as CO_2.*

Ocean fertilization

Ocean fertilization is the ocean equivalent to afforestation – encourage carbon drawdown by increasing the level of biomass growth in the ocean. Historically, ocean fertilization has focused on adding nutrients to the water, particularly iron, which is the limiting growth factor in much of the ocean. This practice has been criticized as it disrupts ecosystems and it is uncertain how much of the carbon sequestered in biomass sinks to the deep ocean, rather than re-entering the atmosphere. New approaches to ocean fertilization aim to make it more measurable and ensure the long-term storage of carbon. Approaches involve digitalizing the farming of macroalgae seaweed, and flooding deserts to create algal blooms that are isolated from ocean ecosystems.

New approaches and technologies

New approaches to ocean fertilization seek to solve the challenges regarding measurability, permanence and ecosystem disruption faced by ocean iron fertilization.

Sinking seaweed: Rather than creating microalgae blooms, where the extent of carbon stored versus reemitted is unclear, one new approach is to create rafts of seaweed that sink once they reach a certain level of biomass.

Desert flooding: Another approach seeks to create microalgae blooms, but to do so in isolated pools that are created by flooding areas along the coasts of desert. The concept is then to remove the algae from the pool, dry it and bury it to permanently sequester it from the atmosphere.

Digitalization: Both of the above approaches rely on novel sensing and monitoring techniques to track and control biomass growth.

Limitations

Ocean systems are hard to manage: Ocean-based projects are difficult to manage because it is expensive to fix things that go wrong (and often not worth it). The equipment must also endure harsh conditions.

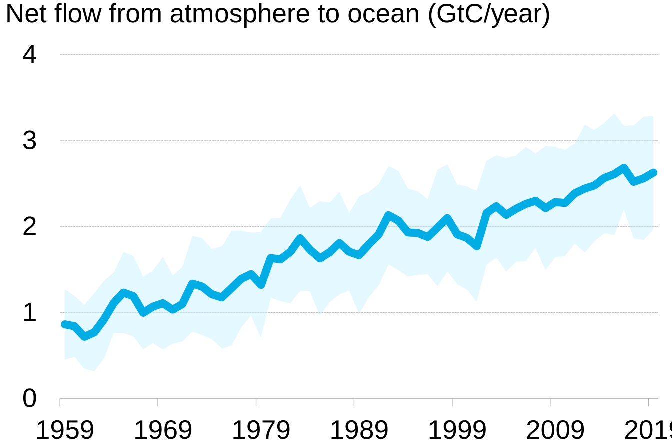
Ecosystem impacts: Even more novel methods that sink macroalgae to ensure more measurable and permanent storage will disrupt growth patterns in the ocean. These projects compete for ocean nutrients and shade lower strata of the ocean. The effect and extent of these impacts is still unclear. For a sense of scale, it is estimated that to capture 0.1GtCO_2/year, this would require 63% of the global coastline, if the seaweed was being grown in a 100 meter wide continuous belt along the coastline.

Controlled-environment algae growth has faced past challenges: There have been previous attempts to use algae as a feedstock for clean fuels and biomaterials. These efforts, however, have consistently run into issues around commercializing the product at scale. Algae are sensitive to environmental conditions and so open pools often suffer from production disruptions if there is any variance in growth conditions.

Potential solutions

More data: Past experiences with ocean fertilization suggest that it has amongst the worst ecosystem impacts of all carbon removal solutions. New solutions that seek to ameliorate this will have to provide significant evidence to convince skeptics that the process is sustainable.

Net carbon absorbed by the ocean annually (from both biological and non-biological sinks)

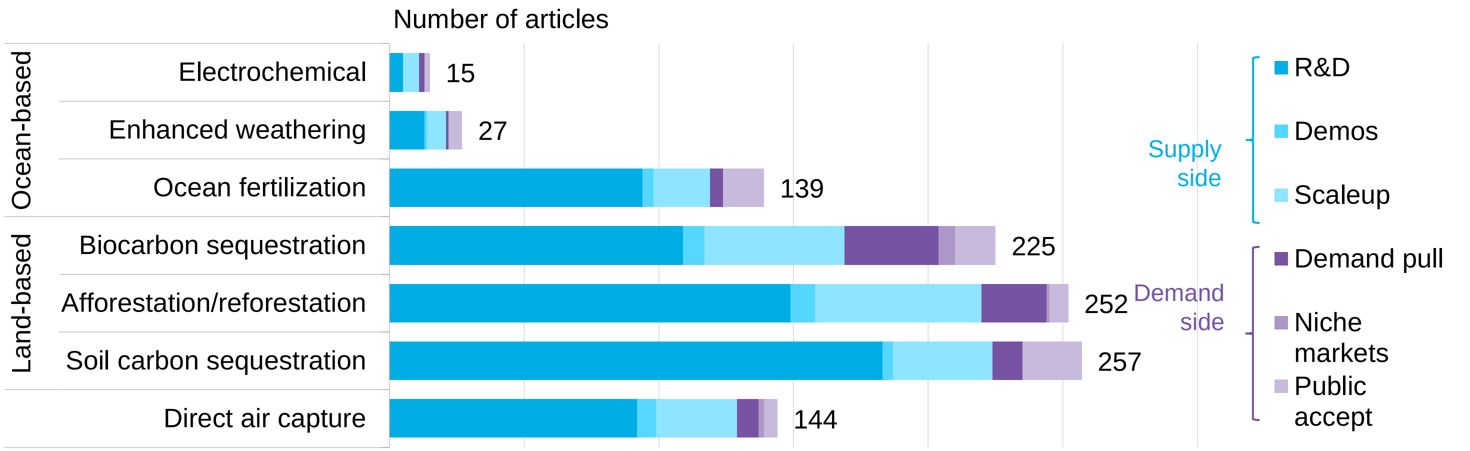


Source: BloombergNEF, The Global Carbon Project. Note: Lines indicate the average of climate models. Lighter shaded areas indicate 95% confidence intervals based on the same set of models. Human emissions amount to around 10GtC annually.

Ocean fertilization

	How does it work?	Maturity
Sinking seaweed – RUNNING TIDE	Running Tide is capturing carbon by growing seaweed on rafts that sink once they reach a certain level of biomass. The biomass sinks thousands of meters below the surface, storing carbon for up to a millennia. The company is developing a whole range of technologies to improve the process, including ocean modeling software, automation for seaweed farming, sensors for environmental monitoring and genetic mapping of seaweed.	Running Tide was founded in 2017 and was selected as part of Stripe's Spring 2021 carbon removal purchase. The company's application to the process stated it was developing 37,000 'microfarms' over the period June 2022 to June 2023, which would amount to 2,000tCO_2 in removal. Running Tide's current cost of removal is \$250/tCO_2, because its initial projects are heavily instrumented with sensors for exploratory data collection. Without this, it says it could deliver removal at a price of \$150/tCO_2 and this would fall to \$70/tCO_2 at scale.
Desert flooding – Brilliant Planet	Brilliant Planet is cultivating the growth of microalgae in large pools. It constructs the pools in coastal desert areas and floods them with seawater. It has developed IP around measurement and control systems to encourage the productive growth of algae. This is typically the element of the process that past efforts have faced difficulties with. Once biomass has grown, it is harvested, laid out to dry so it will not decompose, and buried in soils at a depth of 1-4 meters.	Brilliant Planet was founded in 2013. It emerged from stealth mode in 2022, when it raised \$12 million in a Series A round. It has been running field trials for four years in Oman, South Africa and at its current three-hectare research facility in Morocco. It is currently working on building a 30-hectare demonstration facility. Brilliant Planet targets a capture cost of less than \$50/tCO_2.

Number of research articles by carbon removal category and technology stage (2018)



Research into ocean-based carbon removal strategies lags both synthetic and land-based strategies. Ocean fertilization, however, has received by far the most attention to date in ocean strategies.

Source: BloombergNEF, Negative emissions – Part 3: Innovation and Upscaling. Note: The categories from the source document of this chart have been roughly matched to the section titles of this report. Biocarbon sequestration = BECCS + biochar. Electrochemical ocean-based = ocean alkalinization. All other categories match.

Ocean alkalinity enhancement

The next two approaches to ocean-based carbon removal (enhanced weathering and electrochemical ocean capture) rely on some principles about how oceanic carbon behaves in response to changes in pH – in other words, if the water becomes more acidic or basic. This slide explains this idea: that by controlling pH levels of seawater, you can make it emit or absorb CO_2.

Bjerrum plot and liquid-gas CO_2 exchange

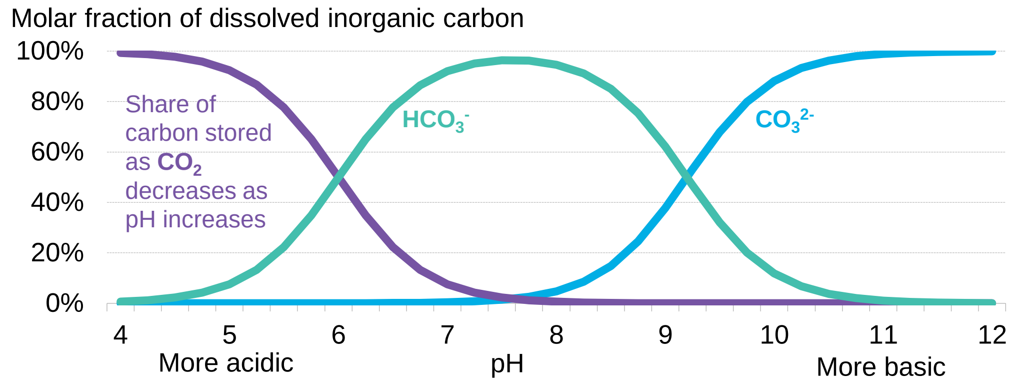
The composition of a carbonate system in a body of water is dependent on its pH. The more acidic it is, the more carbon is stored in the form of CO_2. The more basic, the more carbon is stored in the form of carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-). This relationship is described by the Bjerrum plot on the right.

The rate at which a body of water absorbs or emits CO_2 from the gas with which it is in contact (the air above it) relates to the relative amount of CO_2 in the gas and the liquid. At equilibrium state, the gas and water do not exchange any CO_2. If the CO_2 content in the gas increases, then the water will absorb CO_2 to compensate. If the CO_2 content in the water increases, then the water will emit CO_2 into the gas. This is why a fizzy drink becomes less fizzy when opened. It is emitting CO_2 to the air because the system is not balanced.

These two ideas mean you can make seawater emit CO_2 (by adding acid and lowering the pH) or absorb CO_2 (by adding a base and increasing pH). The main approach being taken in this field to reduce atmospheric carbon is called ocean alkalinity enhancement (OAE). This involves adding materials to the ocean that enhance its alkalinity, increasing its capacity to absorb CO_2. These basic materials can be found in abundant minerals in rocks (such as silicates and carbonates) or synthetically produced via electrochemical routes (such as hydroxides).

A less explored approach is to add acid into seawater in a controlled environment, causing it to emit CO_2, which can then be captured and stored. The CO_2-lean seawater is then returned to the ocean where it will start to absorb more atmospheric CO_2.

Bjerrum plot: concentration of different carbon molecules in water at different pH levels



Source: BloombergNEF. Note: illustrative plot to show relationship.

Understanding of ocean-based carbon removal strategies

	Ocean fertilization	Enhanced weathering	Electrochemical
Efficacy		Research indicates there is more certainty about the ability of OAE strategies to store carbon durably.	
Durability			
Knowledge base		There is also less empirical evidence for OAE processes	
Scalability			
Co-benefits			
Environmental risk			

Source: BloombergNEF, A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration. Note: Darker colors indicate strategy viewed more favorably.

Enhanced weathering

Enhanced weathering is a strategy for enhancing ocean alkalinity that relies on accelerating the natural weathering processes of abundant minerals in the earth's crust – for example, olivine, forsterite and basalt. The strategy works by deploying ground-up minerals in locations where they can be weathered by water. Enhanced weathering has different co-benefits depending on where it is deployed. It can enhance soil quality or be incorporated as part of coastal adaptation projects. The effectiveness and durability of carbon removal with enhanced weathering is well understood, but there is still a lack of understanding regarding the ecosystem impacts and carbon accounting framework that would be implemented for enhanced weathering.

New approaches and technologies

Enhanced weathering (EW) is the process of accelerating the weathering of silicate and carbonate rocks. This is achieved by grinding them up to increase the surface area that can react with the external environment. These materials generate alkalinity in water, increasing the capacity of the oceans to absorb CO_2.

Terrestrial: One EW approach involves dispersing minerals on land. The minerals simultaneously increase the alkalinity of water as well as enhance soil quality. While the weathering takes place on land, the alkalinity (and carbon) is ultimately transferred to the ocean via the water cycle.

Coastal: Coastal EW involves dispersing minerals on beaches. This lacks soil quality benefits but can be incorporated into coastal adaptation projects. Waves also erode the minerals, reducing the need for pre-grinding (and thus the energy footprint).

Limitations

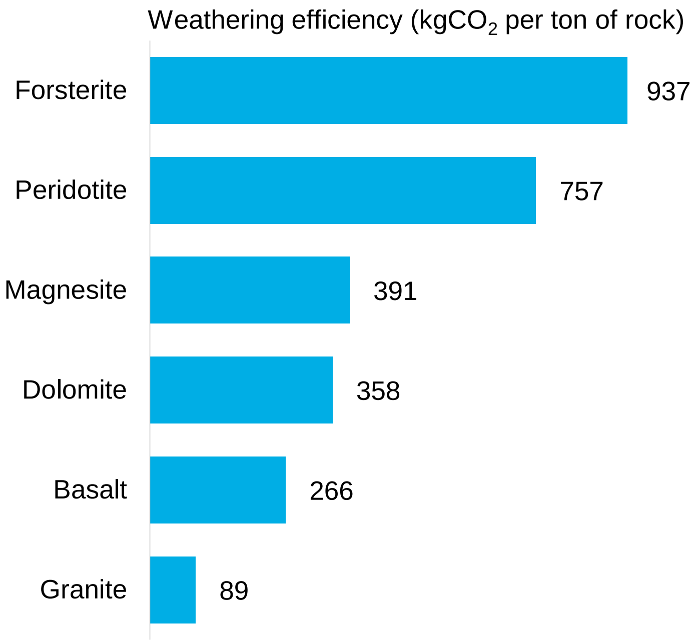
Unexplored impacts: Ocean alkalinity enhancement is a more novel nature-based solution than most discussed in this note, and so the impacts, beyond carbon removal, are less clear. One potential concern is that the widespread depositing of minerals could introduce potential toxic materials, such as small nickel deposits. The addition of different minerals would also benefit different parts of food webs. Calcium carbonate, for example, would benefit calcifiers in the ocean, while silicates could benefit cyanobacteria.

MRV framework: There is no framework for monitoring, recording and verifying the amount of carbon stored via OAE. This will limit the growth of the industry as unmeasurable carbon offsets will not qualify as high-quality permanent offsets. This is one main avenue of innovation in the field: creating monitoring, reporting and verification (MRV) processes and frameworks to assess how much carbon is being stored.

Potential solutions

Partner with miners: If enhanced weathering is to capture gigatons worth of carbon, then the amount of rock that needs to be mined will rival the coal industry by weight. Mining companies have built complex logistics networks to produce and transport minerals at a large scale. Partnerships with them could help reduce the cost of enhanced weathering strategies more quickly.

Carbon storage potential of different minerals



Source: BloombergNEF, A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration.

Enhanced weathering

Enhanced weathering

How does it work?

PROJECT VESTA

Project Vesta's enhanced weathering process deposits ground-up olivine, one of the earth's most abundant minerals, on the coast. Minerals are deposited on the coast so that wave energy can further erode them. This increases the surface area of the rock making it more reactive and accelerating the weathering process. The weathered minerals are then washed into the ocean where they neutralize carbonic acid, reducing acidity and strengthening the ocean carbon sink. Project Vesta is developing IP to monitor, report and verify the amount of carbon that is actually being stored in the ocean through this process, which it says should be useful for verifying all kinds of ocean alkalinity-based carbon removal processes.

Maturity

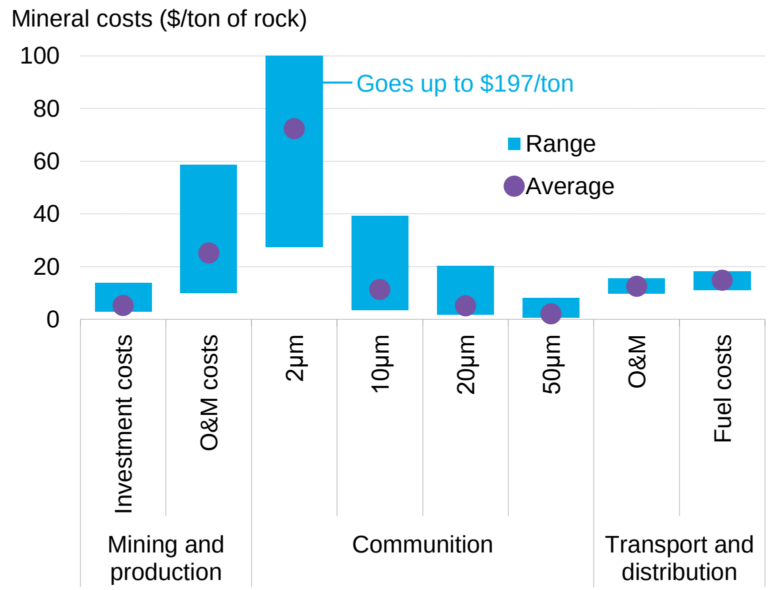
Project Vesta was funded as part of Stripe's first carbon removal purchase. These removals were procured at a price of \$75/tCO_2, and it hopes to reduce the price to \$25/tCO_2 at scale. The company is hoping to run pilot projects in 2022 to verify the ecological safety of its process and scale up to 1MtCO_2 in cumulative removals by 2026.

Eion

Eion is also using olivine to carry out enhanced weathering. It is distinct from Project Vesta in that it is applying olivine to inland soils rather than the coast.

Eion was founded in 2021 and is planning a pilot project this year, applying mineral deposits to soil in the southeastern US. Eion was selected as part of Stripe's Fall 2021 carbon removal purchase and is contracted to deliver its offsets at a price of \$500/tCO_2. It ultimately hopes to achieve costs of \$50-100/tCO_2 at scale.

Cost of producing ground-up rock



Grinding up minerals to very fine levels makes minerals more reactive but increases the cost per ton of rock by up to 160%.

Project Vesta's approach relies on wave energy to break down minerals to smaller sizes. This should reduce the cost of mineral processing while generating a lot of reactivity.

Source: BloombergNEF, Potential and costs of carbon dioxide removal by enhanced weathering of rocks.
Note: Communition refers to the fineness to which rock must be ground up. 'O&M' refers to operation and maintenance

Electrochemical ocean capture

Electrochemical ocean capture processes control ocean pH to strengthen the oceanic carbon sink. There are several electrochemical routes for ocean-based capture, and it is not yet clear which could be cheapest at scale. The cost of pilot projects is in excess of $1,000/t$CO_2$ because they require capital-intensive customized electrolyzers. One of the main challenges associated with electrochemical ocean-based removal is that the processes often produce a huge quantity of acid as a byproduct that must be neutralized. Current demand for acid would only absorb this co-product if the industry was limited to the megaton scale. Electrochemical processes should collocate with industrial sites (such as water treatment facilities and mines) that complement their feedstock and co-product composition to reduce costs.

New approaches and technologies

There are multiple electrochemical routes for strengthening the ocean carbon sink:

Electrochemical ocean alkalinity enhancement: Electrochemistry can be used to produce bases (such as oxides or hydroxides) that, when added to the ocean, enhance alkalinity and drawdown carbon. This process is akin to enhanced weathering, but the source of alkalinity is not a natural mineral.

Direct ocean capture: There are several electrochemical pathways to directly extract CO_2 from seawater. They involve shifting the pH of a stream of seawater to induce a reaction where carbon is expelled from the water in the form of gas or solid carbonate. Proponents argue this should be more energy efficient than DAC because there is 150 times more CO_2 per unit volume in water compared with air.

Limitations

Feedstock, coproducts: Electrochemical routes either require some kind of limited feedstock, such as mine tailings, or produce some kind of acidic or basic co-product that needs to be neutralized. These co-products could be sold to generate revenue. If the processes are done at gigaton scale, however, new markets will need to be cultivated to absorb the sheer amount to co-product that is produced.

High capital costs: The chloralkali process is a widely used industrial electrochemical process that produces caustic soda (sodium hydroxide) – a synthetic base that could be used for ocean alkalinity enhancement. If the caustic soda produced in this mature* process was used as a source of alkalinity, the cost of carbon capture would be $533-668/t$CO_2$, largely the result of an expensive electrolyzer.

**Note: While this is mature, it is not optimized for cheap carbon removal. Innovations in the field should be able to bring costs below this estimate.*

Potential solutions

Pair approaches: Some electrochemical approaches could potentially be used in tandem to improve their efficiency.

Collocation: Collocating electrochemical capture facilities with water treatment sites that are pumping streams of water anyway, or next to industrial sites that can act as suppliers or consumers of feedstock and co-products will likely be essential in making electrochemical ocean capture cost-competitive.

Natural and manufactured sources of alkalinity for ocean alkalinity enhancement

Silicates and carbonates are abundant and can be mined but are less reactive with CO_2. These are used in **enhanced weathering.**

Silicates: $MgSiO_4 + 4CO_2 + H_2O \rightarrow 2Mg^{2+} + 4HCO_3^- + SiO_2$

Carbonates: $CaCO_3 + CO_2 + H_2O \rightarrow Ca^{2+} + 2HCO_3^-$

Hydroxide: $Mg(OH)_2 + 2CO_2 \rightarrow Mg^{2+} + 2HCO_3^-$

Hydroxides are more reactive but must be synthetically produced via electrochemical process and so are more expensive to procure.

Source: BloombergNEF

Electrochemical ocean capture

Electrochemical ocean alkalinity enhancement

How does it work?

Maturity

Ebb Carbon

Ebb Carbon's technology is similar to the chloralkali process – the industrially mature production process for producing caustic soda. Rather than using an electrolyzer to split water like the chloralkali process, Ebb uses electrodialysis (a combination of electrical potential and ion-selective membranes) to split seawater into weak hydrochloric acid and sodium hydroxide solutions. Ebb's process produces a weaker base than the mature chloralkali process, but this has two benefits. First, sodium hydroxide has to be dilute before it is put in the ocean to avoid damaging ecosystems. Second, Ebb's process is 1.5-2 times more energy efficient than the chloralkali process because it uses a lower voltage. Ebb's process produces hydrochloric acid as a byproduct. It says that the current hydrochloric acid market could absorb its co-products if conducted at a megaton scale, but it is also exploring new use cases for HCl to create more demand for the product.

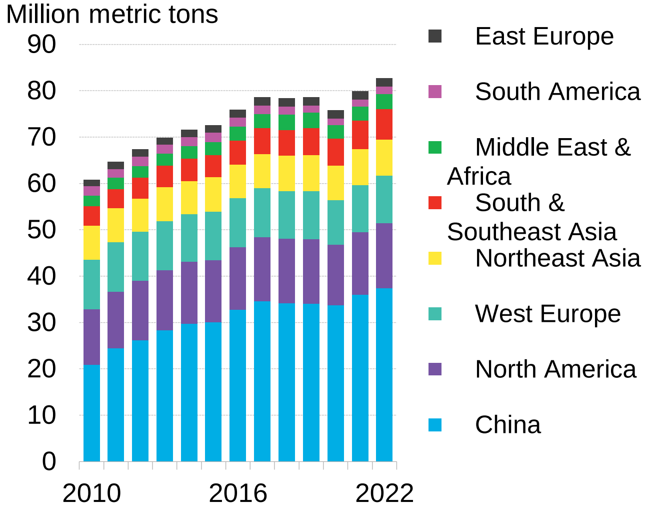
Ebb Carbon was founded in 2021 and has raised $3 million in seed funding. The company was selected as part of Stripe's most recent Fall 2021 carbon removal purchase. The price of its current offsets was set at $1,950/t$CO_2$ and it has not publicly stated what the process might cost at scale.

Planetary

Planetary Technologies has developed an electrochemical process that uses alkaline mine tailings as a feedstock to simultaneously produce hydroxides, hydrogen and valuable metals. The hydroxides are then put in the ocean to enhance alkalinity. The process can produce metals because it is carried out on mine tailings that have small amounts of trace metals that are not worth mining using traditional approaches. This form of metals extraction could be economic using Planetary Technologies' approach because of the additional benefit generated by removing carbon and producing hydrogen.

Planetary Technologies was founded in 2020. The company was originally named Planetary Hydrogen and focused on co-producing hydroxides with hydrogen. It now appears to have shifted focus to processing mine tailing to co-produce metals, hydrogen and hydroxides. Its technology is at pilot stage. Planetary Technologies has raised a total of $7.4 million, which has been generated through a combination of grants, accelerators and seed funding. Most recently, it was awarded $1 million as one of 15 companies selected to receive funding from the Carbon Removal XPRIZE. Planetary Technologies has also received funding from Shopify's Frontier Sustainability Fund.

Caustic soda production by country



Source: BloombergNEF. Note: If the entirety of the production capacity described in this chart were applied to ocean-based carbon removal projects, it would amount to around 70MtCO_2 in removal, demonstrating the vast scale required if gigatons of carbon removal is to occur.

Electrochemical ocean capture

Direct ocean capture

SEACHANGE

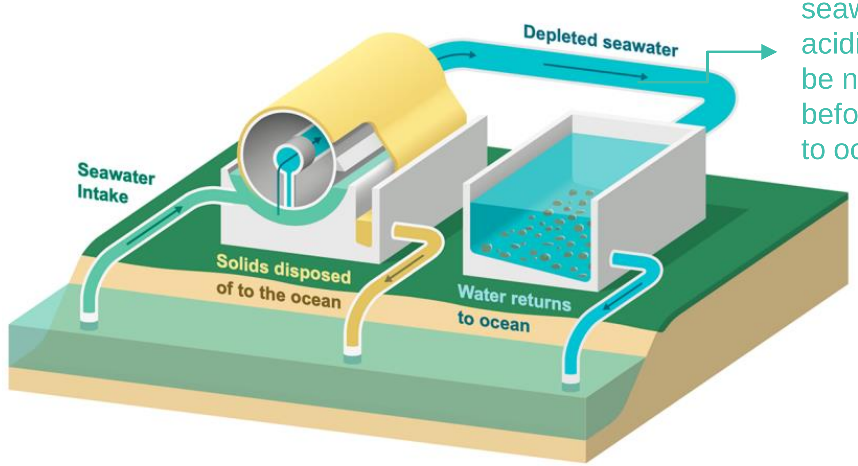
How does it work?

SeaChange uses an electrochemical process on a stream of seawater to induce a precipitation reaction – in other words, carbon in the water reacts with magnesium and calcium to form solid carbonates. This carbon is essentially removed from the water's carbon balance, so when the stream of water returns to the ocean, it starts to absorb more CO_2 from the atmosphere. SeaChange's process uses electrical potential to create conditions of extreme alkalinity around its cathode, inducing the carbonation. The process also generates acid around the anode, which must be separated and treated to rebalance pH before it can be returned to the ocean. Seachange's process produces hydrogen as a byproduct.

Maturity

SeaChange was founded in 2021 based on research conducted at UCLA. The company is aiming to bring its first pilot plant online in 1Q 2023, with a capacity of 365tCO_2/year. SeaChange has not announced any funding it has raised, but it was selected as part of Stripe's carbon removal purchase program. Its offsets were priced at \$1,370/tCO_2. The company has not disclosed future cost estimates, but a paper describing the process estimated a cost of \$145/tCO2 at scale; though it also notes this does not account for the sale of hydrogen produced by the process.

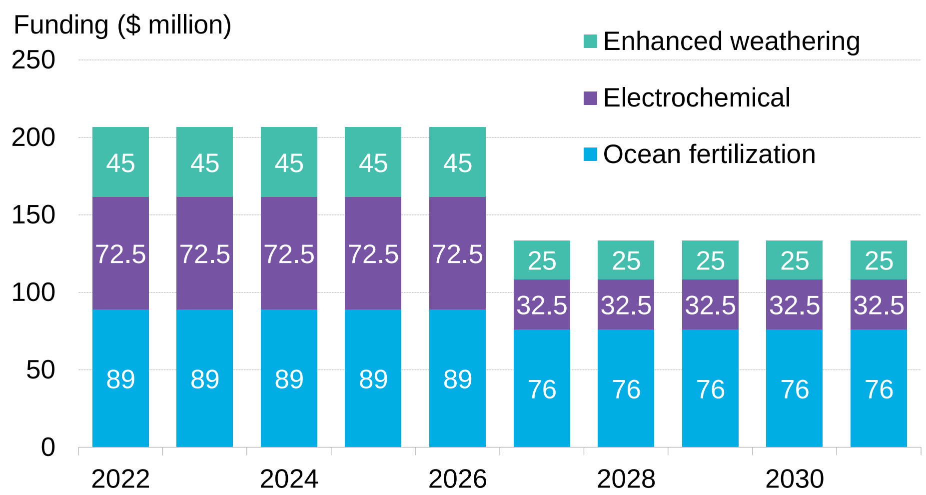
Diagram of SeaChange's process



Depleted seawater is acidic and must be neutralized before returning to ocean

Source: BloombergNEF, Saline Water-Based Mineralization Pathway for Gigatonne-Scale CO_2 Management

Recommended R&D funding plan for developing ocean-based carbon removal



Source: BloombergNEF, A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration.

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Further reading

Relevant research content

Research note	Links
2021 CCUS Market Outlook	web | terminal
Material Tech Highlight: Direct Air Capture	web | terminal
CCUS Projects Database (1.2)	web
Climate-Tech Innovation: The Carbon Cycle	web | terminal
Canada Announces Hefty Credits for Carbon Capture	web | terminal
Long-Term Carbon Offsets Outlook 2022	web | terminal
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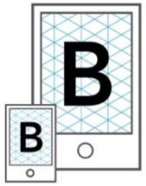

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