# Carbon Removal Landscape Analysis

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# Executive Summary

Carbon removal (also known as carbon dioxide removal or negative emissions technologies) refers to a collection of natural and technological methods for removing carbon dioxide ($CO_2$) from the atmosphere to reduce—and possibly reverse—climate change. The Intergovernmental Panel on Climate Change recently concluded that large-scale carbon removal will be essential to meeting global climate goals. Carbon removal captures $CO_2$ from the air *after* it has been emitted, as opposed to carbon capture and storage (CCS), which captures $CO_2$ emissions *before* they enter the atmosphere; carbon removal, however, may employ the same transport and storage infrastructure used by CCS. Carbon removal also differs from carbon capture and utilization (CCU), which involves recycling $CO_2$ for use in the production of goods or the provision of services; the $CO_2$ being recycled, however, may derive from carbon removal (or CCS).

For carbon removal to be effective, recovered $CO_2$ must be stored permanently; temporary storage of $CO_2$ captured from the atmosphere (by trees, for example) is insufficient because it will eventually be re-emitted (because of wildfires, pests, disease, or natural death). Thus, *technological* carbon removal methods, which typically store $CO_2$ permanently in geological formations underground, should be prioritized over natural removal methods, which store $CO_2$ in plants and soils. At present, three technological methods appear capable of removing large amounts of $CO_2$ from the atmosphere:

- Bioenergy with carbon capture and storage (BECCS) combines bioenergy with CCS by capturing the $CO_2$ released when energy is extracted from biomass—$CO_2$ that was previously taken from the air during photosynthesis—and storing it underground; since the $CO_2$ sequestered by BECCS is effectively relocated from the atmosphere to the subsurface, permanent carbon removal is achieved. BECCS would require large quantities of biomass, posing risks to food and water security, biodiversity, and land tenure.

- Direct air capture (DAC) captures $CO_2$ by "scrubbing" it directly from the ambient air; if the captured $CO_2$ is then injected underground, it is stored permanently. DAC involves significant energy requirements, and therefore is most effective when powered by low- or no-carbon energy sources.

- Ocean alkalinity enhancement (OAE) would entail adding large amounts of alkaline (that is, basic, as opposed to acidic) materials to the ocean to promote oceanic absorption of atmospheric $CO_2$ while simultaneously reducing ocean acidification. Compared to BECCS and DAC, OAE is much less researched.

Carbon removal would be slow to act and expensive to implement, and currently there are few incentives to pay for it. Most observers assume that carbon removal will ultimately be incentivized using carbon markets, but markets must be modified, expanded, and/or supplemented if they are to promote innovation and upscaling. Markets must also be designed both to mitigate the moral hazard that implementing technological carbon removal might undermine decarbonization, and to allocate financial responsibility for removing atmospheric $CO_2$ on a durable and ideally equitable basis. In addition, research, development, and demonstration must be adequately funded by governments.

Global governance structures have not yet evolved to address carbon removal in a serious way, but several meaningful policy frameworks are beginning to emerge at regional and national levels. In Europe, the European Commission is providing limited funding for research on technological carbon removal methods, but more significant is its current work drafting a proposal for a Carbon Removal Certification Mechanism which might ultimately allow for the inclusion of carbon removal activities in Europe's Emissions Trading System, the world's most important carbon market. In the United States (US), Congress has authorized at least $8 billion in research funding for technological carbon removal since 2021, while the recently passed Inflation Reduction Act significantly expanded tax credits to incentivize DAC and BECCS deployment. The US has emerged as the global leader in "technology-push" and "demand-pull" policies for promoting technological carbon removal, both of which will be essential to scaling up and bringing down the costs of these methods.

While all civil society groups engaged on the topic of carbon removal support at least some forms of natural carbon removal, a divide has opened over the question of technological removals. In general, organizations based in the US tend to support the development of methods like BECCS and DAC, while those based in Europe tend to oppose such development. This pattern is also apparent when comparing emerging policy frameworks in the US and Europe. The "European" perspective (which is shared by many American and other political actors) is grounded in the view that natural methods *work with* nature whereas technological methods *interfere with* nature. The prevalence of this view impedes the upscaling and learning-by-doing necessary to bring down the high costs associated with BECCS and DAC, which pose the most significant structural constraints on meaningful deployment of carbon removal.

This analysis leads to the following recommendations:

**Recommendation 1: Convene a collaborative process involving civil society actors, scientists, and other relevant stakeholders with the goal of prioritizing permanence as the key criterion for evaluating carbon removal methods, to build support for the meaningful inclusion of technological removal methods in evolving policy and governance frameworks.**

**Recommendation 2: Organize a series of workshops to devise and assess market and policy design options for incorporating carbon removals into carbon markets in environmentally and socially sustainable ways.**

**Recommendation 3: Fund research on OAE to confirm—or disconfirm—its potential as an especially promising future option for large-scale permanent carbon removal (and means to counter ocean acidification).**

**Recommendation 4: Support a project to collect, systematize, and share data on research funding for carbon removal.**

# Carbon Removal Landscape Analysis

**Introduction**

This study provides an overview of the science, methods, governance, policy, and politics of carbon removal, for the purpose of offering recommendations for strategic interventions in this space by the Rockefeller Foundation. Carbon removal refers to a collection of natural and technological methods for removing carbon dioxide ($CO_2$) from the atmosphere to reduce—and possibly reverse—climate change; to be effective, $CO_2$ removed from the atmosphere must be stored permanently. The need for permanent, large-scale carbon removal means that technological methods—such as bioenergy carbon capture and storage (BECCS), direct air capture (DAC), and ocean alkalinity enhancement (OAE)—will play a more significant role than natural methods. Because technological methods are less mature and more costly, however, they require policies to encourage innovation and upscaling. Yet political resistance to such methods inhibits demand, limiting opportunities for economies of scale and learning-by-doing to bring down costs and facilitate deployment.

To characterize the carbon removal landscape, this report proceeds as follows. First, basic science and policy considerations related to carbon removal will be reviewed, with special attention paid to BECCS, DAC, and OAE, including their development status. This will be followed by sections on key constraints, global governance, emerging policy frameworks, and critical measures for funding research and incentivizing technology development. Next, civil society actors and activities will be considered, followed by a discussion of how the perceived distinction between nature and technology is shaping the politics and trajectory of carbon removal. Finally, four specific recommendations informed by this landscape analysis will be made. They include:

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**Recommendation 2: Organize a series of workshops to devise and assess market and policy design options for incorporating carbon removals into carbon markets in environmentally and socially sustainable ways.**

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**Recommendation 4: Support a project to collect, systematize, and share data on research funding for carbon removal.**

**Basic Science and Policy Considerations**

$CO_2$ is the primary greenhouse gas (GHG) in the atmosphere, accounting for about three-quarters of total GHG emissions. These emissions are amplifying the natural greenhouse effect and causing global warming and climate change. Once emitted, the atmospheric lifetime of $CO_2$ is between 300 and 1,000 years, which means that past, present, and future $CO_2$ emissions are effectively permanent in policy-relevant terms. The only way to lower atmospheric concentrations of $CO_2$ and dial back the greenhouse effect, therefore, is to remove the gas from the air *and* store it permanently. Temporary storage of $CO_2$ captured from the atmosphere (by trees, for example) is insufficient because it will eventually be re-emitted (because of wildfires, pests, disease, or natural death). Given likely global emissions trajectories, the Intergovernmental Panel on Climate Change (IPCC) recently concluded that large-scale $CO_2$ removal from the atmosphere will be "unavoidable" if the world is to meet net-zero $CO_2$ and other key climate goals (IPCC 2022a).[1]

Removing $CO_2$ from the atmosphere, also referred to as carbon removal, carbon dioxide removal (CDR), and negative emissions technologies (NETs), will need to be large-scale due to the enormous quantity of $CO_2$ already emitted combined with the huge amount of future emissions "locked in" as a result of continuing global investments in fossil fuel-based energy and industrial infrastructure and other path-dependent carbon-intensive practices. Specifically, experts estimate that meeting the Paris Agreement temperature targets of less than 2 °C warming and ideally no more than 1.5 °C warming above preindustrial levels will require the world to remove approximately 10 gigatonnes (Gt, or one billion metric tons) of $CO_2$ per year by 2050 and approximately 20 Gt annually by 2100 (global $CO_2$ emissions in 2021 were approximately 36 Gt) (NASEM 2019).[2]

Carbon removal is slow and expensive, but its risks are primarily local. It is *slow* because the climate effects of $CO_2$ in the atmosphere have lag times of at least a decade, which creates considerable inertia in the climate system. Hence, just as there is a delayed climate response to adding $CO_2$ to the atmosphere, there will be a delayed response to removing $CO_2$ from the atmosphere. Carbon removal is *expensive* because $CO_2$ is relatively dilute in the atmosphere; its current concentration is approximately 415 parts per million (ppm) (the significant effect of $CO_2$ on the climate even at seemingly low levels reflects its potency as a GHG). The low concentration of $CO_2$ in the atmosphere means that substantial energy is required to remove it, and this makes the removal process costly. The risks entailed in carbon removal, however, are mostly *local* (except for "moral hazard"—see below). Specific risks vary depending on the

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[1] Net-zero $CO_2$ refers to a future point in time at which emissions of $CO_2$ exactly equal removals of $CO_2$ from the atmosphere by natural and human means.

[2] One rationale for developing carbon removal technologies has focused on their potential role in offsetting emissions from so-called "hard-to-abate" sectors, or industries such as cement, steel, and chemicals for which reducing emissions is especially technically and economically challenging. While carbon removal has a role in substituting for particularly costly or practically unachievable emissions cuts, its primary function clearly will be to remove $CO_2$ from the atmosphere at planetary scale.

removal method under consideration (see below), and some risks may be significant at local scale. But at the global level, the risks of carbon removal are comparatively low.

Currently, actors have few incentives to pay for carbon removal. Most observers assume that carbon removal will ultimately be incentivized using mandatory ("compliance") carbon markets.[3] Such markets, also known as emissions trading schemes (ETSs) or cap-and-trade systems, set overall limits on $CO_2$ emissions within defined boundaries over a set period; distribute an equivalent number of emissions allowances (or carbon credits) to power plants, factories, and other regulated entities; allow these entities to trade credits; and, at the end of the period, require entities to turn over allowances equal to their emissions. Over time, the total emissions limit is reduced to (close to) zero. In principle, credits for carbon removal could be integrated into existing markets for emissions reductions, or new markets strictly for carbon removal could be created.

Carbon removal is not the same as carbon capture and storage (CCS). CCS refers to capturing $CO_2$ emissions from "point sources" like power plants or steel mills *before* they enter the atmosphere by separating it from flue gas, compressing it into liquid form, transporting it (typically via pipeline), and injecting it underground into saline aquifers or depleted oil fields (onshore or offshore) for permanent storage. (An emerging form of carbon storage, not conventionally recognized as a possible component of CCS, is known as carbon mineralization. Carbon mineralization entails injecting $CO_2$ underground into basalt or ultramafic rock formations, with which $CO_2$ reacts to form solid minerals and is thereby permanently sequestered.) Carbon removal, by contrast, captures $CO_2$ from the air *after* it has been emitted (rather than from the top of a smokestack). $CO_2$ captured from the atmosphere, however, may be transported and stored underground using the same transport and storage infrastructure used to sequester $CO_2$ from point sources.

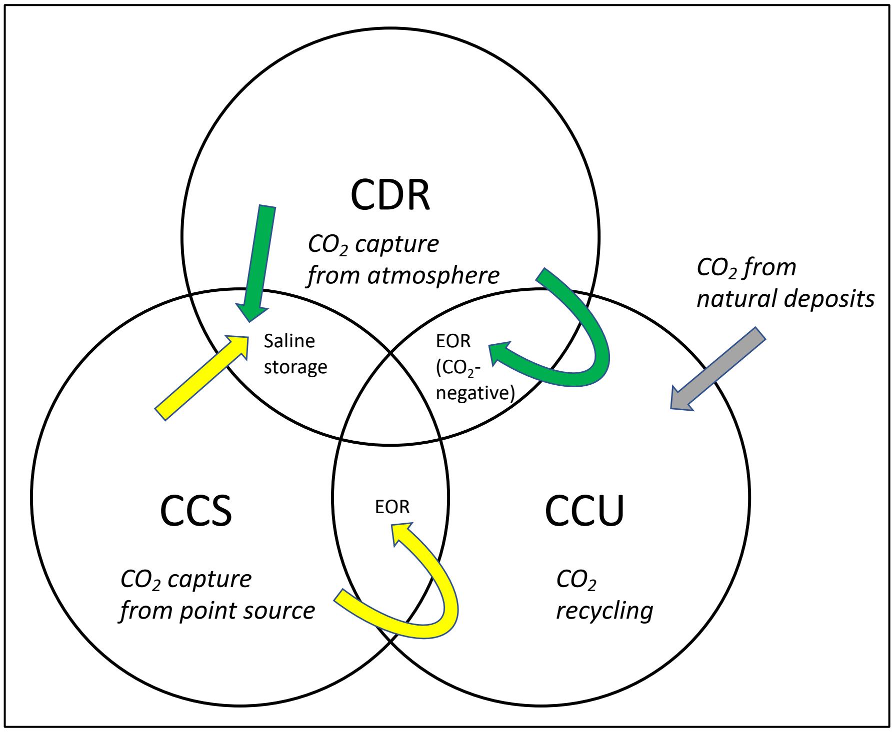
In addition, carbon capture and utilization (CCU) differs from both carbon removal and CCS. CCU involves recycling $CO_2$ for use in the production of goods like fuels and chemicals or to provide services, primarily enhanced oil recovery (EOR). (EOR entails injecting $CO_2$ into depleted oil fields to extract otherwise unrecoverable oil—the injected $CO_2$ remains underground permanently.) $CO_2$ recycled for CCU may be sourced from either CCS or carbon removal. The $CO_2$ embedded in CCU products is usually re-emitted to the atmosphere. CCU achieves carbon removal only when 1) the $CO_2$ used in CCU derives from carbon removal, 2) the sum of emissions involved in removing $CO_2$ from the atmosphere and converting it into an end-product or using it for EOR is *less than* the quantity of $CO_2$ removed from the atmosphere, *and* 3) the $CO_2$ embedded in the end-product or used in EOR is stored permanently. (CCU overlaps with CCS when point-source $CO_2$ used in CCU applications is sequestered on a long-term basis.) In practice, only low-efficiency EOR (in which no more than two barrels of oil are recovered per ton of $CO_2$ injected) and construction materials that are made from carbonated steel slag meet these criteria (de Kleijne et al. 2022). But CCU is relevant to carbon removal insofar as demand

[3] The incentives provided by voluntary markets will likely be insufficient.

for CCU products and EOR provides incentives for carbon removal technology development and cost reductions.[4]

Figure 1 illustrates the relationship between carbon removal, CCS, and CCU.

**Figure 1: Relationship Between CDR, CCS, and CCU**




Note: Arrows represents flows of $CO_2$.

Many different carbon removal methods have been proposed, and some have already been developed. From a climate policy perspective, the most important ones are those that appear capable of removing and storing large amounts of $CO_2$ for long periods of time. The *durability of storage* is critical because stored $CO_2$ must remain sequestered from the atmosphere. $CO_2$ stored in geological formations (saline aquifers or depleted oil fields) will stay underground for at least 10,000 years; geological storage is regarded as "permanent."[5] $CO_2$ stored in plants and soils, by contrast, is vulnerable to natural and human-caused disturbances which may lead to storage reversals and re-emissions to the atmosphere; it is thus "non-permanent." Methods that store $CO_2$ in plants and soils are frequently referred to as "natural," "nature-based," "land-

[4] Additionally, the term carbon capture, utilization, and storage (CCUS) is sometimes used to refer to CCS and CCU together. Since CCUS excludes $CO_2$ sourced from carbon removal (it only pertains to $CO_2$ captured from point sources), this term is not used in this report.

[5] The use of modern site characterization protocols, monitoring systems, and other risk management practices, developed based on decades of experience with geological storage, is now widely regarded as sufficient to prevent significant leaks from faults, fractures, or damaged or defective wellbores.

based," "terrestrial," or "biological" carbon removal.[6] For simplicity, the term "natural carbon removal" will be used in the remainder of this report.[7] Box 1 provides an overview of the leading existing and proposed forms of natural carbon removal.

**Box 1: Natural Carbon Removal Methods**

Natural options rely on the uptake of $CO_2$ by plants and soils to remove carbon from the atmosphere and store it in natural carbon sinks. Many of these methods generate substantial co-benefits at the local level (for example, soil carbon sequestration enhances agricultural productivity). Pursuing such methods may thus be important for reasons unrelated to carbon removal. Natural options include:

Afforestation/Reforestation—Forestry projects have been used as offsets in both voluntary and mandatory carbon markets for decades. The vulnerability of forests to wildfires, diseases, subsequent deforestation, and other threats raises questions about the permanence of $CO_2$ stored in trees. May compete for land with agriculture and conservation. Monoculture plantations could threaten biodiversity.

Soil Carbon Sequestration in croplands and grasslands—Consists of a suite of agricultural practices that stimulate $CO_2$ uptake in soils, typically enhancing productivity. Practices include no-till farming, planting cover crops, and crop rotation. Net removal per hectare is small and difficult to monitor.

Peatland and coastal wetland restoration—Peatlands are a significant carbon sink, and restoring them—for example, through rewetting—can increase the amount of $CO_2$ they store. Similarly, restoring coastal wetlands such as mangroves can enhance carbon storage in vegetation and soil. Opportunities may be limited.

Agroforestry—Broadly refers to integrating trees, shrubs, and reforestation initiatives with crop and livestock systems to improve land use efficiency, prevent soil erosion, facilitate water infiltration, improve yields and water use, and store $CO_2$. Agroforestry can enhance biodiversity and improve system resilience.

Improved forest management—Measures to increase carbon stocks in managed forests include longer rotations, reduced harvests, planting more resilient species, etc. Improved forest management can enhance biodiversity and increase productivity.

Biochar—Biochar is a charcoal-like substance composed of stable $CO_2$ produced when biomass is heated under low-oxygen conditions. It can be produced using multiple feedstocks and

[6] "Nature-based" carbon removal options are sometimes conflated with "nature-based solutions," a group of measures—for example, ecosystem-based adaptation—which occupy the space where carbon removal and climate adaptation overlap.

[7] "Natural" carbon removal methods also, of course, rely on technology. Tree planting, for example, depends on a broad technical apparatus for its practical implementation.

spread over agricultural land to improve crop yields and enhance resilience to drought. Inappropriate production methods could cause pollution and promote unsustainable biomass harvest.

Preservation of "blue carbon" in coastal wetlands—Reducing conversion of carbon stocks in mangroves, marshes, and seagrass ecosystems to avoid emissions from degradation or loss. Loss of blue carbon cannot be easily reversed. Efforts to preserve blue carbon may boost coastal protection and increase biodiversity but may also cause ecological disruptions. Carbon removal potential is small.

Ocean fertilization—Adding nutrients like iron to the ocean to promote phytoplankton growth and associated carbon uptake via photosynthesis; when phytoplankton die, some settle in the deep ocean where carbon is stored on a long-term basis. Ocean fertilization may increase productivity including for fisheries. Research indicates that ocean fertilization would negatively affect marine ecosystems, including by altering oceanic food webs.

Natural carbon removal methods are characterized not only by unreliable storage, but also by limited removal potential. *Removal potential* is critical because, as noted, the world will need to remove $CO_2$ from the atmosphere at large (Gt) scale. Except for large-scale tree planting, Gt-scale removal potentials are restricted to large-scale technological systems. These systems are typically referred to as "technological," "technology-based," "industrial," or "engineered" carbon removal. The term "technological carbon removal" will be applied to these options in the remainder of this report.[8] There are three main large-scale technological removal methods: BECCS, DAC, and OAE.[9] Each of these methods also involves permanent storage, in geological formations for BECCS and DAC and in the ocean for OAE (see below). Given the overriding importance of durability and scale for effective carbon removal, this study will therefore focus primarily on BECCS, DAC, and (to a lesser extent considering its relative immaturity) OAE. These will now be considered in greater detail.

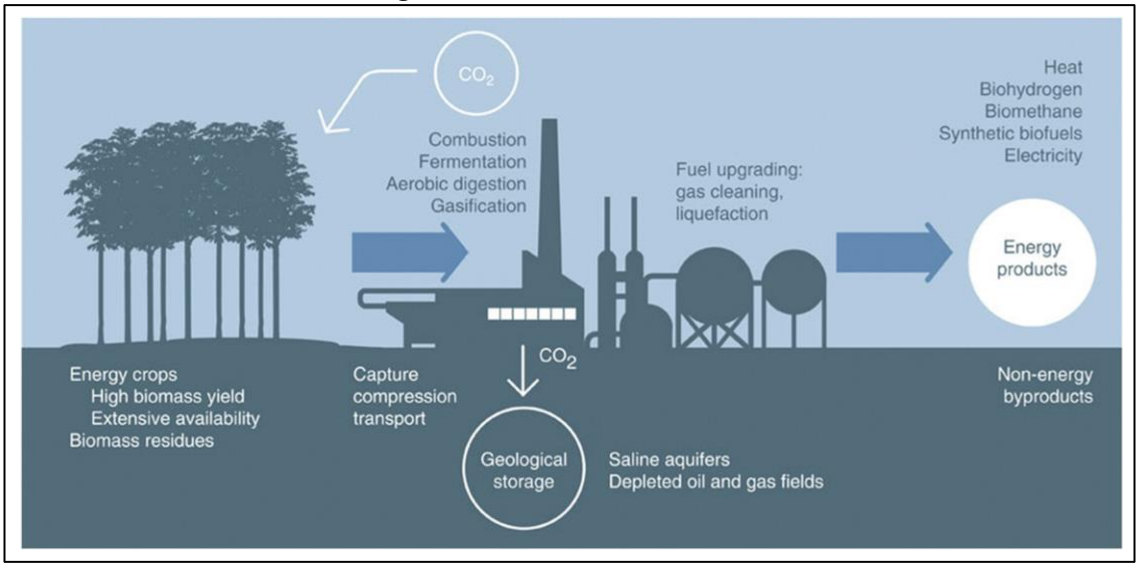
**BECCS**

BECCS combines bioenergy with CCS by capturing the $CO_2$ released when energy is extracted from biomass—$CO_2$ that was previously taken from the air during photosynthesis—and storing it underground; since the $CO_2$ sequestered by BECCS is effectively relocated from the atmosphere to the subsurface, permanent carbon removal is achieved. BECCS has the additional benefit of producing energy—electricity, heat, and/or biofuels—which can be sold in energy markets. Biomass feedstocks for BECCS include residues and waste from agriculture and

[8] "Technological" carbon removal methods also, of course, rely on nature. DAC, for instance, exploits natural chemical or physical processes to absorb or adsorb, respectively, $CO_2$ (see footnote 12 below).
[9] Enhanced weathering (EW) is a smaller-scale technological removal method. With EW, natural chemical rock weathering could be accelerated by grinding rocks like olivine and basalt and spreading the powder over croplands or forests in tropical and subtropical areas, drawing down atmospheric $CO_2$. The mining, grinding, and distribution infrastructure required to implement EW would be vast, costly, and energy-intensive. EW is similar to OAE, except that operations would take place on land. Given its low removal potential, EW will not be considered further.

forestry, municipal solid waste, and possibly dedicated energy crops. Biomass is converted into energy at power plants, combined heat and power (CHP) plants (biomass is typically co-fired with coal at power plants and CHP plants), and biorefineries. $CO_2$ is captured at these facilities, compressed, transported, and injected underground. The global technical carbon removal potential of BECCS is estimated to range from 0.5 to 11 $GtCO_2$ per year (IPCC 2022b). Cost estimates range from $15 to $400 per $tCO_2$ (IPCC 2022b). Figure 2 illustrates how BECCS works.

**Figure 2: Illustration of BECCS**




Source: Canadell and Schulze 2014.

To operate at large scale, BECCS would require large quantities of biomass, and this entails several risks and limitations. Fundamentally, demand for biomass may bring BECCS into competition with other forms of land use. Agriculture may come under pressure, particularly if energy crops become a primary source of biomass for BECCS. Competition for farmland may lead to higher food prices and could threaten food security. Growing energy crops would also require significant water use, and so would the carbon capture process at point sources; both forms of water consumption would compete with irrigation for agriculture and exacerbate water stress more generally. Nature conservation may also come under pressure from competition for land driven by BECCS, compounding risks to biodiversity. Addressing these sustainability concerns would require implementing safeguards and impose limits on the contribution BECCS could make to carbon removal at the global level.

The largest BECCS facility currently in operation is the Illinois Industrial Carbon Capture and Storage (IL-ICCS) demonstration project located at an Archer Daniels Midland (ADM) plant in Decatur. The IL-ICCS project captures a pure stream of $CO_2$ generated as a byproduct of ethanol production and injects it into a nearby saline aquifer for permanent storage; approximately 1 million metric tons of $CO_2$ ($MtCO_2$) are sequestered annually. The purity of the $CO_2$ stream produced by the manufacture of ethanol eliminates the need to separate $CO_2$ from flue gas, thus reducing the capture cost. The Decatur project is supported by the US government.

Recently, Drax Power Limited, owner and operator of the Drax Power Station in the United Kingdom (UK), submitted plans for the Drax Bioenergy Carbon Capture and Storage Project to authorities for approval. This project would capture $CO_2$ from existing biomass generating units, transport it via pipeline, and inject it into a saline aquifer under the North Sea at a rate of up to 8 $MtCO_2$ per year.[10] Construction could begin as soon as 2024. If built, the Drax BECCS Project would be the world's first BECCS power plant and the world's largest CCS project.[11] Drax is the only major company presently focused on BECCS technology development.

A handful of small-scale BECCS pilots and demonstrations are currently in operation worldwide, as shown in Table 1. Ethanol production, with its capacity for efficient carbon capture while generating a valuable, marketable end-product, has been a critical driver of early BECCS development. Most $CO_2$ captured from biomass processing to date, however, has been used for EOR. The IL-ICCS project run by ADM is the only BECCS facility involving storage in a saline aquifer.

[10] The biomass used in these units consists of wood pellets sourced from the southern US, the harvest of which has been criticized as unsustainable.
[11] The Drax project would constitute one part of the broader Zero Carbon Humber partnership, a proposed industrial cluster also involving hydrogen production and CCS. In turn, Zero Carbon Humber is one component of the larger East Coast Cluster collaboration, which following official selection as a "Track-1" cluster is currently pursuing support from the UK government.

**Table 1: BECCS Facilities in Operation Worldwide**

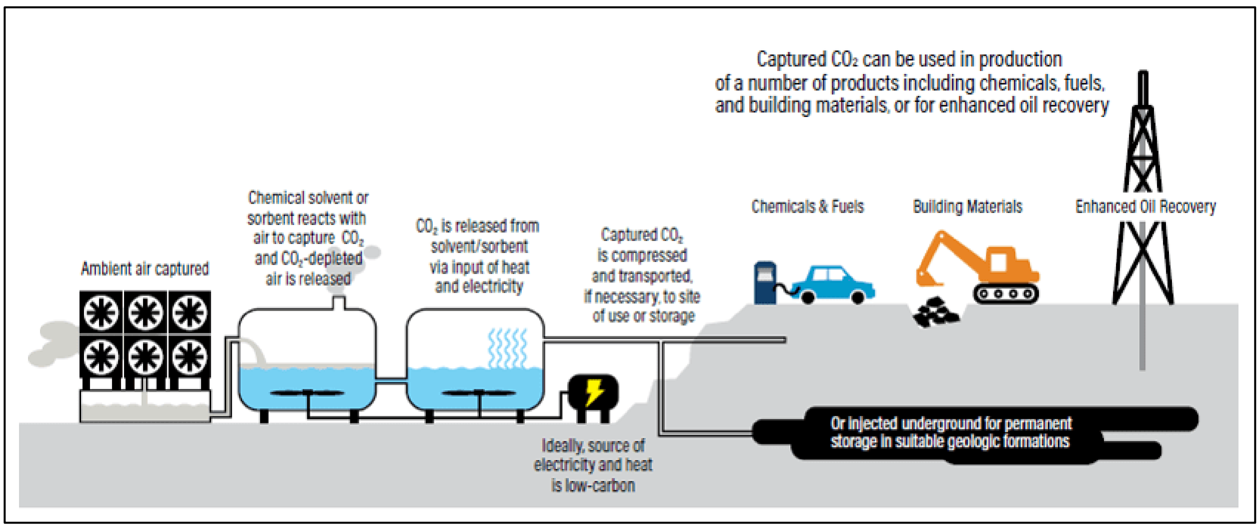
| Name | Company | Country | Sector | Storage or Utilization | Start-Up Year | Capture Capacity ($tCO_2$ /year) |
|---|---|---|---|---|---|---|
| $CO_2$ Compression Facility | Arkalon Energy | US | Ethanol production | Utilization | 2009 | 290,000 |
| Mikawa Post Combustion Capture Demonstration Plant | Sigma Power Ariake | Japan | Power generation | N/A | 2009 | 3,000 |
| OCAP | Abengoa | Netherlands | Ethanol production | Utilization | 2011 | 100,000 |
| CCUS EOR | Bonanza BioEnergy | US | Ethanol production | Utilization | 2012 | 100,000 |
| Lashburn and Tangleflags $CO_2$ Injection in Heavy Oil Reservoirs Project | Husky Energy | Canada | Ethanol production | Utilization | 2012 | 90,000 |
| Norway Full Chain CCS | Norcem | Norway | Cement production (>30% biomass) | N/A | 2013 | Variable |
| Purification facility | Lantmannen Agroetanol | Sweden | Ethanol production | Utilization | 2015 | 200,000 |
| $CO_2$ recovery plant | Calgren Renewable Fuels | US | Ethanol production | Utilization | 2015 | 150,000 |
| Bio-refinery $CO_2$ recovery plant | Alco Bio Fuel | Belgium | Ethanol production | Utilization | 2016 | 100,000 |
| Wheat processing $CO_2$ purification plant | Cargill | UK | Ethanol production | Utilization | 2016 | 100,000 |
| Waste Incineration Plant | Saga City | Japan | Waste-to-energy | Utilization | 2016 | 3,000 |
| IL-ICCS | ADM | US | Ethanol production | Storage | 2017 | 1,000,000 |

Source: Consoli 2019.
Note: “N/A” indicates that the facility vents captured $CO_2$ to the atmosphere.

**DAC**

In contrast to BECCS, which draws down $CO_2$ from the atmosphere indirectly via biomass, DAC captures $CO_2$ by "scrubbing" it directly from the ambient air. If the captured $CO_2$ is then injected underground, it is stored permanently—this is sometimes referred to as direct air carbon capture and storage or DACCS. (When DAC is used to remove $CO_2$ from the atmosphere for utilization in end-products or in EOR—which as noted may have storage benefits—DAC is comparable to CCU.) $CO_2$ is removed from the air using either liquid solvents or solid sorbents; both methods are energy-intensive and thus expensive.[12] Given its significant energy requirements, DAC is most effective when powered by low- or no-carbon energy sources. Unlike BECCS, DAC depends on neither (biomass) supply chains nor downstream energy markets, which provides it with comparatively greater siting flexibility (subject to the availability of storage resources). The global technical carbon removal potential of DAC is estimated to range from 5 to 40 $GtCO_2\ yr^{-1}$ (IPCC 2022b). Cost estimates range from \$84 to \$386 per $tCO_2$ (IPCC 2022b). Figure 3 illustrates how DAC works.

**Figure 3: Illustration of DAC**




Source: Lebling 2020.

Carbon Engineering, a Canadian company founded in 2009, began operating a liquid solvent-based DAC pilot plant in 2015 in Squamish, British Columbia, that captures 1 $tCO_2$ per day. Starting in 2017, these DAC operations were coupled with renewable hydrogen production to synthesize alternative low-carbon transport fuels. In 2020, Carbon Engineering licensed its technology to 1PointFive, a development company owned by Oxy Low Carbon Ventures (a subsidiary of Occidental Petroleum), which plans to build a larger "Commercial Validation Plant" in the Permian Basin in West Texas expected to be operational by 2024. If completed, this facility would be capable of removing between 0.5 and 1 $MtCO_2$ per year for injection for

[12] A sorbent is a material that can be used to absorb or adsorb (hold on the surface) substances. The solid sorbent DAC process involves *adsorption* of $CO_2$.

EOR. The storage associated with its planned EOR operations would in effect make this facility the world's largest DACCS plant.[13] 1PointFive and Carbon Engineering have jointly developed a modularized global DAC "deployment approach" aimed at building 70 DAC plants worldwide by 2035.

Climeworks, a Swiss company also founded in 2009, began operating the first of what is currently a fleet of fifteen solid sorbent-based DAC demonstration plants in Europe in 2017. Initially, Climeworks sold approximately two thousand metric tons of captured $CO_2$ annually for use by food and beverage manufacturers and greenhouses and in the production of alternative fuels. About 50 metric tons of $CO_2$ captured annually at its plant in Hellisheidi, Iceland, however, were stored underground using carbon mineralization in collaboration with the Icelandic storage company Carbfix. DAC operations in Iceland were subsequently expanded with the 2021 launch of the Orca plant, which removes up to four thousand metric tons of $CO_2$ per year for permanent sequestration via carbon mineralization. Orca is powered by geothermal energy and is the world's first DACCS plant. Construction is now underway on an even larger plant in Iceland called Mammoth, which will be capable of capturing 36,000 metric tons of $CO_2$ per year. Mammoth is expected to become operational in 2024.[14] In addition to building plants, Climeworks is also pioneering new business models for carbon removal, including offering removal as a service on a subscription basis.

In addition to Climeworks and Carbon Engineering, Global Thermostat is another major player involved in DAC technology development. Founded in the US in 2010, Global Thermostat has built two pilot plants and is collaborating with ExxonMobil to improve and scale up its technology. Global Thermostat is also working with alternative fuels company HIF to build an air-to-fuel pilot plant in Chile.

Table 2 shows DAC plants currently in operation worldwide. Like BECCS, most operational DAC facilities use captured $CO_2$ to produce goods or provide services, including in combination with surplus electricity in so-called "power-to-X" schemes to manufacture fuels or chemicals.

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[13] Carbon Engineering is also working with carbon removal developer Storegga on plans to build a DAC project in Scotland, as well as constructing a larger air-to-fuel plant in Canada intended to be operational in 2026.

[14] Climeworks is currently exploring possibilities for an additional project with Carbfix joined by Northern Lights, a Norwegian offshore $CO_2$ transport and storage project (see below), and a new project with 44.01, an Oman-based carbon mineralization startup.

**Table 2: DAC Plants in Operation Worldwide**

| Name | Company | Country | Sector | Storage or Utilization | Start-Up Year | Capture Capacity ($tCO_2$ /year) |
|---|---|---|---|---|---|---|
| - | Global Thermostat | US | R&D | Not known | 2010 | 500 |
| - | Global Thermostat | US | R&D | Not known | 2013 | 1,000 |
| - | Climeworks | Germany | Customer R&D | Utilization | 2015 | 1 |
| AIR TO FUELS pilot plant | Carbon Engineering | Canada | Power-to-X | Utilization | 2015 | ≤365 |
| Celbicon | Climeworks | Switzerland | Power-to-X | Utilization | 2016 | 50 |
| Capricorn | Climeworks | Switzerland | Greenhouse fertilization | Utilization | 2017 | 900 |
| Arctic Fox | Climeworks | Iceland | $CO_2$ removal | Storage | 2017 | 50 |
| | Climeworks | Switzerland | Beverage carbonation | Use | 2018 | 600 |
| STORE&GO 1 | Climeworks | Switzerland | Power-to-X | Utilization | 2018 | 3 |
| STORE&GO 2 | Climeworks | Italy | Power-to-X | Utilization | 2018 | 150 |
| STORE&GO 3 | Climeworks | Germany | Power-to-X | Utilization | 2019 | 3 |
| - | Climeworks | Netherlands | Power-to-X | Utilization | 2019 | 3 |
| - | Climeworks | Germany | Power-to-X | Utilization | 2019 | 3 |
| - | Climeworks | Germany | Power-to-X | Utilization | 2019 | 50 |
| - | Climeworks | Germany | Power-to-X | Utilization | 2020 | 50 |
| - | Climeworks | Germany | Power-to-X | Utilization | 2020 | 3 |
| - | Climeworks | Germany | Power-to-X | Utilization | 2020 | 3 |
| Orca | Climeworks | Iceland | $CO_2$ removal | Storage | 2021 | 4,000 |

Source: Budinis et al. 2022.
Note: “Power-to-X” refers to utilizing surplus electric power to produce fuels or chemicals.

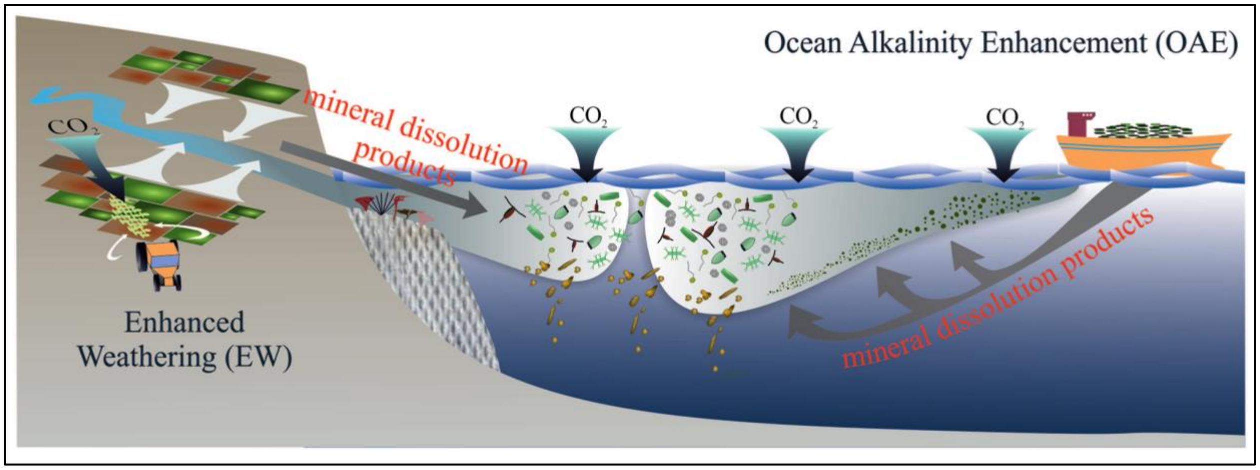
**OAE**

Compared to BECCS and DAC, OAE is much less developed and has been studied primarily using models. The basic idea behind OAE is that large amounts of alkaline (that is, basic, as opposed to acidic) materials—silicate or carbonate rocks or their dissolution products—added to the ocean will transform $CO_2$ dissolved in seawater into stable bicarbonates and carbonates, raising pH and helping counter ocean acidification.[15] This carbon removal will induce additional drawdown of atmospheric $CO_2$ into surface waters. OAE thus holds the promise of addressing

[15] Ocean acidification is caused by oceanic uptake of $CO_2$ from the atmosphere, which lowers ocean pH and thereby reduces the ability of marine calcifying organisms such as corals to build shells; these and other disruptions pose serious risks to marine ecosystems and related human activities like fishing.

*both* climate change and ocean acidification.  The global technical carbon removal potential of OAE is estimated to range from 1 to 100 $GtCO_2$ per year (IPCC 2022b).  Cost estimates range from \$40 to \$260 per $tCO_2$ (IPCC 2022b).  Figure 4 illustrates how OAE works.

**Figure 4: Illustration of OAE**




Source: Bach et al. 2019.

The impacts of enhanced alkalinity on marine ecosystems, however, are not fully understood. Moreover, obtaining and delivering the necessary quantities of alkaline materials for OAE would require a brand-new, global-scale industry to mine, process, pulverize, transport, and distribute the requisite minerals at sea.  Such an industry may pose local environmental risks and entail significant $CO_2$ emissions.[16]  Yet despite these uncertainties and risks, the magnitude of the carbon removal potential associated with OAE combined with its apparent capacity to counter ocean acidification make this method worthy of further consideration.

The first outdoor OAE experiments were recently conducted off the Canary Islands (in 2021) and the coast of Norway (in 2022), using “mesocosms” or free-floating experimental enclosures.  These experiments were conducted within the framework of the OceanNETs ocean-based carbon removal research project led by the GEOMAR Helmholtz Center for Ocean Research Kiel based in Germany.

**Limitations and Governance Challenges**

As a rule, the risks associated with carbon removal scale with the magnitude of removals.  Since large-scale removals generally require technological methods, technological carbon removal is typically riskier than natural carbon removal.  Most of the risks and disadvantages related to technological carbon removal, however, are context-dependent or technology-specific.

[16] For example, manufacturing quicklime from (carbonate) limestone via calcination (heating to a high temperature) for deposit in the ocean—a version of OAE sometimes called “ocean liming”—would entail significant $CO_2$ emissions.

Limitations and constraints applicable to individual technologies—land-use concerns for BECCS, energy requirements for DAC—were covered in the preceding sections. Yet a handful of broader risks pertain to all technological methods of carbon removal.

One is the possibility that discussing, studying, or implementing technological carbon removal might reduce incentives to decarbonize, a prospect typically referred to as "moral hazard." Moral hazard might occur because the promise of future technologies capable of cleaning up current emissions may cause actors to view mitigation as less urgent. This is partly a function of people's tendency to discount the future relative to the present. Moral hazard might also stem from the active promotion of technological carbon removal as an alternative to emissions cuts by fossil-fuel interests or others opposed to mitigation for commercial and/or ideological reasons.

The possibility of moral hazard is problematic for at least three reasons. First, since reducing emissions is usually cheaper than removing $CO_2$ from the atmosphere, substituting technological carbon removal for emissions cuts would be unnecessarily costly. Second, forgoing emissions cuts today in favor of technological carbon removal tomorrow would entail accepting otherwise avoidable climate damages in the interim. And third—and most fundamentally—there is no guarantee that the potential for future technological carbon removal suggested by early research will be realized in practice; the promise of technological removal, in other words, may turn out to be a case of "magical thinking" (Rayner 2016).

The limited empirical research that has been conducted on the potential moral hazard effect of technological carbon removal shows very little evidence that exposure to information about technological removal affects support for decarbonization (Sol Hart et al. 2022). The oil and gas industry has taken some initial steps toward greater involvement in technological carbon removal, as exemplified by Oxy Low Carbon Ventures' partnership with Carbon Engineering in the Permian Basin.[17] This is unsurprising given its pioneering role in EOR and related control over core elements of the industrial base needed to build, operate, and maintain pipelines and injection sites for carbon removal by BECCS and DAC (Ortiz, Samaras, and Molina-Perez 2013). However, although the oil and gas sector has a long history of fighting against efforts to regulate $CO_2$, its nascent involvement in technological carbon removal does not appear motivated by a desire to undermine climate action but instead by dual interests in boosting oil production from depleted fields and profiting from early opportunities in an emerging industry. Contrary to the logic of moral hazard, oil and gas companies like Oxy seem to view technological carbon removal as a supplementary source of income in an increasingly carbon-constrained world, rather than as a means to subvert carbon controls.

Nevertheless, historically bad behavior on the part of the oil and gas industry warrants deep skepticism about its present and future intentions, and prudence dictates that some degree of moral hazard should be anticipated. To guard against this possibility, one proposed solution is

[17] Other examples include investments in Carbon Engineering made by Chevron, Occidental Petroleum, and BHP as well as by oil sands financier N. Murray Edwards.

to separate technological carbon removal from emissions reductions in carbon markets, either by establishing separate markets for each activity or by capping the number of technological carbon removal credits within a unified market (McLaren et al. 2019). Making technological carbon removal credits and emissions reduction credits non-fungible would limit substitutions of the former for the latter, thereby helping protect the integrity of critical emissions reduction goals.

The expense of technological carbon removal compared to emissions reductions stands as an additional constraint on the technology independent from its role in moral hazard. As noted above, technological carbon removal will be very expensive, and someone will have to pay for it. For example, a representative estimate of the cost of carbon removal in 2100 is 3.9 percent of global gross domestic product (GDP). When adjusted to reflect historical emissions, this figure rises to 15 percent of GDP in developed countries (Bednar, Obersteiner, and Wagner 2019). Clearly these sums are huge, and even fractions of these estimates are bound to generate considerable disagreements over who should pay both among and within countries. One proposed solution is to make emitters of $CO_2$ responsible for removing it from the atmosphere by issuing "carbon removal obligations" integrated into carbon markets; adding interest payments to this carbon debt would help accelerate near-term emissions reductions (Bednar et al. 2021).

A final problem relates to the need to develop technological carbon removal early and quickly to maximize the likelihood that sufficient capacity is available later this century; this has been labeled "innovation and upscaling" (Nemet et al. 2019, 3). Put simply, a huge gap exists between present capabilities and the enormous scale of removals anticipated to be required in the decades ahead. Technologies must mature and costs must decline—both rapidly—for carbon removal to play its expected role in reducing climate risks. Bringing down costs, accelerating development, and ultimately bridging this gap will depend on two complementary approaches, "technology-push" and "demand-pull" (Nemet 2009). Technology-push consists of research and development (R&D) and pilot and demonstration projects, all of which typically require government funding. Demand-pull entails promoting market demand via public policies such as subsidies, technology mandates, and provisions in intellectual property law.

Table 2 summarizes the major constraints and potential governance solutions associated with technological carbon removal. Governance solutions vary in terms of their likely feasibility and effectiveness.

**Table 2: Constraints and Potential Governance Solutions Associated with Technological Carbon Removal**

| Constraint | Governance Solutions | Notes |
|---|---|---|
| Moral hazard | Separate markets | Weak evidence to date |
| High cost | Carbon removal obligations | Who should pay? |
| Innovation and upscaling | Technology-push, demand-pull | Gap between present capabilities and future needs |

## Global Governance

Global governance structures have not yet evolved to address technological carbon removal in a serious way. Indeed, they rarely distinguish between natural and technological removal methods. The following provides descriptions of those treaties and multilateral environmental agreements that address at least some aspect of carbon removal:

- United Nations Framework Convention on Climate Change (UNFCCC)—The UNFCCC is the principal international governance framework for addressing climate change and is the framework within which both the Kyoto Protocol and the Paris Agreement were developed. The original text of the UNFCCC endorsed carbon removal by "sinks" and storage in "reservoirs," and the Paris Agreement calls for achieving net-zero in the second half of this century. The Clean Development Mechanism (CDM), a carbon offset program operated under the Kyoto Protocol, issued a limited number of credits for afforestation and reforestation (tree planting), but not for BECCS, DAC, or OAE. (Although it was never used, the CDM did approve a methodology for CCS). The CDM is now being transitioned into a successor market mechanism under the Paris Agreement currently referred to as the "Article 6.4 Mechanism," based on existing methodologies (including, presumably, for CCS). The Article 6.4 Mechanism is envisioned to issue credits for an expanded suite of carbon removal activities which may include technological removal.

- Convention on Biological Diversity (CBD)—The CBD is intended to protect global biodiversity. The CBD has taken some initial steps to address carbon removal. By far the most important was its Decision X/33 adopted in 2010, which urged parties to prohibit all carbon removal activities (natural and technological) that could negatively impact biodiversity, except for "small scale scientific research studies." This "invitation," however, is not legally binding, and the US is not a party to the CBD. Nevertheless, the broad call to abstain contained in Decision X/33 is now widely referred to as an international "moratorium" on carbon removal.

- London Convention/London Protocol (LC/LP)[18]—The LC/LP regulates ocean dumping. In 2013, parties to the Protocol adopted Resolution LP4(8), which if ratified by enough countries to bring it into force would amend the agreement to prohibit ocean-based carbon removal except for "legitimate scientific research." The amendment, however, has not entered into force.

- United Nations Environment Assembly (UNEA)—UNEA is the governing body of the UN Environment Programme, the highest international political body for the environment. At its fourth session in 2019 (UNEA-4), Switzerland planned to introduce a draft resolution which would have initiated a formal technology assessment of carbon removal methods. Switzerland withdrew the resolution prior to the start of the meeting, however, due to unresolved disagreements.

**Emerging Policy Frameworks**

Several carbon removal policy frameworks are beginning to emerge at regional and national levels against a background of uniformly low public awareness of carbon removal (e.g., Cox, Spence, and Pidgeon 2020). These frameworks usually distinguish between natural and technological carbon removal methods, and support both, yet they are at different stages of development and include varying blends of technology-push and demand-pull measures. The following describes the most important of these frameworks—especially as they relate to technological carbon removal—organized according to jurisdiction (for more see Schenuit et al. 2021):

- European Union (EU)—As the sole EU institution with authority to initiate legislation, the European Commission has played a key role in early European involvement in natural and technological carbon removal. This year the Commission awarded €180 million ($180 million) from the EU Emissions Trading System (ETS) Innovation Fund to support the BECCS Stockholm project in Sweden, and it is currently preparing to award up to €21 million ($21 million) in grants under the Horizon Europe research and innovation funding program to carbon removal research projects including for technological methods. (The predecessor to Horizon Europe, Horizon 2020, helped fund the Hellisheidi DAC collaboration between Climeworks and Carbfix as well as the OceanNETs OAE experiments, both mentioned above.) The Commission has also provided political and funding support to the Porthos $CO_2$ transport and storage project in the Netherlands and the Northern Lights transport and storage project in Norway.[19] On the demand side, by the end of 2022 the Commission plans to propose a Carbon

[18] The LC, signed in 1972, specifies materials that either may not be dumped in the ocean or may be dumped but only if a permit is obtained; materials not specified may be dumped without restriction. In contrast, the LP, signed in 1996, specifies materials that may be dumped but only with permits (this is referred to as a "reverse list"); materials not specified may not be dumped. The LP is intended to eventually supersede the LC.
[19] Norway is not a member of the EU, but its offshore geological storage resources are considered a critical destination for $CO_2$ captured in northern Europe in the future—this is the basis of Commission support for the Northern Lights project.

Removal Certification Mechanism (CRC-M), including rules for monitoring, reporting, and verification. Whether the CRC-M will encompass technological methods is currently unknown. The Commission will report to the European Parliament by 2025 on the possible inclusion of carbon removal activities in the EU ETS.

- US—The US is emerging as a leader in promoting both natural and technological carbon removal. The Energy Act of 2020 established a Carbon Dioxide Removal Program for research led by the Department of Energy (DOE), a $100 million Commercial Direct Air Capture Technology Prize Competition, a $15 million Pre-Commercial Direct Air Capture Technology Prize Competition, and a Carbon Storage Validation and Testing Program. The 2021 Bipartisan Infrastructure Law established a Regional Direct Air Capture Hubs program at DOE with $3.5 billion in funding to create four hubs each capable of removing at least 1 $MtCO_2$ per year, while separately providing $4.6 billion in funding to support the Carbon Dioxide Transport/Front-End Engineering Design (FEED) Program. Also in 2021, DOE launched a "Carbon Negative Shot" initiative linking together many of its research efforts and organized around the goal of reducing the cost of technological carbon removal to less than $100 per $tCO_2$. Although prospects for a national cap-and-trade system remain dim, the recently passed Inflation Reduction Act (IRA) of 2022 expanded a previously existing tax credit known as "45Q" from $50 to $85/$tCO_2$ stored in saline formations and from $35 to $60/$tCO_2$ used for EOR (both applicable to BECCS), and from $50 to $180/$tCO_2$ captured directly from the air and stored in saline formations and from $50 to $130/$tCO_2$ from DAC used for EOR.[20]

- UK—The UK has been an early innovator in natural and technological carbon removal. Since 2020, the Department for Business, Energy and Industrial Strategy has managed the £70 million ($81 million) Direct Air Capture and Greenhouse Gas Removal Programme distributing grants to multiple research projects including for BECCS, DAC, and OAE. Separately, this year UK Research and Innovation launched a £31.5 million ($36 million) Greenhouse Gas Removal Demonstrators Programme in support of technological carbon removal research including on BECCS.

- Sweden—Through its Industrial Leap program, Sweden is providing up to 100 million Swedish kroner ($9 million) in research and innovation funding for BECCS through 2022 and will provide up to 50 million Swedish kroner ($5 million) from 2023 to 2027. The country's 2017 climate law set a goal of net-zero GHGs by 2045 and specified that achieving this must involve emissions reductions of at least 85 percent below 1990 levels; the remainder may be accomplished through "supplementary measures" consisting of carbon removal—including BECCS—and international offsets. Establishing a floor for cutting emissions is intended to help avoid reliance on carbon removal. The government plans to conduct reverse auctions for BECCS removals—in which it will act as the sole buyer of the most competitively priced removals—starting in 2023.

[20] Other 45Q enhancements provided by the Inflation Reduction Act include a longer commence-construction window, a direct payment option, and lower thresholds for facilities to qualify for the credit.

Table 3 summarizes key components of these emerging policy frameworks relating to technological carbon removal. Efforts have tended to focus more on technology-push than on demand-pull approaches up to now.

**Table 3: Key Components of Emerging Policy Frameworks for Technological Carbon Removal**

| Jurisdiction | Technology-Push | Demand-Pull |
|---|---|---|
| EU | Innovation Fund, Horizon Europe research funding | CRC-M proposal |
| US | Carbon Dioxide Removal Program (research); Carbon Storage Validation and Testing Program; Regional Direct Air Capture Hubs; Carbon Dioxide Transport Program; Carbon Negative Shot | 45Q (expansion); Direct Air Capture Technology Prize Competitions |
| UK | Direct Air Capture and Greenhouse Gas Removal Programme; Greenhouse Gas Removal Demonstrators Programme | |
| Sweden | Industrial Leap research funding | Net-zero supplementary measures, reverse auctions |

**Innovation: Technology-Push and Demand-Pull**

The technology-push and demand-pull measures jointly driving technological innovation in carbon removal have not been adopted solely by national (or regional) governments, but instead by a complex blend of international and national public authorities and for-profit and nonprofit private entities. Together, these various actors, policies, and processes constitute an innovation ecosystem. Measures for both prodding and inducing innovation, inside and outside those emerging policy networks discussed in the preceding section, comprise the substantive governance of carbon removal. Key technology-push and demand-pull measures within the broader technological carbon removal innovation ecosystem are described in what follows.

Technology-push measures in the carbon removal context relate primarily to funding for research, development, and demonstration (RD&D). Investments in carbon removal RD&D are split among regional and national governments, for-profit technology developers, and philanthropies. Although individual spending figures for a few highly visible initiatives led or supported by governments were noted in the previous section, detailed assessments of cumulative aggregate public funding for research on carbon removal, natural and/or technological, are generally unavailable, for two reasons. First, such funding has been highly scattered and fragmented: public funding in Europe has been spread across multiple supranational and intergovernmental institutions as well as national and subnational governments both within and outside the EU, while public funding in the US has been spread across multiple federal departments and agencies as well as across states like California and New York. And second, the terms and labels used to describe carbon removal technologies within and across governments have varied widely over the years, making comparative analysis difficult. Programs and projects often fail to distinguish between natural and technological removals. Consequently, we are aware of only a single comprehensive (but still limited) study of public funding for technological carbon removal RD&D, carried out for the US, the results of which show that federal funding for DAC between 2009 and 2019 totaled a mere $11 million (Hezir et al. 2018). (Federal funding for research on geological storage, however, totaled $1.8 billion from 2000 to 2018, much of it associated with the Regional Carbon Sequestration Partnerships Initiative.)[21]

Levels of private spending by for-profit companies seeking to develop technological carbon removal for sale in the marketplace are also challenging to assess, not only due to similar confusion over terminology, but more importantly because these companies are competing with one another and have strong incentives not to disclose information about R&D budgets and related trade secrets. This is exacerbated by the fact that many of these companies are privately held. Information about investments in carbon removal technology developers, usually in the form of venture capital provided by "catalytic capital" (i.e., impact investors such as Prime Coalition and Breakthrough Catalyst) or startup accelerators (i.e., fixed-term, cohort-based seed investment programs such as Third Derivative) is similarly difficult to track. Publicly available information about R&D spending by technological carbon removal startups and other developers is thus limited. We are not aware of any comprehensive studies of commercial R&D spending on technological carbon removal.

Philanthropic support for carbon removal R&D, provided by actors like ClimateWorks and the Grantham Foundation, is again difficult to assess due to terminological issues and variable reporting requirements. The sole analysis of which we are aware estimates global foundation support for carbon removal at $50 million over the period 2015 to 2020 (Desanlis et al. 2021). This figure, however, does not distinguish between natural and technological, nor does it distinguish between giving directed toward R&D and other forms of grant-making.

Hence, precise, or even approximate, estimates of research funding for carbon removal are currently unavailable. Yet what is clear from the limited data that are available is that US federal government support for technological carbon removal R&D exceeds that provided by other public and private sources by an order of magnitude. Congress has authorized at least $8 billion since 2021 for RD&D on DAC and transport and storage infrastructure (and almost certainly more including for BECCS).

Separate from this, demand-pull measures relevant to carbon removal include tax credits, multiyear corporate purchase agreements, prize competitions, and standard-setting. As the only country offering tax credits for technological carbon removal, and with these credits now significantly expanded, the US is similarly exceptional in this regard. Enhanced 45Q credits promise to stimulate greater investment in BECCS and especially DAC, and companies have already decided to launch new projects based on the availability of these stronger incentives.

[21] The Regional Carbon Sequestration Partnerships Initiative was a DOE-led, region-based network of projects engaged in early research on geological storage including multiple injection tests, which lasted from 2003 to 2021.

Although governments have yet to announce any plans to procure carbon removals directly from suppliers, a growing number of multinational corporations have made multiyear carbon removal purchase agreements on a voluntary basis with a wide variety of startups. Apart from seeking to reduce corporate carbon footprints, these purchases are motivated by multiple public policy goals including boosting demand for carbon removal, promoting early investments in emerging technologies, enhancing predictability for technology developers, and ultimately bringing down costs by expanding the market and encouraging economies of scale. Some purchased removals have been generated by technological methods, including more than 400,000 metric tons removed by DAC purchased at a total cost of $1.4 million from 2020 to now (Hoglund 2022). Notable efforts include:

- Stripe, an e-commerce payment processing company, has purchased $15 million in carbon removals from multiple startups including companies working on DAC and OAE. The company has also launched Stripe Climate, a program that allows customers to direct a percentage of their sales flowing through Stripe toward carbon removal purchases.

- Shopify, another e-commerce service provider, has purchased $32 million in carbon removals from multiple startups including companies working on DAC and OAE. Shopify has pledged to invest at least $1 million annually in carbon removal companies.

- Microsoft has purchased more than 1.3 Mt$CO_2$eq carbon removal including BECCS and DAC.

In early 2022, Stripe, Shopify, Alphabet (Google), Meta (Facebook), and McKinsey came together to create Frontier, an advance market commitment to purchase $925 million worth of carbon removal by 2030 from nascent carbon removal companies, to accelerate R&D and lower costs. Frontier is owned by Stripe and modeled on a previous effort to spur vaccine development. Working through Frontier, Stripe has purchased an additional $2.4 million in carbon removals from multiple startups including companies developing DAC. Separately (and with some overlap), corporate members of the new First Movers Coalition have pledged to purchase at least 50,000 metric tons or $25 million in technological carbon removals by the end of 2030.

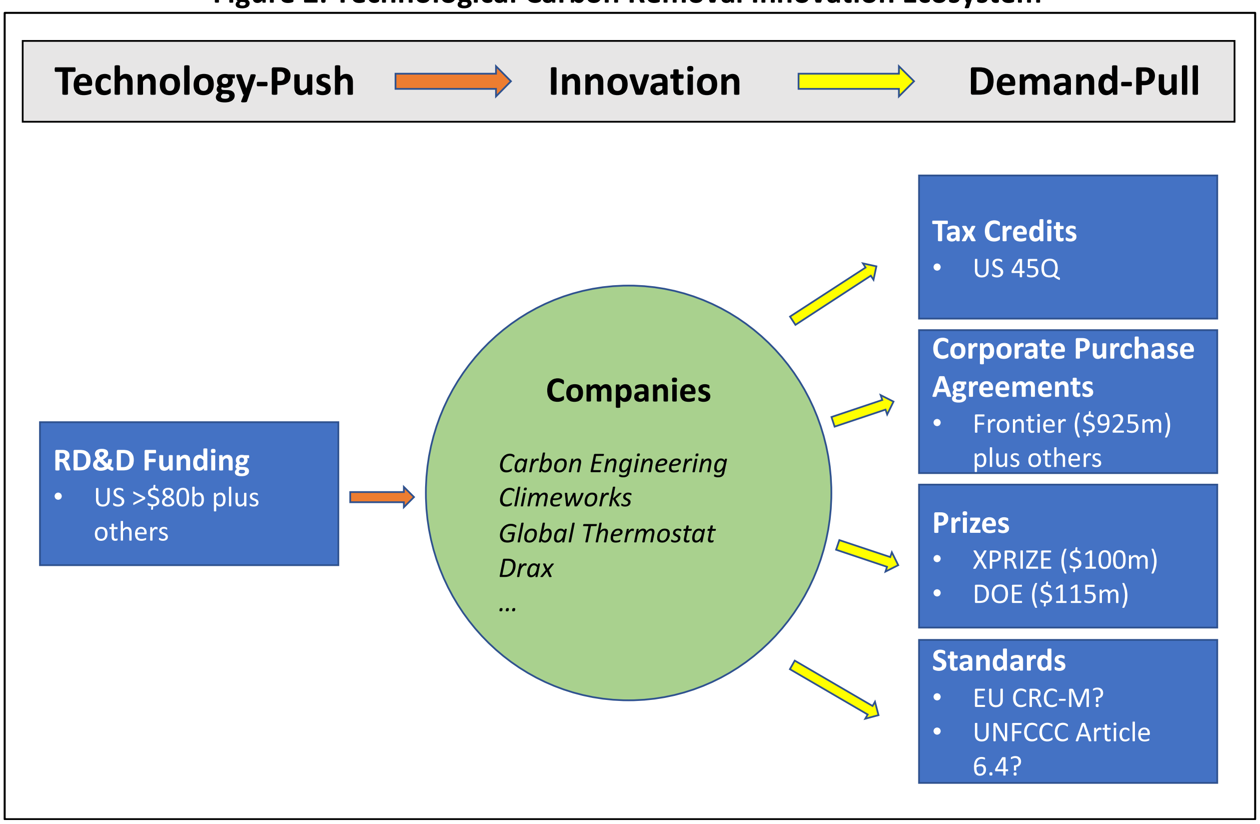
A handful of prize competitions for carbon removal technologies have been announced. Most prominent among them is the $100 million XPRIZE Carbon Removal funded by Elon Musk and the Musk Foundation, launched in 2021 and continuing until 2025. The XPRIZE is a demonstration competition with a $50 million grand prize; $1 million “Milestone Prizes” have already been awarded to DAC and OAE developers. In addition to the XPRIZE, DOE anticipates specifying rules for its Direct Air Capture Prize Competitions by the end of the year.[22]

[22] The Virgin Earth Challenge was launched in 2007 with a $25 million prize for innovations in carbon removal. In 2019, however, the competition was closed because no entries had satisfied the prize criteria.

The final demand-pull measure currently being deployed for carbon removal is standard-setting, specifically credit certification procedures and methodologies. Certification bodies have been slow to integrate technological carbon removals into either voluntary or compliance markets (see Arcusa and Sprenkle-Hyppolite 2022). Puro.Earth, based in Finland, has developed a methodology for "geologically stored carbon" applicable to BECCS or DAC for awarding "$CO_2$ removal certificates"; it is currently the only voluntary certificate provider for such methods. Similarly, the California Air Resources Board, with its approved CCS Protocol applicable to BECCS or DAC for awarding credits under the state's Low Carbon Fuel Standard, is the only compliance entity addressing such methods. Over the next decade, however, EU adoption of a certification framework and UNFCCC elaboration of the Article 6.4 Mechanism may facilitate deeper integration of carbon removal credits into global carbon markets, incentivizing more rapid development of technologies like BECCS, DAC, and perhaps OAE.

Figure 2 illustrates how public and private actors are working together to promote advances in technological carbon removal by supporting and incentivizing technology development in an emerging global innovation ecosystem.

**Figure 2: Technological Carbon Removal Innovation Ecosystem**



**Civil Society**

A growing number of civil society groups are engaging on the topic of carbon removal. All of them support at least some forms of natural carbon removal, and most of them are headquartered in Europe or North America. They include environmental and other NGOs, think-tanks, and trade associations with a mix of national, regional, and international orientations. In general, those organizations that are based in the US tend to support the development of technological carbon removal methods like BECCS and DAC, while those based in Europe tend to oppose such development. Notable supporters of technological removal include:

- Additional Ventures—Additional Ventures is a nonprofit organization that supports the development of high-risk innovative solutions to public policy problems. It leads a philanthropic consortium called the Ocean Alkalinization Enhancement R&D Program focused on ocean science and technology innovation.

- Bellona—Bellona is a European NGO focused on climate action in partnership with civil society, academia, and business. Bellona supports integrating technological carbon removals into voluntary and compliance markets, including the EU ETS, on a sustainable basis.

- Carbon180—Carbon180 is a relatively new but influential NGO dedicated to designing and advocating for policies to advance technological carbon removal. It is focused primarily on the US government and increasingly interested in promoting environmental justice. Carbon180 has been actively involved in recent legislative developments such as the IRA.

- Carbon Business Council—The Carbon Business Council is a US-based trade association advocating for carbon removal. The Council supports all removal methods and is exploring greater inclusion of removals in voluntary markets as well as market separation to divide reductions from removals.

- Carbon Capture Coalition—The Carbon Capture Coalition, convened by the Great Plains Institute, advocates broad deployment of CCS, CCU, and carbon removal technologies, including by lobbying the US federal government. Its membership encompasses private companies, labor unions, and environmental NGOs. The Coalition supports DAC and BECCS technology development.

- Carbon Gap—An NGO working to promote research and policy support for natural and technological carbon removal in Europe.

- Clean Air Task Force (CATF)—A US-based, internationally active environmental NGO that advocates for research and eventual deployment of technological carbon removal. CATF has taken a particular interest in the proposal for certifying carbon removals currently under development by the European Commission.

- Coalition for Negative Emissions—This new group is essentially an international trade association for carbon removal technology developers. Its purpose is to advocate for national and international policies and public-private partnerships that promote technological carbon removal.

- DAC Coalition—An international group of DAC developers and stakeholders that coordinates advocacy for the technology.

- Environmental Defense Fund (EDF)—EDF is a mainstream US-based environmental NGO grounded in scientific and economic analysis and frequently supportive of using market-based instruments to address environmental problems. EDF supports research on development of carbon removal methods including BECCS and DAC.

- Linden Trust for Conservation—The Linden Trust is a philanthropy focused on US climate policy. Its initiative on carbon removal includes efforts devoted to community education, policy analysis and program design, and policy advocacy, with an emphasis on measures capable of attracting bipartisan support. Projects supported by the Linden Trust have called for technological carbon removal.

- New Carbon Economy Consortium—The New Carbon Economy Consortium is a US-based alliance of universities, national labs, and NGOs working with industry leaders to promote carbon removal. They advocate research on a wide range of methods including BECCS and DAC.

- Rethinking Removals—Rethinking Removals is a public-private policy initiative seeking to play the role of "systems orchestrator" in support of natural and technological carbon removal and foster international dialogue. It is managed by Valence Solutions, a global consulting firm.

- The Nature Conservancy (TNC)—TNC is a US-based global conservation organization specializing in financing and helping manage local conservation projects through a collaborative approach. TNC has announced a goal of removing 3 $GtCO_2$ per year by 2030 using natural methods embedded in their conservation projects. TNC also supports development of technological carbon removal options.

- Ocean Visions—Ocean Visions is a network of academic and other institutions that promotes research on ocean-based carbon removal, collaborates with technology developers, and seeks to accelerate deployment. It has released an OAE R&D Road Map for developing the technology.

- Union of Concerned Scientists (UCS)—UCS is a science-oriented environmental NGO based in the US. UCS acknowledges the need for carbon removal and supports research on technological methods.

- World Resources Institute (WRI)—WRI is a US-based think-tank operating around the world which conducts policy-relevant research on environmental issues including climate change. WRI has begun to incorporate carbon removal into its core research portfolio and supports R&D on technological methods.

An overview of civil society supporters of technologies like BECCS and DAC is provided in Table 4. Some groups restrict their support to calls for research, while others advocate deployment, but all accept the need for technological removals. Unsurprisingly, these actors cluster around the political center. With the exceptions of Bellona, based in Norway, and Carbon Gap, based in the UK, every one of these organizations operates from the US.

**Table 4: Civil Society Actors *Supporting* Technological Carbon Removal**

| Actor | Headquarters Country | Geographical Scope | Focus | Political Leaning |
|---|---|---|---|---|
| Additional Ventures | US | Global | OAE | Center |
| Bellona | Norway | Europe | Climate change | Center |
| Carbon180 | US | US | Carbon removal | Center-left |
| Carbon Business Council | US | US | Carbon removal | Center |
| Carbon Capture Coalition | US | US | Carbon management | Center |
| Carbon Gap | UK | Europe | Carbon removal | Center |
| CATF | US | Global | Climate change | Center-left |
| Coalition for Negative Emissions | UK | Global | Carbon removal | Center |
| DAC Coalition | US | Global | DAC | Center |
| EDF | US | Global | Environment | Center-left |
| Linden Trust | US | US | Climate change | Center |
| New Carbon Economy Consortium | US | US | Carbon removal | Center-left |
| Ocean Visions | US | Global | Carbon removal (ocean-based) | Center-left |
| Rethinking Removals | US | Global | Carbon Removal | Center-left |
| TNC | US | Global | Conservation | Center |
| UCS | US | US | Environment | Center-left |
| WRI | US | Global | Environment | Center-left |

In contrast, civil society groups that are negatively disposed toward technological carbon removal include:

- Action Group on Erosion, Technology, and Concentration (the ETC Group)—The ETC Group is an activist NGO opposed to emerging technologies based on their exploitative potential. Starting in the late 2000s, the ETC Group shifted much of its attention to natural and technological carbon removal; it was the driving force behind the call for a moratorium adopted by the CBD.

- Biofuelwatch—An international activist NGO opposed to large-scale industrial bioenergy including BECCS.

- Center for International Environmental Law (CIEL)—CIEL is a transatlantic advocacy organization focused on environmental law. It is opposed to technological carbon removal but not to natural methods.

- Climate Action Network (CAN) International—CAN International is a global network of more than 1,500 climate advocacy groups. In 2021 it issued a position statement on carbon capture in which it expressed opposition to BECCS and DAC.

- European Environmental Bureau (EEB)—The EEB is a federation of European environmental NGOs. While it acknowledges the need for some carbon removal, the EEB strongly favors natural methods over technological options, and strongly prefers compliance to voluntary markets.

- FERN—FERN is a European NGO dedicated to regional and global forest protection. FERN does not strictly oppose carbon removal, but it is deeply concerned about the risks associated with technological methods, particularly BECCS.

- Greenpeace—Greenpeace is an international activist environmental NGO. Greenpeace accepts the need for limited carbon removal, but objects to technological removals and the use of removals as offsets in carbon markets.

- Institute for Agriculture and Trade Policy (IATP)—IATP is a global advocacy organization that promotes sustainable food systems. IATP opposes incorporation of natural "carbon farming" and technological removal methods into carbon markets on the basis that doing so would incentivize industrial agriculture and divert attention away from the need for immediate emissions cuts.

- Natural Resources Defense Council (NRDC)—NRDC is a mainstream US-based environmental NGO that specializes in legal advocacy and operates largely through the courts. NRDC has raised concerns about both BECCS and DAC as carbon removal options. A former president of NRDC (Frances Beinecke) now serves as a member of the Climate Overshoot Commission.

- Oxfam—Oxfam is a global organization dedicated to fighting inequality and poverty especially in developing countries. Oxfam has expressed apprehension about carbon removal based on concerns regarding both moral hazard tied to net-zero pledges, and competition for land driven by tree planting (potentially for BECCS).

- The Sierra Club—The Sierra Club is a long-standing progressive US environmental NGO. The Sierra Club acknowledges the necessity of carbon removal but favors natural over technological methods.

- Third Generation Environmentalism (E3G)—E3G is a Europe-based, climate-oriented think-tank. While acknowledging the need for carbon removal, E3G opposes integrating technological removals into carbon markets in the foreseeable future due to fears that doing so will undermine emissions reductions through moral hazard.

- World Wide Fund for Nature (WWF)—WWF is an international environmental NGO. WWF accepts the need for carbon removal, including in the context of climate overshoot, but prefers natural compared to technological options.

Table 5 gives an overview of civil society groups that resist development of technological removal methods. Such resistance ranges from expressions of concern over the risks entailed, to total rejection of anything resembling BECCS, DAC, or OAE. Typically, groups voicing skepticism or hostility toward technological methods are politically left of center. Except for IATP, NRDC, and the Sierra Club, such organizations are based outside of the US, primarily in Europe.

**Table 5: Civil Society Actors *Resisting* Technological Carbon Removal**

| Actor | Headquarters Country | Geographical Scope | Focus | Political Leaning |
|---|---|---|---|---|
| Biofuelwatch | UK | Global | Bioenergy | Far left |
| CAN International | Germany | Global | Climate change | Left |
| CIEL | Switzerland | Global | Environment | Far left |
| E3G | UK | Europe | Climate change | Center-left |
| EEB | Belgium | Europe | Environment | Left |
| ETC Group | Canada | Global | Emerging technologies | Far left |
| FERN | Belgium | Europe | Forests | Left |
| Greenpeace | Netherlands | Global | Environment | Far left |
| IATP | US | Global | Food | Far left |
| NRDC | US | Global | Environment | Center-left |
| Oxfam | Kenya | Global | Poverty | Left |
| Sierra Club | US | US | Environment | Center-left |
| WWF | Switzerland | Global | Environment | Center-left |

In addition to groups that have adopted positions for or against technological carbon removal methods, a handful of civil society actors strive to remain neutral on this question. They include:

- Carnegie Climate Governance Initiative (C2G, formerly Carnegie Climate Geoengineering Governance Initiative or C2G2)—C2G was launched as an initiative of the Carnegie Council for Ethics in International Affairs in 2017, with the goal of raising awareness of natural and technological carbon removal among global policymakers and climate governance stakeholders including NGOs. It is led by Janos Pazstor, a former UN Assistant Secretary-General for Climate Change. C2G played an important role in facilitating Switzerland's ill-fated plan to initiate a carbon removal technology assessment at UNEA in 2019.

- Global Commission on Governing Risks from Climate Overshoot (Climate Overshoot Commission)—The recently launched Climate Overshoot Commission aims to compile and communicate an integrated strategy for reducing risks anticipated to result from exceeding the 1.5 °C temperature target contained in the Paris Agreement; this strategy is likely to include use of carbon removal. The Commission consists of sixteen eminent persons active in politics, diplomacy, environmental protection, and civil society, a majority of whom come from the Global South.

- Institute for Carbon Removal Law and Policy (ICRLP)—ICRLP is an initiative of American University's School of International Service which produces and catalyzes policy-relevant research, commentary, and resources. The Institute operates an initiative called the Carbon Removal Working Group to promote dialogue among US NGOs about the potential roles of natural and technological carbon removal in US and global climate policy.

**Politics: Nature Versus Technology**

The central political issue in the field of carbon removal today revolves around the desirability of technological removal methods. The brief survey of civil society engagement in carbon removal presented above shows a transatlantic split between comparatively centrist US-based groups in favor of accelerated research on and/or deployment of technological methods like BECCS and DAC, and relatively left of center Europe-based organizations resistant to an expanded role for technological removals. The divide between otherwise likeminded environmental NGOs in their views regarding technological carbon removal is presumably explained in part by the fact that the political center of gravity in Europe is generally to the left of that in the US. Undoubtedly these characterizations are oversimplifications of more complex political realities, yet they appear to capture key properties of the evolving carbon removal policy landscape.

This geographical pattern is also manifest when comparing emerging policy frameworks in the US and Europe. The technology-push exerted by RD&D funding in the US is far larger than any stimulus provided by European investments in research. The US government seeks to incentivize technological carbon removal methods through significantly enhanced 45Q tax credits as well as prize competitions, but Europe has nothing comparable. Instead, European authorities seek to regulate carbon removal methods through the CRC-M. Controlling what counts as carbon removal and how it is counted, compared to rewarding innovation, point toward two different policy priorities: Europe is pursuing a cautious approach to technological carbon removal, while the US is actively promoting its development.

This (limited) evidence suggests that there is variation in levels of consistency in support for both natural and technological carbon removal methods; in other words, actors reflecting what might be called an "American" perspective evince support for natural *and* technological removal, while actors reflecting what might be called a "European" perspective evince support for natural methods but skepticism or opposition regarding technological methods. Where this inconsistency prevails, research suggests it is grounded in the view that natural methods *work with* nature, by leveraging photosynthesis to remove $CO_2$ from the atmosphere, whereas technological methods *interfere with* nature by using artificial, human-made technical means to extract $CO_2$ from the atmosphere (see, for example, Wolske et al. 2019).

This position, of course, is debatable insofar as it is premised on a particular conception of nature as something separate and apart from humanity that is inherently good and should not be tampered with (the corollary assumption that natural carbon removal methods do not involve tampering with nature is also questionable—see footnote 7). What is relevant for present purposes is not whether this view is correct but rather the fact that it is widely held and helps explain the resistance to technological carbon removal evident in Europe and elsewhere. The prevalence of this position matters because it works to hinder the development and deployment of those removal methods like BECCS, DAC, and OAE—capable of large-scale removals and permanent storage—that will be most critical to future carbon drawdown. Uncertainty over whether and to what extent the EU ETS—the world's most important carbon market—will eventually incorporate technological carbon removals signals that the commercial prospects for these technologies may be limited. Circumscribed demand-pull at the global level, in turn, impedes the upscaling and learning-by-doing necessary to bring down the high costs associated with BECCS and DAC, which pose the most significant structural constraints on meaningful deployment of carbon removal.

**Recommendations**

There is a pressing need to accelerate processes that will ultimately lead to long-term cost reductions for technological carbon removal methods. As noted earlier, the primary levers for promoting the innovation that will be required to accomplish this are technology-push and demand-pull measures. Attempting to moderate political resistance to technological methods is one approach to unlocking broader incentives for technology development.

As discussed in the previous section, much of this resistance stems from a belief that technological methods would interfere with nature and that this is undesirable. Such views are often deeply held, and it is neither easy to change them nor obvious that they should be challenged. At the same time, however, the policies implied by such views—excluding technologies like BECCS, DAC, and OAE from serious consideration—are set to become increasingly incompatible with the broader objective of reducing risks from climate change. At a minimum, skeptics and opponents of technological carbon removal must understand the dilemma they face.

Evidence indicates that not all of them do. For instance, WWF, arguably the world's premier international environmental NGO, stated the following in its 2018 position paper on carbon removal: "We should prioritise those approaches which remove carbon dioxide from the atmosphere and permanently sequester it in natural systems" (WWF 2018, 1). But it is inarguable that natural carbon removal is inherently non-permanent: wildfires, pests, and diseases—risks of which will all be *heightened* by climate change—render storage in biomass and other natural systems acutely insecure. Notably, however, WWF was careful not to actively oppose BECCS, DAC, and similar technologies: "they should neither be ruled out nor actively supported" (WWF 2018, 3).

The Sierra Club, America's oldest environmental organization, offers a similar example. In an official 2020 policy document, the Sierra Club stated: "The amount of permanent CDR removal that is possible through natural systems is debatable, and some argue that natural systems can accomplish the entire 10 gigaton [per year by 2050] goal" (Sierra Club 2020, 64). There is little real debate on this, however, with natural carbon removal methods widely recognized by scientists as insufficient to the task. Yet this statement was followed immediately by a declaration that, "Rather than attempt to resolve this debate, the Sierra Club advocates for maximizing natural solutions first, but also supporting a diverse portfolio of environmentally acceptable and just CDR technological options to back up and supplement the natural systems solutions" (Sierra Club 2020, 64).

These observations suggest that, among at least some of those civil society groups exhibiting resistance toward technological carbon removal, there is both scope for learning and some degree of flexibility in their positions.  Given the influence of such groups on public policy, this presents an opportunity to steer a collective reconsideration of civil society and broader policy community perspectives on technological carbon removal, with an eye toward softening opposition to BECCS, DAC, OAE, and potentially other technologies grounded in a common, science-based understanding of the fundamental importance of permanence and the inherent limitations of natural removals in this respect.  A convening of this type could be centered on environmental NGOs and other civil society groups, and respected scientific experts on carbon removal, climate change, and the carbon cycle.  To promote knowledge sharing and international dialogue, actors from both Europe and the US—and probably beyond—should be involved.  Participants might also include prominent purchasers of carbon removals (for example, Frontier), relevant trade associations (for example, the Coalition for Negative Emissions), and policymakers (for example, officials from the European Commission).

The purpose behind such an initiative would be to focus attention on the primacy of permanence as a criterion for evaluating carbon removal options.  Doing so would invariably lead to recognition of the critical role played by technological carbon removal.  Such recognition could be paired with explicit acknowledgment of the valuable co-benefits and adaptation synergies disproportionately associated with natural carbon removal methods.  Given the taxonomic confusion surrounding carbon removal methods, this effort might be usefully framed as a policy community initiative to reach consensus on a common framework for categorizing and classifying alternative options.

**Recommendation 1: Convene a collaborative process involving civil society actors, scientists, and other relevant stakeholders with the goal of prioritizing permanence as the key criterion for evaluating carbon removal methods, to build support for the meaningful inclusion of technological removal methods in evolving policy and governance frameworks.**

Looking beyond immediate needs, a complicated set of issues relates to how carbon removals—especially removals provided by technological methods—might be integrated into new or expanded carbon markets.  As discussed in the context of limitations and constraints, incorporating removals into markets organized around emissions reductions poses several technical and political challenges including mitigating the risk of moral hazard and determining who should pay for removals and how.  Interesting proposals for market separation and carbon removal obligations have been advanced to address these issues, yet sustained research aimed at critiquing such proposals, identifying any overlooked problems, devising new proposals for addressing familiar and unfamiliar issues, and exploring how to integrate policy innovations with each other as well as with existing and planned instruments and mechanisms, has not been pursued.

Limited work of this sort is presumably taking place as part of the European CRC-M proposal process, but its nature and extent—including whether it covers any technological removal methods—is currently unknown. Such research will probably also be needed to inform future elaboration of the Article 6.4 Mechanism under the Paris Agreement. In general, insofar as large-scale carbon removal will depend on incentivizing actions through carbon markets, knowledge about how to ensure that such actions are both effective and sustainable will be critically important.

A useful way to catalyze such knowledge production and dissemination would be to organize a series of workshops intended to explore the complex issues involved in seeking to incorporate carbon removals into carbon markets, evaluate current proposals, and develop new proposals, all in a way that is tied to ongoing policy developments within the EU, at the UNFCCC, and perhaps elsewhere. Participants would include academic experts, certification bodies, trade groups, civil society organizations, and policymakers. The entry point could be discussions of proposals for market separation and carbon removal obligations, with the output taking the form of a systematic cataloging and assessment of market and policy design options for responsibly incorporating large-scale carbon removals into carbon markets.

**Recommendation 2: Organize a series of workshops to devise and assess market and policy design options for incorporating carbon removals into carbon markets in environmentally and socially sustainable ways.**

OAE has been researched much less than either BECCS or DAC, yet its estimated technical removal potential of 1-100 $GtCO_2$ per year at an estimated cost of \$40-\$260 per $tCO_2$, combined with its apparent capacity to reduce ocean acidification, make OAE a particularly compelling possible future option for large-scale permanent carbon removal. But much more research is required. This must include a comprehensive multidisciplinary assessment of the environmental and social risks posed by adding alkalinity to marine ecosystems and building a brand-new global-scale extractive industry for mining alkaline rocks, grinding them into powder, and delivering powder to appropriate deposition sites at sea. Such an assessment must include life-cycle analyses of $CO_2$ emissions across the entire value chain.

The most pressing questions arguably pertain to the potential for ecological harms caused by deposition of alkaline materials in the open ocean (NASEM 2022). Key issues to resolve include whether OAE would cause significant physiological effects on marine biota, how it would affect community structure, and how it would affect biogeochemical cycles at different depths. Laboratory, mesocosm, and field experiments could all help answer these questions and reduce associated uncertainties.

Relatively modest investments in research appear capable of generating substantial gains in knowledge. It may make sense to partner with existing organizations already working to advance R&D on OAE, such as Additional Ventures (mentioned above). It may also make sense to sponsor studies or efforts to formulate detailed research agendas. Selectively purchasing removals produced specifically by OAE would be another way to (indirectly) fund research.

**Recommendation 3: Fund research on OAE to confirm—or disconfirm—its potential as an especially promising future option for large-scale permanent carbon removal (and means to counter ocean acidification).**

Finally, as discussed previously, the amount of funding provided by public and private actors to support research on carbon removal methods is unclear. There are two main reasons for this. One is that confusion over terminology frustrates efforts to compile and aggregate information on natural and technological carbon removal. The other is that information about research funding is widely dispersed within and across countries and governments, and considerable work is required to collect it. The lack of such data impedes both social science research on carbon removal and strategic planning regarding funding priorities, actor mobilization, portfolio design, etc.

A project focused on compiling and aggregating information on research funding for carbon removal and characterizing emergent patterns or trends would advance policy discussions on both these fronts. Resource requirements would be minimal, and project outputs would benefit all stakeholders. Information could be centralized in an open-access database. Because success would depend on clarifying terminological and ultimately taxonomic issues, such a project might be usefully linked to elements of Recommendation 1.

**Recommendation 4: Support a project to collect, systematize, and share data on research funding for carbon removal.**

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