MANAGING ATMOSPHERIC CARBON LEVELS

A survey of carbon dioxide removal (CDR) and carbon capture, utilization, and storage (CCUS) technologies, their prospective role in climate policy, and emerging support mechanisms

By Nils Zimmermann • nzimmermann@worldbank.org
Consultant to the Climate Change Group, The World Bank
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EXECUTIVE SUMMARY

Carbon dioxide removal (CDR) methods, the principal focus of this report, comprise a diverse array of approaches for removal of previously emitted excess carbon from the environment – from the atmosphere, upper ocean waters, or biosphere – **so that it can no longer affect the climate.** The range of existing and proposed CDR methods is very wide, encompassing land-based and ocean-based, nature-based and engineered, biological, geochemical, and electrochemical carbon removal methods.

Carbon capture and storage (CCS), carbon capture and utilization (CCU), and carbon capture, utilization, and storage (CCUS) methods, taken together, are a secondary focus of this report. CCS, CCU, and CCUS methods capture CO_2 from point sources (typically from the flue gases of industrial plants), concentrate it, and either dispose of it deep underground (CCS) as a straightforward exercise in carbon waste management, or use the carbon captured as an input material for industrial processes or materials (CCU and CCUS). Some of these carbon-incorporating products displace equivalent fossil fuels-based products, but after their utilization ultimately re-release their carbon content into the atmosphere, as when synthetic jet fuel is combusted; in such cases, the term of art is CCU. In other cases, captured carbon is processed in ways that lead to its durable storage away from the carbon-climate cycle, e.g., when carbon is mineralized as synthetic limestone and used to make solid paving or building materials; in these cases, the term of art is CCUS. (Nota bene: Some reports use the term CCUS as a catch-all term to mean 'carbon capture, followed either by utilization or storage or both utilization and storage'.)

Here we use the general term "carbon management" to encompass CDR, CCS, CCU, and CCUS.

Key takeaways regarding CDR:

- Limiting global warming to 1.5°C by 2100 will likely require the global CDR industry to grow into one of the biggest industries in the world by mid-century, reaching a scale of 17 to 20 billion tons of CO_2 removal ($GtCO_2$) per year on average in the second half of the century, at an annual financial volume in the \$1-\$3 trillion range, paid via results-based payments. This will only occur if robust policy measures require it. There is no business case for CDR absent strong policy drivers (regulations, carbon prices, subsidies).

- At least 850 billion tons of CO_2 will have to be removed in aggregate by 2100, perhaps much more, depending on several factors: the speed of emissions reductions in coming years and consequent aggregate emissions between now and a future global net-zero emissions year; the level of climate policy ambition (the global target for maximum acceptable global temperature increase in 2100); and the physical response of the climate system to global heating: if warming oceans or biosphere become less effective at naturally soaking up carbon than they are today, as some scientists fear could happen, this would have to be compensated by higher amounts of CDR.

- The primary role of CDR and CCS/CCUS technologies is carbon management in the service of a global public good: restoring safe atmospheric CO_2 levels. If climate policy ambition is increased by future generations to a target of limiting global warming in 2100 to 1.0°C rather than 1.5°C, as some influential climate scientists are urging, the required CDR amount could rise to about 2,000 $GtCO_2$ by 2100, or about 40 $GtCO_2$ per year on average during the second half of the century.

- How to scale up funding for the CDR industry a thousandfold by 2050 is an unsolved policy challenge that requires serious attention. There is no business case for carbon removal from the atmosphere or environment, or for carbon capture from point sources, absent strong climate policy drivers – to include regulatory compliance markets, carbon capture and removal prices, and legislated funding mechanisms – because although captured carbon can be used as an input to industrial and agricultural production processes (via CCU and CCUS methods), fossil hydrocarbons can, in the absence of regulations imposing carbon dioxide emissions restrictions or stiff carbon prices, provide carbon inputs more cheaply.

- Crucially, developing and scaling up high-volume marketable products that use CO_2 from captured carbon as an input material will help offset CDR costs. At present, expectations are that the bulk of CO_2 captured via environmental CDR or point-source carbon capture efforts will not be utilized as input into production processes; instead, it will be treated as waste (removed via mineralization or burial).

- In 2023, funding for CDR was provided by voluntary carbon markets and government grant monies. No CDR compliance market exists yet. The volume of delivered CDR was 2.2 $GtCO_2$, all but a tiny fraction of which was via afforestation/reforestation. Other CDR methods (variably referred to as 'novel,' 'technology-based,' or 'engineered' CDR) contributed 1.3 million tons (0.06% of total CDR deliveries), of which 2/3 was biochar and 1/3 was bio-energy carbon capture and storage (BECCS), plus nominal amounts from demonstration projects of novel CDR methods such as enhanced rock weathering.

- Nature-based CDR methods, i.e., afforestation/reforestation, natural ecosystem restoration (wetlands, peat bogs, coastal mangrove forests), and soil carbon enhancement, have substantial aggregate potential and many co-benefits. However, technology-based CDR methods will also be needed, because even in aggregate, nature-based CDR volumes likely will not suffice, on their own, to meet global warming target limits. Moreover, increasing forest fires and droughts in a warming world put the permanence of nature-based CDR methods at increasing risk. Technology-based CDR methods can mitigate this risk by mineralizing carbon rather than storing it in biomass.

- It is not yet clear which technology-based CDR methods will prove cost-effective and scalable. Most engineered CDR methods are at an early stage and require much more investment in technology R&D and in the seeding and development of regional CDR supply chains.

- To help guide future investment in CDR, some subject matter experts suggest setting up an actively curated inventory of highly detailed physical-chemical models of each CDR method in an Open Source publicly accessible database and inviting technical experts to progressively improve the models.

- To identify the most promising, cost-effective, scalable engineered CDR methods, a useful strategy could involve providing public funding for public research groups (universities, national laboratories) to each concurrently run parallel experiments in several distinct CDR methods, e.g., several different marine CDR technologies, with a requirement that research results be open-access. One publicly funded research group testing several different ocean alkalinity enhancement methods in parallel, for example, will be in a good position to assess which of those methods is likely to prove most cost-effective and technologically tractable. This R&D funding approach will enable more objective comparative assessments of novel CDR methods than can be achieved by exclusive reliance on various startups, each working on a single CDR method, since each CDR startup has a financial incentive to strongly promote its particular technology irrespective of comparative merit. The best way forward will combine both publicly funded open-access comparative research into suites of CDR methods and a broad ecosystem of CDR startups.

- Novel CDR technology RD&D and supply chain development is underfunded: in a scenario of achieving at least 1 $GtCO_2$ global CDR volume annually from 2030 using technology-based CDR methods (i.e., CDR other than and in addition to nature-based CDR), funding for technology-based CDR would have to be ramped up more than 100-fold from \$1.3 bn in 2023 to >\$150 bn per year by 2030.

- The literature on funding large-scale CDR deployment suggests different funding models will be required over time. For example, in the short term, a global CDR development fund could be co-funded by voluntary contributions from interested oil-, gas-, and coal-rich countries, with an early focus on funding a broad suite of R&D projects and seeding regional supply chains through creation of regional centers of excellence. In the medium term, among other possibilities, a flat levy on fossil fuels could be a suitable funding option, and in the longer term, as fossil fuels use dwindles while CDR volumes increase, levies on one or more additional financial quantities could emerge as workable CDR funding solutions.

- Technology development efforts, funding, and startup ecosystems for engineered CDR methods are, to date, largely confined to industrialized countries in North America and Europe. A global CDR development fund could pay for the creation of regional CDR hubs in developing countries. A global fund would enable siting future large-scale CDR operations cost-effectively in remote regions, even as the money to pay for CDR will be raised internationally, primarily from industrialized economies.

Key takeaways regarding CCS, CCU, and CCUS:

- CCS and CCU/CCUS deployments will be policy driven. There is no business case for CCS absent strong policy drivers, since adding CCS to industrial plants drives up the unit costs of their products. No company can unilaterally adopt CCS, because doing so would price its products out of the market. A level playing field is necessary in the form of regulatory carbon emissions avoidance requirements and/or carbon prices that apply to all suppliers in a regional or global market. Alternatively, the full costs of adding CCS to an industrial facility can be provided through public subsidies.

- In a limited number of cases, captured CO_2 can be used in enhanced oil recovery operations in aging oil fields, and CCS costs can be recovered that way. After 50 years of operational experience, the CCS industry is still small, at only 50 million tons of CCS per year, much of it deployed in enhanced oil recovery (EOR) operations. The plausible scale of EOR opportunities is unlikely to enable scaling CCS to Gigatons per year; new policy drivers will be needed. New US tax incentives and EU subsidies provide a start.

- The Intergovernmental Panel on Climate Change Assessment Report 6, Working Group III, projected a volume of carbon capture and storage in the year 2050 between 3.8 to 8.8 billion tons of CO_2 ($GtCO_2$) per year, based on a review paper published in 2019. An IEA net-zero by 2050 scenario estimated 7.6 $GtCO_2$ per year in 2050, of which 5.3 $GtCO_2$ was captured from fossil fuels use, the rest from BECCS or CDR. Strong regulatory drivers were assumed in the scenarios that generated these CCS volume ranges.

- CCS will especially find applications in capturing carbon from chemical process-related emissions from industrial sources, e.g., cement making or chemical plants. CCS could also be applied to capturing emissions from coal or gas fueled thermal power stations, although the dramatic decline in renewable energy equipment costs in recent years means that it will in most cases be faster and cheaper (as measured in $ per ton of avoided emissions and in $ per MWh) to replace thermal power plants with renewable energy generation and energy storage capacity than to retrofit thermal power plants with CCS systems.

- In some industrial sectors, e.g., steelmaking, if investments in new non-fossil-fuels-based production technologies yield continuing reductions in unit costs, then replacing legacy coal-fueled steel mills with new clean technologies, e.g., with hydrogen direct reduced iron (H_2 DRI) mills, may eventually prove cheaper than retrofitting legacy coal-fueled steel mills with CCS systems (or building new coal-fueled mills with integrated CCS systems). The speed and extent of unit cost declines in such clean technologies will help determine the plausible future scope and scale of CCS in a climate policy constrained world.

- The cost range of CCS systems has remained fairly steady for decades as measured in CCS system CapEx and OpEx and in energy use per ton of CO_2 captured and stored. Total costs are often in the $60 to $130 per ton range. The three main cost factors are: (i) cost of capture for a given plant type; (ii) cost of transport to the nearest suitable geological storage site (via pipeline, truck, train, and/or ship); and (iii) cost of storage at the disposal site, determined by the type of geological reservoir. Basic physics limits the scope for future CCS process cost reductions because heavy infrastructure costs and energy penalties are involved at each step (capturing, compressing, transporting, and injecting the carbon dioxide underground).

- CCUS - BECCS: Recent expert reviews of the plausible scope of various CDR methods suggest the prospective role of BECCS (bio-energy carbon capture and storage), although significant, was overestimated in many pre-2020 IAMs and reports based on them. BECCS is an expensive way to generate electricity and can have uncertain net carbon sequestration benefits. It tends to provoke opposition from environmental campaigners because it competes for limited biomass, land, and water with agriculture, forestry, biochar production, biodiversity, amenities, and bio-economy products. However, waste biomass may play a key role in some hard-to-abate industrial sectors. For example, in cement-making, combustion of waste biomass can supplement coal as a heat source, and biomass ash can replace clinker.

- CCUS – Turquoise hydrogen: The process of making "turquoise hydrogen" via pyrolysis of natural gas achieves permanent mineralized storage of much of the carbon content of natural gas by co-producing hydrogen and carbon black, two marketable materials. Carbon black is a solid, insoluble, chemically inert form of elemental carbon. Turquoise hydrogen is at an exploratory stage of technology development. Expert evaluations suggest that once it achieves technical maturity, turquoise hydrogen may be cheaper than 'green hydrogen' produced via electrolysis of water using renewable energy.

SECTION 1 – INTRODUCTION

OBJECTIVE

This report aims to provide an overview of technologies for Carbon Capture and Storage (CCS), Carbon Capture and Utilization (CCU), Carbon Capture, Utilization and Storage (CCUS), and especially Carbon Dioxide Removal (CDR). It explores the potential scale of CCUS and CDR industries in coming decades and describes a range of existing and possible future financial support mechanisms. The primary focus is on engineered CDR technologies – a wide range of novel methods for removing previously emitted carbon from the environment and sequestering it permanently away from interaction with the climate system.

TARGET AUDIENCE

This report is intended for professionals interested in climate policy who are new to CCS/CCUS and CDR. It is a knowledge product of the technical workstream of the Transformative Carbon Asset Facility (TCAF). TCAF is a World Bank-managed trust fund supporting transformative climate change mitigation activities in developing countries through results-based payments, RBPs (TCAF 2023).

THEMATIC FOCUS: CARBON MANAGEMENT FOR CLIMATE SAFETY

CCS, carbon capture and storage, involves capturing CO_2 emissions from flue gases issuing from large point sources – such as thermal power plants or industrial plants (e.g. steel- or cement-making or chemicals production) – and either disposing of so that it can no longer affect the climate, often by permanently storing it underground, e.g,. in deep saline aquifers.

If the captured carbon is utilized in other industrial processes instead of simply being disposed of, the terms of art are CCU and CCUS. An example of CCU, carbon capture and utilization, is making synthetic jet fuel with captured carbon: the carbon is re-released to the atmosphere as CO_2 after the fuel is combusted. An example of CCUS, carbon capture, utilization, and storage, is pumping CO_2 under pressure into depleted oil fields, restoring pressure to them and enabling increased oil production (CO_2 enhanced oil recovery, CO_2-EOR); about 90% of the CO_2 stays underground, no longer affecting the climate, although increased oil production consequent to EOR leads to additional emissions. Another example of CCUS is production of carbon black as a solid co-product of natural gas pyrolysis for hydrogen production ("turquoise hydrogen"). CCUS methods can generate value to help offset the cost of CCS.

This report gives an overview of CCS/CCUS methods and their prospects in Sections 8, 9, and 10.

CDR, carbon dioxide removal, refers to a wide range of technologies and practices that remove previously emitted CO_2 from the environment (atmosphere, oceans, or biosphere) and either mineralizing it, storing it underground, incorporating it into durable products, or otherwise removing it from the fast carbon cycle so that it cannot affect the climate. Sections 2 through 7 of this report are about CDR methods and policy or financial support mechanisms for CDR.

CARBON DIOXIDE REMOVAL (CDR): NATURE-BASED VS ENGINEERED CDR

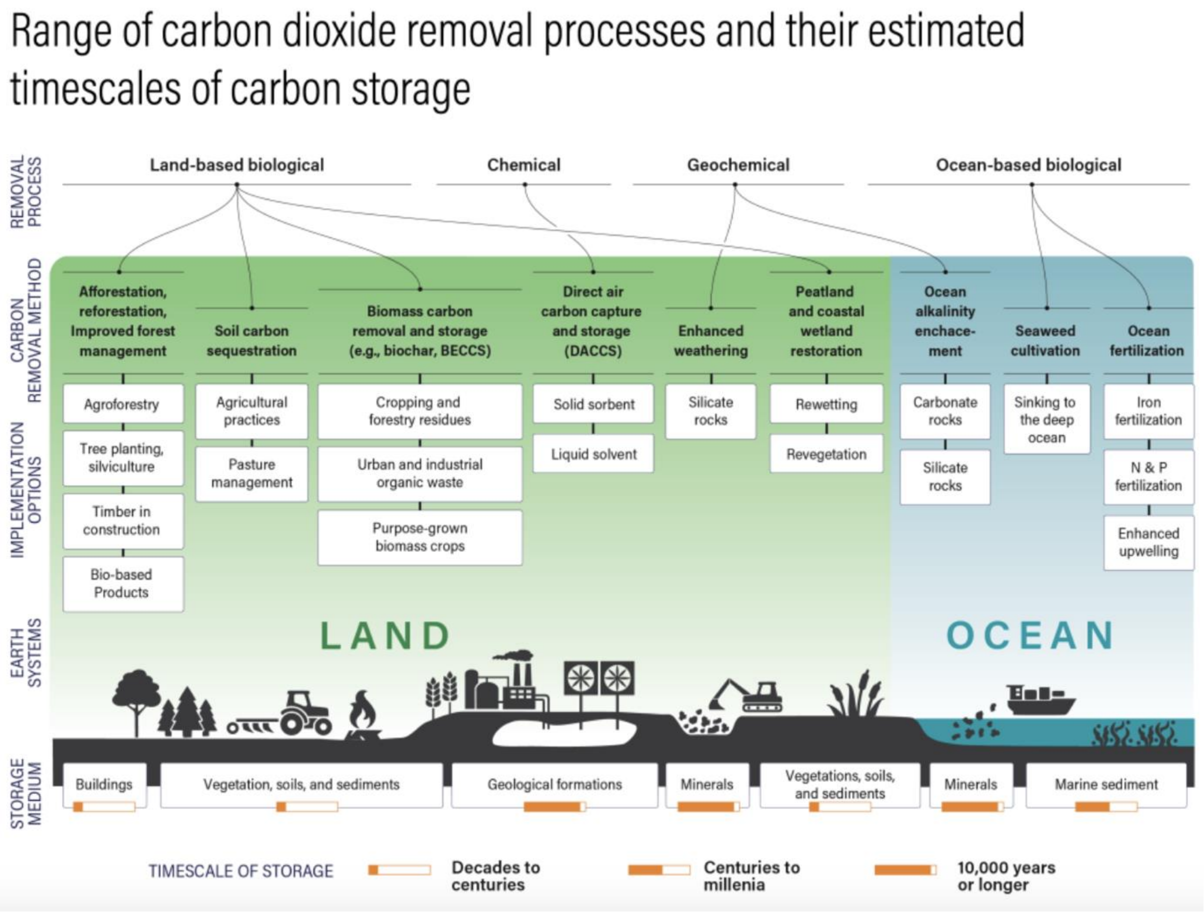
The principal focus of this report is on CDR, and specifically on a wide range of novel engineered, geochemical, or unconventional biology-based CDR methods, i.e. CDR methods other than 'nature-based' CDR methods or 'natural climate solutions' (NCS) that rely on ecosystem restoration – e.g., afforestation/reforestation; soil carbon sequestration through improved agricultural methods; or restoration of peat bogs, wetlands, mangroves, and grasslands.

Nature-based CDR methods are extremely valuable and have many co-benefits, and should be deployed to the maximum extent feasible. However, according to a much-cited study by Griscom et al. (2017), 'Natural climate solutions,' NCS methods are unlikely to provide sufficient volumes of CDR, by themselves, to achieve global climate targets of limiting the planet's average annual surface air temperature to less than 1.5°C in 2100. Using 2030 as a reference year, Griscom et al. estimated that nature-based solutions could cost-effectively provide about 11 GtCO$_2$ per year by 2030 in carbon storage or avoided carbon emissions, assuming a social cost of CO$_2$ pollution >$100 per ton (in 2016 US dollars). Under their scenario, in the context of a goal to keep global warming by 2100 below 2°C, NCS could provide 37% of the necessary CO$_2$eq mitigation between 2017 and 2030 and 20% of the necessary mitigation between 2017 and 2050. Note that stabilizing global warming below 1.5°C, the target that has been more frequently cited since the publication of the IPCC's Special Report on 1.5°C in 2018 (a year after Griscom et al. published their paper in 2017), will require far more net carbon removal than stabilizing warming below 2°C.

A US National Academy of Sciences report published in 2019 entitled 'Negative Emissions Technologies and Reliable Sequestration: A Research Agenda (see Table 8.1 of that report) estimated the total potential of afforestation/reforestation and improved forest management to be about 2.5 GtCO$_2$ globally, and improved agricultural practices to enhance soil carbon at 3 GtCO$_2$, plus 'coastal blue carbon' at a maximum of 0.8 GtCO$_2$, for a combined total of 6.3 GtCO$_2$ per year from these terrestrial and coastal nature-based solutions. Contrast this with an estimated 20 GtCO$_2$/year CDR needed to return to 1.5°C in 2100.

These estimates establish that the predominant expert assessments suggest that the majority of 'negative emissions' (carbon removal) volume will have to be supplied by engineered, technology-based CDR methods, rather than by nature-based solutions.

The figure below, taken from the IPCC Assessment Report 6, shows the range of currently known main CDR methods, including both nature-based and engineered methods.



Source of image: WRI, based on IPCC 2022 AR6.

The present report describes the current state of development and potential future scalability of several technology-based CDR technologies. The scope of CDR's future role in global climate policy is outlined, along with the current role of results-based payments, carbon markets, and other financial mechanisms in promoting CDR technologies in the jurisdictions that have the most active CDR technology communities to date: the USA, Canada, and Europe. Key documents on CDR technology and policy are identified, as are influential CDR business and governance organizations.

PURPOSES OF CCS/CCUS AND CDR

Carbon Capture and Storage, CCS, and Carbon Capture, Utilization, and Storage, CCUS. The purpose of CCS/CCUS is to capture and sequester CO_2 emissions from industrial point sources. This includes, but is not limited to, CO_2 emissions caused by combustion of fossil hydrocarbons for energy provision; technologies are available, and continue to be improved, for post-combustion, pre-combustion and oxy-fuel combustion capture systems (IEA 2020). CO_2 emissions also result from chemical processes in key industries. For example, CO_2 is emitted in large quantities as a byproduct of cement-making when limestone, which is mostly calcium carbonate ($CaCO_3$), is 'calcined' via heating in a cement kiln to produce lime, or CaO, plus CO_2 as a byproduct. In another example, CO_2 is released as a byproduct of fermentation during ethanol production. In a third example, the Haber process for ammonia synthesis usually involves hydrogen won from steam reforming of natural gas, which gives off CO_2 as a byproduct.

CCS and CCUS methods prevent captured CO_2 from being released into the atmosphere and affecting the climate. The technical potential of CCS/CCUS is broad – it can, in principle, be applied to nearly any stream of concentrated carbon dioxide. Our World in Data offers an overview of GHG emissions by sector; some sectors involve point-source emissions, e.g., thermal power stations, steel mills, and cement making facilities, and so would allow CCS/CCUS implementation, while others, e.g., most agriculture and forestry operations, or road and air travel, don't involve point-source emissions. However, fitting an industrial or power plant with CCS equipment involves high capital expenditures, and operating CCS processes is energy-intensive and expensive. Where 'green' industrial or energy production technologies are available that provide comparable products but do not involve generating CO_2 as a byproduct and so do not require capturing any CO_2, a cost comparison can assess, on a case-by-case basis, whether shifting to the new 'green' technologies or fitting legacy CO_2-emitting industrial plants with CCS/CCUS is the cheaper option for emissions mitigation.

Carbon Dioxide Removal, CDR. The two main purposes of CDR are:

- to return the amount of CO_2 in the atmosphere to a lower, safer level later this century by removing enormous quantities of previously emitted CO_2 from the environment (atmosphere, oceans, biosphere). This will entail achieving 'net negative emissions' of greenhouse gases at a scale of many billions of tons (Gigatons CO_2, $GtCO_2$) per year over several decades – totaling at least several hundred $GtCO_2$ cumulatively by 2100 (potentially more than a thousand $GtCO_2$); and
- to offset continuing CO_2 or other greenhouse gas (GHG) emissions from hard-to-abate sectors for which alternative 'green' technologies are unavailable or unaffordable and in which CCS/CCUS is impractical, i.e., sectors whose GHG emissions can neither be readily avoided nor captured at source, e.g., emissions from kerosene-burning jet aircraft or from most agricultural operations.

BOTH CCS AND ENGINEERED CDR METHODS HAVE SEEN ONLY MINOR AMOUNTS OF DEPLOYMENT TO DATE

Just 49 million tons of CO_2 were processed in the world's 41 operating CCS facilities in 2023, and only 100,000 tons of non-A/R (non-afforestation/reforestation) CO_2 were captured and stored via CDR in 2023 (although a larger amount, 1.3 million tons, was pre-ordered in 2023 for future delivery).

These are negligible amounts compared to the more than 37.4 billion tons of CO_2 (Gigatons of CO_2, Gt CO_2) emitted through fossil fuels combustion for energy in 2023 (IEA), more than in any previous year, or compared to total greenhouse gas (GHG) emissions of 53.8 $GtCO_2$-equivalent (EU data) (the $GtCO_2$-equivalent amount includes CO_2 emissions from fossil fuels combustion and CO_2 emissions from deforestation and other land use changes, plus emissions of methane from multiple sources, nitrous oxides from farming, synthetic hydrofluorocarbons, and other GHGs).

CCS AND CDR: NO BUSINESS CASE ABSENT STRONG POLICY DRIVERS

The reason there has been little CCS or CDR deployment to date is that there can be no large-scale carbon removal market and no business case for CCS or CDR absent strong policy drivers. Policy drivers can take the form of a high price per ton of carbon dioxide emissions (providing a disincentive against emissions), or regulatory compliance regimes requiring emissions avoidance, or comprehensive subsidy regimes (public money paid per ton of avoided (CCS) or removed (CDR) or for some other quantity correlated with climate goals), or a combination of carbon prices, compliance regimes, and subsidies.

Such policy drivers are, broadly speaking, not yet in place. There are partial regional exceptions, e.g. the European Union's Emissions Trading System (ETS) and ETSs in a few other jurisdictions. These do not yet incorporate payments for CDR, but they do provide a price incentive to avoid emissions. CCS systems are one way to avoid emissions, though as is discussed in Section 8, CCS is an expensive process that adds to the final cost of a product, and in some cases, lower-cost means of avoiding emissions are available. For example, it may be cheaper to replace a coal power plant with an equivalent amount of solar and wind power plus energy storage and transmission capacity, rather than retrofit the coal power plant with CCS.

The absence of policy drivers for emissions avoidance and the high cost of CCS are, in combination, the reasons why CCS continues to be little used. Companies have a fiduciary duty to shareholders and cannot unilaterally incur competitive disadvantages compared to competitors in the same markets. A voluntary approach to emissions avoidance cannot work except in edge cases. Rather than voluntary carbon markets, a level playing field composed of strong emissions avoidance policy measures will be needed. Similarly, voluntary markets for carbon removal (CDR) are tiny in scale, and policy measures that provide funding for CDR at the $GtCO_2$ per annum scale do not yet exist.

This is the global context in which about 54 $GtCO_2eq$ of unabated greenhouse gases continue to be emitted annually, and emissions continue to rise by about 1% year on year.

FUNDING CDR IS AN UNSOLVED PROBLEM

A major unresolved global public policy challenge emerges: The question of how to fund the removal of more than a thousand billion tons of previously emitted excess carbon dioxide from the environment over the course of this century, at a projected rate of about 20 billion tons of CDR per year during the second half of the century, to return to 1.5°C above pre-industrial-era global average temperature by 2100 after a period of overshooting 1.5°C. This will entail an annual price tag in the range of $1 trillion to $5 trillion (likely $2 to $3 trillion). Current funding mechanisms for CCS and CDR are limited to research, development, and demonstration project subsidies provided by some OECD governments and a small number of major corporations. The total sum of committed funding to date is modest (more details below).

CDR will require different financial mechanisms than CCS/CCUS. The costs of implementing technological measures to avoid ongoing emissions can be tied directly to point-source emitters, e.g., steel mills could be required via regulations to choose between implementing CCS or switching to 'green steel' technology, or risk losing their operating license. In contrast, CDR is generally disconnected in space and time from any specific source of emissions. Some CDR operations can be tied to ongoing emissions from hard-to-abate sectors, e.g., air travel, and paid for via offset credits. However, given the near certainty that the world will overshoot the level of atmospheric CO_2 consistent with keeping temperature rise in 2100 at or below 1.5°C above pre-industrial, we will also have to remove hundreds of billions of tons of CO_2 that were emitted decades earlier by a wide range of both distributed and point sources. This will require some form of remedial GHG waste management fund, or climate cleanup fund, that taps financial flows on a non-voluntary basis to pay for the vast scale of CDR needed to restore safe atmospheric GHG levels (or perhaps several climate cleanup funds operating in parallel). A process for co-designing and agreeing the sources, scope, and terms of any such climate cleanup funds has not yet been embarked upon.

SECTION 2: HOW MUCH CARBON DIOXIDE REMOVAL WILL BE NECESSARY BETWEEN NOW AND THE YEAR 2100 IF GLOBAL CLIMATE TARGETS ARE TO BE MET?

A key concept in climate policy, of direct relevance to future CDR requirements, is the 'global carbon budget.' The logic of this concept is straightforward – rising levels of CO_2 and other greenhouse gases (GHGs) in the atmosphere trap infrared radiation more effectively and thereby drive up global average annual surface air temperatures, so setting a limit to global temperature rise – e.g., to 1.5°C above the 1850-1900 average – requires limiting the amount of GHGs in the atmosphere, especially the most important GHG that, once emitted, stays in the atmosphere for centuries, affecting the planet's infrared radiation balance: CO_2.

Calculating the remaining carbon emissions budget consistent with a given target temperature rise (e.g., 1.5°C) is not at all straightforward. The calculation requires complex Earth system models, including global climate models as well as "integrated assessment models," IAMs, that project the impact of different trajectories of GHG emissions in combined political-economic and climate model scenarios out to 2100, the assessment year conventionally used by policymakers when a global warming temperature limit is under discussion.

In the standard definition used by United Nations Framework Convention on Climate Change (UNFCCC) policy forums, the "global carbon budget" is the net amount of greenhouse gases, GHGs, that can still be emitted without causing the global average annual surface air temperature in the year 2100 to be higher than a target amount above the average temperature during the period 1850-1900. UNFCCC negotiations in 2015 led to a global agreement, the "Paris Agreement," to limit the target temperature increase [in 2100] to "well below 2.0°C" and to strive to limit it to 1.5°C above the 1850-1900 average.

WHY STRIVE TO STAY BELOW 1.5°C GLOBAL HEATING?

In recent years, political leaders have increasingly emphasized the goal of limiting global warming to 1.5°C by the end of this century, rather than the previous target of 2°C, because the UN's Intergovernmental Panel on Climate Change Special Report on Global Warming of 1.5°C, "SR15," published in 2018, concluded that crossing the 1.5°C threshold poses a grave risk of unleashing severe climate change impacts, including much more frequent and severe droughts, heatwaves, and floods caused by heavy rainfall events.

Since 2018, additional research and reviews[1] by several climate science research teams have concluded that global temperatures at or above 1.5°C, if sustained long enough, pose serious risks of pushing several major Earth systems over phase-transition boundaries, or "tipping points." These risks increase as temperatures increase, and they also increase with the duration of time that temperatures remain elevated (some tipping points will be activated much more quickly than others). The consequences could include (among other things) a wave of species extinctions resulting from the loss of many of the world's tropical coral reefs and the conversion of much of the Amazon biome from rainforest to dry savanna (with climate change impacts exacerbated by deforestation), possibly within the 21st century; triggering of irreversible ice mass meltdown dynamics in the West Antarctic and Greenland Ice Sheets, ultimately leading to >10 meters of sea level rise on a timescale of several centuries, and the consequent loss of the world's coastal cities and lowlands; thaw of increasing volumes of circumpolar Arctic permafrost soils, which are an enormous global carbon reservoir (Arctic and boreal permafrost region soils contain 1460–1600 Gt organic carbon), with increasing releases of methane and CO_2 from the decay of long-frozen organic matter, in a potentially self-reinforcing feedback loop (IPCC Special Report on the Ocean and Cryosphere in a Changing World, 2019); loss of Arctic Ocean ice cover, with severe consequences to global heat dynamics, including frequent severe heat waves in Europe; and a partial or complete shutdown of the Atlantic Meridional Overturning Circulation

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[1] Among others: Wunderling et al. (2023), Global Tipping Points Report 2023; Armstrong McKay et al. (2022), Exceeding 1.5°C global warming could trigger multiple climate tipping points; Wang et al. (2023), Mechanisms and Impacts of Earth System Tipping Elements; and Wunderling et al. (2022), Global warming overshoots increase risks of climate tipping cascades in a network model.

(AMOC), possibly later this century, which, should it occur, could plunge Europe into a Siberia-like climate by stopping the northward transfer of heat from tropical waters.

The most up-to-date research (summarized in the Global Tipping Points Report (Dec. 2023)) suggests the risk of these tipping points is already with us and grows with each 1/10th degree increment of warming. It is therefore crucial to minimize the extent to which global warming will rise above 1.5°C and to limit the time duration spent above 1.5°C.

Moreover, as the tipping point literature indicates, the world perhaps should not consider 1.5°C as a sufficiently safe long-term target. A risk-and-damages averse strategy would aim to bring temperatures back down well below 1.5°C. A target return to 1.0°C global warming by 2100 has been proposed by Breyer et al. (2023) as an interim target for a safer future, with several of the same authors suggesting, in Abbott et al. (2023), a possible longer-term target (e.g., for the mid-22nd century) of returning atmospheric GHG concentrations to pre-industrial levels so as to stabilize ice sheets and prevent cumulative sea level rise from submerging coastal cities and lowlands.

Since most existing climate policy reports and scenarios are focused around the 1.5°C by 2100 target as per the UNFCCC Paris Agreement of 2015 and the IPCC's subsequent 2018 Special Report SR15 outlining the dire consequences of exceeding 1.5°C, the present report remains within the 1.5°C policy frame. However, it should be kept in mind that in future, perhaps before mid-century, it is possible that the policy consensus may shift toward a more ambitious target, e.g., 1.0°C by 2100, if continuing advances in climate science indicate that the consequences of a 1.5°C trajectory would be too costly and dangerous. As we will see below, a target of 1.0°C by 2100 would entail nearly double the annual volume of CDR (carbon dioxide removal) required to achieve 1.5°C by 2100.

WHAT MUST BE DONE TO STAY BELOW 1.5°C?

Climate model scenarios developed for SR15 and for IPCC Assessment Report 6 (AR6), published in stages between 2021 and 2023, estimated that to limit global warming to 1.5°C, global greenhouse gas emissions must peak before 2025 at the latest and decline 43% by 2030. The AR6 included scenarios estimating 6 to 17 $GtCO_2$ carbon dioxide removal (CDR) per year during the second half of the century, after net-zero ongoing annual emissions have been achieved, as part of the requirements for keeping warming to 1.5C in 2100 (along with a rapid shift away from fossil hydrocarbon use). Unfortunately, fossil hydrocarbon use has continued to increase, and global GHG emissions have continued to rise by more than 1% annually, and it is now very likely that global emissions will continue to rise at least until 2030, perhaps beyond. To compensate for the higher-than-hoped level of emissions in coming years, much larger amounts of carbon dioxide removal (CDR) will be needed later this century to take additional excess CO_2 back out of the atmosphere than was envisaged in AR6.

An authoritative global scientific assessment, the State of CDR Report (2023), concluded that: "We are not on track to meet the Paris temperature goal [limiting global heating to no more than 1.5°C by 2100], in terms of either current or proposed Carbon Dioxide Removal (CDR). Closing the gap means expanding conventional [nature-based] CDR on land and rapidly scaling up novel [technology-based] CDR at the same time as urgently cutting emissions."

HOW MUCH CDR WILL BE CUMULATIVELY NECESSARY BY 2100?

An excerpt (below) from the State of CDR Report (2023, first edition) describes its scientific team's review of hundreds of scenarios run via Integrated Assessment Models (IAMs) during the preparation of IPCC AR6 to estimate the amounts of carbon dioxide removal (CDR) necessary during the remainder of this century to meet climate policy targets. Again, note that the numbers in what follows are too optimistic: they underestimate the CDR volumes that will be necessary to meet 1.5 (or 2.0°C) targets for 2100, since they are predicated on now-outdated IPCC AR6 scenario assumptions that global emissions would peak no later than 2025 and decline by nearly half by 2030. Given that global GHG emissions are continuing to rise year-on-year, the CDR estimates based on the median results of IAM scenarios prepared for AR6 are unrealistic and CDR estimates will have to be revised upward in future rounds of IAMs.

> Many IAMs use a "cost-effective" approach to estimate economic and energy transitions, in that they try to reach a given climate goal at minimal costs for the global economy. … **Most scenarios assume idealized conditions where currently nascent mitigation technologies become available in the next decade or so, while stringent global climate action starts immediately.** However, IAMs are also used to study scenarios in which climate policy and the low-carbon transition are delayed or in which not all technologies are (fully) available. As such, IAMs are a key resource to explore the constraints or possibilities that shape how we meet climate goals, including the key roles of CDR methods in doing so. We use the collection of scenarios compiled for the Intergovernmental Panel on Climate Change's Sixth Assessment Report (IPCC AR6) as a starting point here. The database features 1,202 scenarios with climate assessments from 14 modelling teams.
>
> **All scenarios that limit global temperature rise to 1.5°C or 2°C feature substantial increases in CDR in addition to sustained and deep emission reductions. Failing to deliver these emission reductions in the short term increases scale and dependence on CDR in the long term.** All emissions pathways that limit global warming to 2°C or lower feature multiple gigatons of CDR annually, making CDR a critical component of any mitigation strategy relevant to the Paris Agreement. **In assessed scenarios,** CDR does not play this role in the near term; absolute emission reductions dominate mitigation activities during the first half of the 21st century. For example, **by 2030, net CO_2 annual emissions decline by 19 (14-27) $GtCO_2$ and 8 (0-17) $GtCO_2$ relative to 2020 levels in 1.5°C and 2°C pathways, respectively.** During that same timeframe, annual deployment of conventional [nature-based] CDR on land – such as via afforestation/reforestation – increases by 0.8 (-0.1 to 3.0) $GtCO_2$, while novel [technology-based, a.k.a. engineered] CDR – such as Bioenergy with Carbon Capture and Storage (BECCS) or Direct Air Carbon Capture and Storage (DACCS) – increases by 0.01 (0-0.83) $GtCO_2$.
>
> CDR levels expand faster in 1.5°C pathways than 2°C pathways, growing by 2.6 (0.8-5.4) $GtCO_2$ removals annually by 2030 compared with 2020 levels. Both CDR types reach their maximum deployment only after mid-century... **Conventional CDR on land is responsible for 99% (78-100%) of 2030 CDR in both 1.5°C and 2°C pathways.** Conventional CDR on land [afforestation/reforestation, peat bog restoration] continues to grow thereafter until its peak around 2050, approximately doubling in 1.5°C pathways and increasing by around 50% in 2°C pathways compared with 2020 levels. **Novel [technology-based] CDR methods such as BECCS or DACCS are typically scaled up throughout the century.**
>
> **1.5°C scenarios achieve net-zero CO_2 emissions by around mid-century**, and the vast majority (93%) of 2°C scenarios do so on average about two decades later. **CDR grows steadily in these deep mitigation pathways.** At the time of net-zero CO_2, CDR levels range between 5.5 and 16 $GtCO_2$ per year in 1.5°C pathways and between 6.8 and 16 $GtCO_2$ per year in 2°C pathways. During the second half of the century, after the point of net-zero CO_2 emissions, CDR becomes an increasingly dominant feature of climate change mitigation efforts. **All 1.5°C and most 2°C pathways feature a sustained period of net-negative CO_2 emissions from enhanced levels of CDR that reduces atmospheric carbon concentrations** and (often) leads to a drawdown in global mean temperatures. Almost all pathways achieve net-zero or net-negative CO_2 emissions through utilization of CDR, and many achieve net-zero greenhouse gases (GHGs) in the long term.
>
> However, as Chapter 3 (Innovation) [of the State of CDR Report] illustrates, **new [CDR] technologies can take decades to mature and reach large-scale adoption. Steady near-term progress in deploying novel [engineered] CDR – such as BECCS and DACCS – is critical to achieving the required scale-up in the long term.**

> The level and composition of CDR deployed in scenarios varies widely and depends on several factors within a given scenario, as discussed in Section 7.3. Table 7.2 [of the 2023 first edition State of CDR Report] shows cumulative CDR deployment across the 21st century, where values for 2°C pathways range between 440 $GtCO_2$ and 1,100 $GtCO_2$, with a median value of 630 $GtCO_2$. More ambitious **scenarios that limit warming to 1.5°C with no or limited overshoot** show very similar levels of CDR deployment and **reach a median value of 740 $GtCO_2$ with a range of 420-1,100 $GtCO_2$.** To still limit warming to 1.5°C in 2100 but with a high temporary overshoot of temperatures (>0.1°C), the range of required cumulative CDR increases by about 110 $GtCO_2$ on average. This is about 14% higher than in limited overshoot 1.5°C scenarios. The **additional CDR is needed to draw down temperature levels after peaking.** As a result, **every year of delaying rapid and sustained emission reductions increases the requirements for CDR deployment in the long term.**
>
> **Scenarios to date have focused on a narrow set of CDR methods, principally afforestation/ reforestation and BECCS.** This requires great care in interpreting the scale of CDR methods in climate change mitigation and the role of individual CDR methods. In this report, **we interpret BECCS deployments as being representative of a broader set of novel [engineered] CDR methods, and afforestation/reforestation as being representative of conventional [nature-based] CDR on land.** Modelling teams have recently begun to incorporate other novel CDR methods, such as DACCS or enhanced rock weathering, into their modelling frameworks. **As IAM modeling teams expand their representation of CDR methods, trade-offs across the CDR portfolio have become more apparent.** Table 7.2 [of the State of CDR Report 2023] highlights the variability in the composition of CDR portfolios in existing scenarios. BECCS is present in almost all scenarios considered (502 of 507), and deployment levels vary widely, spanning 170-760 $GtCO_2$ cumulatively throughout the century. Conventional [nature-based] CDR on land is also included in most scenarios (407 of 507) and has a slightly smaller span of cumulative removals (130-560 Gt CO_2). In contrast, fewer than 1% of pathways considered include active contributions from enhanced rock weathering.
>
> A range of studies have reported that **including other [engineered] CDR methods in addition to BECCS might reduce not only the range of mitigation costs but also the impact of CDR on energy use, emissions, land, and water. However, contributions of these methods to CDR are sensitive to the rate at which they can be scaled up, which remains highly uncertain** (Box 7.3 of State of CDR Report 2023).

What this scientific assessment in the 2023 (first edition) State of CDR Report tells us is that **even under the unrealistically optimistic assumptions of the Integrated Assessment Models used in IPCC AR6,** which generally assumed global emissions would peak by 2025 and steeply decline thereafter, the **expected cumulative levels of CDR required during the remainder of the century are enormous:** CDR volumes in 2°C pathways range between 440 $GtCO_2$ and 1,100 $GtCO_2$, with a median value of 630 $GtCO_2$. More ambitious **scenarios that limit warming to 1.5°C with no or limited overshoot reach a median value of 740 $GtCO_2$ with a range of 420-1,100 $GtCO_2$.** As the report further says, in AR6 scenarios that posited a temporary overshoot above 1.5°C during the 21st century (any overshoot larger than at least 0.1°C above 1.5°C), which is now generally understood to be almost inevitably what will occur, the range of required cumulative CDR increases by about 110 $GtCO_2$ on average, i.e. **the median value of CDR required this century rises to 850 $GtCO_2$ and the higher-end scenario CDR estimates to >1,200 $GtCO_2$.** Compare these figures to estimates of how much CO_2 has been emitted into the atmosphere from fossil fuels burning since the beginning of the industrial revolution (until 2023): around 1,600 $GtCO_2$; to this figure must be added another ca. 800 $GtCO_2$ from land use changes, principally deforestation to provide land for agriculture and ungulate pasture.

If we make a plausible scenario assumption that each ton of CDR will cost $100, those additional 110 $GtCO_2$ we may need to draw down before 2100 in the>1.5°C overshoot scenario would entail $11 trillion of additional spending on CDR (in addition to $74 trillion we would have to spend on CDR under the median estimate of 740 $GtCO_2$ in the no-overshoot scenario) because of a failure to ramp down fossil fuels during the 2020s. Assuming a $100/ton average cost of CDR, every 100-billion-ton increment of CDR will cost the coming generation another $10 trillion. Each increment also poses the difficult challenge of finding ways to physically remove another 100 billion tons of CO_2 from the carbon-climate cycle. It would be easier and cheaper, in the long run, to ramp down emissions more quickly than to ramp up CDR to even higher levels later this century.

TWO POLICY PRIORITIES: AVOID UNNECESSARY EMISSIONS; DRIVE AVERAGE COST OF CDR AS LOW AS POSSIBLE BY INVESTING IN NOVEL CDR TECHNOLOGY R&D AND SUPPLY CHAIN DEVELOPMENT

The foregoing considerations should provide motivation for **two policy priorities:**

(i) **Avoid unnecessary emissions.** This means aggressively shifting away from fossil fuels use and toward clean technologies. Where shifting away from fossil fuels is impossible or comparatively too expensive, carbon capture and storage (CCS) or carbon capture, utilization, and storage (CCUS) technologies can be implemented to limit the climate impact of fossil fuels use. For the energy system, a growing literature based on techno-economic energy system models presents global and regional calculations of least-cost pathways for accelerating the ramp-up of cheap solar, wind, and battery renewable energy systems and geothermal heat as low-cost post-fossil-fuels energy supply solutions. On the demand side, shifting to renewable electricity as the main global primary energy supply implies electrifying every sector – including transportation, space heating/cooling, agriculture, and a wide range of industrial processes.

(ii) **Drive the average cost of CDR as far below $100 as possible.** Invest heavily in research and development of novel engineered CDR methods and in scaling up CDR supply chains to achieve economies of scale. Concurrently, increase global biomass, restoring forests, peat bogs, and other natural carbon sinks on a net basis, while reducing the scope of actions that degrade ecosystems.

Another point made in the State of CDR Report (2023) is that the IAMs created in the preparation of AR6 oversimplified their representations of the CDR technology toolkit, with afforestation/reforestation, BECCS, and DACCS the only CDR techniques modeled in most IAM scenarios. In reality, as we outline in a special section on BECCS further below, it may prove unrealistic to expect BECCS to achieve very large scale (>1 $GtCO_2$ per annum), because doing so would entail growing very large volumes of bioenergy crops to feed BECCS thermal power generation plants, presenting competition for land use and biomass against higher-value uses – agriculture, agroforestry, bio-economy raw materials, amenities, and biodiversity.

As for DACCS, the other novel CDR method that plays a prominent role in the IAMs: it is technically scalable to at least several $GtCO_2$ per annum later this century, although in its current state of technological development, it is very costly and energy-intensive per ton CDR. Various reports have proposed pathways to reduce the cost of DACCS, e.g., Küng et al. (2023) offer a "A roadmap for achieving scalable, safe, and low-cost direct air carbon capture and storage." How well DACCS will fare when compared to other possible engineered CDR methods on energy efficiency and cost-effectiveness criteria cannot yet be known. DACCS is at an early stage of technological evolution, but most of the other novel CDR methods (e.g. enhanced rock weathering, electrochemical seawater processing, incorporation of biochar in durable products, among others) are at even earlier stages. **Determining the relative efficiency of DACCS vs. other potentially promising novel engineered CDR methods and technologies can be expected to be a growing priority in climate policy and carbon management related research and development.**

21ST CENTURY TOTAL CDR REQUIREMENTS FOR A 1.5°C BY 2100 TARGET MAY BE IN 850 TO >1,000 GIGATON CO_2 RANGE

Regardless of which CDR methods are assumed in IAMs, given the reality that the numbers cited for the cumulative CDR volumes required before 2100 are often based on AR6 IAM scenarios and those scenarios made assumptions about global emissions reductions in the 2020s that are proving overly optimistic, there is a high likelihood that global cumulative CDR volumes that will have to be deployed before 2100 to keep global temperatures at or below 1.5°C by 2100 will have to be well in excess of 1,000 $GtCO_2$.

IAM modeling teams developing new IAM scenarios ahead of IPCC Assessment Report 7 (due by 2030) will develop revised emissions trend scenarios. The updated AR7 median projections for 21st century CDR requirements (in cumulative $GtCO_2$) will likely be significantly higher than the AR6's median CDR projections. For now, we estimate that under a scenario of moderate temporary overshoot above 1.5°C during this century (such an overshoot may now be unavoidable), **if 1,000 $GtCO_2$ must be removed by 2100 to return to 1.5°C by 2100, then if we assume the bulk of the removals will occur after 2050, this means an annual CDR volume (averaged over the 50-year period) of about 20 $GtCO_2$.** A scenario of only minor and brief temporary overshoot above 1.5°C during this century would mean implementing CDR of about 17 $GtCO_2$ per annum given a median estimate from AR6 IAMs of 850 $GtCO_2$ total CDR during the century. CDR requirements of less than 850 $GtCO_2$ now seem implausible, given continuing year-on-year emissions increases and little sign that emissions will peak during the present decade.

CO_2 IS NOT THE ONLY GREENHOUSE GAS

Several different anthropogenic GHGs are known to retain infrared radiation and so increase global surface air temperature. The most important are CO_2 (carbon dioxide), CH_4 (methane) N_2O (nitrous oxides), and fluorinated gases, especially CFCs (chlorofluorocarbons). These gases combined are responsible for the enhanced greenhouse effect and global warming observed over the past century. The contributions in terms of percentage of global warming above pre-industrial levels are approximately: CO_2: 65%, CH_4: 25%, N_2O: 6%, fluorinated gases: 2% (IPCC AR6).

Each of these different kinds of gas has a different "global warming potential," i.e. one molecule of CH_4 in the atmosphere traps much more infrared (heat) radiation than does one molecule of CO_2 over a 100-year period. This is why rising emissions of methane leaking from the natural gas supply chain are even more damaging than rising CO_2 emissions. (Natural gas is mostly methane.)

In 2023, about 41 $GtCO_2$ of anthropogenic CO_2 were emitted, of which 37 $GtCO_2$ was from fossil fuels combustion. Two-thirds of the other 4 $GtCO_2$ were from land use change (deforestation, peat bog draining, soil degradation), and the remainder was from cement-making and other industrial processes.

By convention, climate scientists translate the global warming potential of the non-CO_2 greenhouse gases into CO_2-equivalent amounts, denoted CO_2eq, for two reasons: first, to get a standard measure of overall climate impact; and second, because offsetting the global warming impact of non-CO_2 emissions can most readily be achieved by CDR methods, i.e. removing CO_2 from the atmosphere, upper ocean waters, or biosphere, and storing the captured carbon in a form that no longer interacts with the carbon-climate cycle.

Measured in CO_2eq terms, total anthropogenic GHG emissions in 2023 are estimated to have been 54 $GtCO_2eq$. This includes contributions from CO_2 and from methane (CH_4), nitrous oxide (N_2O), and fluorinated gases, which have much higher global warming potentials per molecule than CO_2.

CAN PARTIAL ATMOSPHERIC METHANE REMOVAL BE MADE PRACTICAL?

Some research groups are investigating possible ways of reducing the lifetime of methane in the atmosphere, so as to reduce its global warming impact. Methane has more than tripled in atmospheric concentration since the beginning of the Industrial Revolution and according to NASA is responsible for an estimated 25% to 30% of global heating. Converting as much as possible of the methane into the atmosphere into CO_2 more quickly than occurs naturally would be helpful. The importance of methane, the main constituent of natural gas, in driving global warming is such that UNEP, the UN Environment Programme, has concluded that "without relying on future massive-scale deployment of unproven carbon-removal technologies, **expansion of natural gas infrastructure and usage is incompatible with keeping warming to 1.5°C."**

WHAT IF 1.5°C IS TOO DANGEROUS, AND 1.0°C IS EVENTUALLY SET AS A NEW TARGET FOR 2100?

There is another critical factor that could drive 21st century CDR volume requirements even higher than 1,000 $GtCO_2$ – possibly much higher. As noted above, some climate scientists have taken the view that 1.5°C is already much too high a level of global heating, too dangerous. Some say that the global climate policy target should be to drive atmospheric ppm CO_2 levels back down to 350 ppm CO_2eq by 2100 or soon thereafter (and further down after that), where "CO_2eq", carbon dioxide equivalent, is a number that takes into account the radiative forcing effect of both CO_2 and other GHGs (methane, nitrous oxide, fluorocarbons) emitted by human activities. A seminal paper taking this view is Hansen et al. 2017, "Young People's Burden: Requirement of Negative CO_2 Emissions." Building on Hansen et al., Breyer et al. (2023) have proposed a 1.0°C target for 2100.

Hansen et al. note that global temperature has risen well out of the pre-industrial-era Holocene range and Earth is now warmer than it was during the most recent prior (Eemian) interglacial period, when sea level was 6–9 m higher than today's. The Eemian interglacial period, also known as the Last Interglacial, began approximately 130,000 years ago and ended around 115,000 years ago. It was characterized by relatively warm temperatures, similar to or slightly warmer than the present interglacial period, the Holocene. Hansen et al. estimated the Eemian average global surface air temperature was 1°C above the pre-industrial Holocene average. They suggest that "targets for limiting global warming thus, at minimum, should aim to avoid leaving global temperature at Eemian or higher levels for centuries," and note that "such targets now require 'negative emissions', i.e., extraction of CO_2 from the air." This is their basis for recommending a return of the atmospheric CO_2 concentration to 350 ppm or lower by about 2100, and prospectively further down toward the pre-industrial level (in the year 1750 CE) of 277 ppm after that.

In this context, it is noteworthy that more recently (in the years since Hansen et al.'s 2017 paper), it has been discovered through paleoclimate research (Christ et al. 2021) that **Greenland was mostly ice-free about 416,000 years ago, during an interglacial period called Marine Isotope Stage 11 (MIS 11)**. This may be highly relevant to future reconsiderations of global ppm CO_2 policy targets, given that the **atmospheric CO_2 level never rose above 280 ppm during that interglacial period**. Candy et al. (2014) note that "the pattern of insolation variability that occurs during MIS11 matches that which occurs in the Holocene more closely than in any other warm stage of the past half a million years. In addition, there is now an extensive range of evidence for MIS11 paleoclimates and palaeo-environments from marine, ice core, lacustrine and terrestrial sequences." They propose that this makes MIS11 a useful analog for the current Holocene interglacial that began 11,700 years ago and in which human civilization emerged.

For comparison, the pre-industrial-era CO_2 level during the Holocene ranged from 260-280 ppm and was 277 ppm in the year 1750 CE. This suggests that **the Greenland Ice Sheet's meltdown tipping point may be only slightly above the Holocene-era average CO_2 level. The loss of Greenland's ice sheet would by itself cause 7.2 meters of sea level rise.** Greenland is already losing hundreds of billions of tons of ice annually, and the rate of ice mass loss is accelerating. **A risk-averse policy would be to target a return of the atmospheric CO_2 concentration to about 275 ppm** (and a concomitant return of atmospheric methane levels to pre-industrial concentrations) **to ensure ice sheet stability,** and to achieve that target **soon enough to avoid activation of irreversible ice-melt feedback loops** that would cause the loss of the Greenland and West Antarctic Ice Sheets (loss of the latter would lead to another 5.3 meters of sea level rise). For both ice sheets, there are "tipping points" beyond which continued ice mass loss can no longer be stopped, and while it is uncertain when the tipping points will have been crossed, there are serious concerns that maintaining current elevated atmospheric CO_2 levels for a few decades or centuries would eventually trigger them, as global oceans gradually heat up and ocean circulation patterns change in dangerous ways.

The table below shows the atmospheric concentrations of the principal greenhouse gases affecting Earth's climate at they were in the year 1750 and in 2024. As far as paleoclimate research has been able to determine, the rate of change in the concentrations of these gases is unprecedented in the entire geological history of our planet. Such changes normally have taken thousands or millions of years. The last time Earth's CO2 concentration was at 2022's level (420 ppm) was about 14 to 16 million years ago during Middle Miocene Climatic Optimum of the Cenozoic era, according to new research by Hoenisch et al. (2023), when forests grew in the Arctic and parts of Antarctica and sea levels were much higher than today's.

TABLE: ATMOSPHERIC GHG CONCENTRATIONS IN 1750 AND 2024

Greenhouse Gas	Concentration in 1750	Concentration in 2024	Increase
CO_2	~280 ppm	~420 ppm	~50%
CH_4	~700 ppb	~1900 ppb	~170%
N_2O	~270 ppb	~330 ppb	~22%
O_3 (tropospheric ozone)	Varies (low)	Varies (higher)	Increase due to pollution
H_2O (water vapor)	Highly variable	Highly variable	Controlled by temperature
CFCs	0 ppb (not present)	Varies (present in parts per trillion)	Introduced by humans

Data sources: NOAA Global Monitoring Laboratory, IPCC Assessment Report 6 (A.1.3).

Hansen et al. suggest that returning global average annual surface temperature to no more than 1.0°C above the 1850-1900 average would require a return to 350 ppm CO_2eq by 2100 or soon thereafter. This would impose a much larger aggregate CDR requirement for the rest of the 21st century than the estimated ppm CO_2eq target corresponding to a return to 1.5°C by 2100.

The current global CO_2 level in 2024 is 423 ppm. It will continue to rise in coming years due to continuing GHG emissions, which were higher than ever before in each of the past three years. In 2021, global CO_2 level was 419 ppm. However, the CO_2-equivalent (CO_2eq) ppm figure for 2021, which takes into account the additional global warming potential of atmospheric methane, nitrous oxide, and fluorocarbons, was much higher, the equivalent of 472 ppm CO_2, according to a report by the European Environment Agency (EEA). The EEA report estimates that CO_2eq must return to 411 (390-430) ppm by 2100 to limit global temperature increase to 1.5°C.

If CO_2eq were instead to be returned to 350 ppm by 2100 as Hansen et al. suggest in "Young People's Burden," this would mean a further 61 ppm reduction in CO_2. Reducing atmospheric carbon by 1 ppm CO_2 requires about 18 $GtCO_2$ of CDR, according to a 2015 report by the US National Research Council's Committee on Geoengineering Climate. Removing an additional 61 ppm CO_2eq from the atmosphere beyond the amount required to reach 1.5°C by 2100 under the median estimate of 850 $GtCO_2$ generated by the State of CDR Report team (see above) given the strong likelihood of temporary overshoot above 1.5°C, could thus entail a further 61*18 = 1,098 $GtCO_2$, for a total 21st century CDR requirement of 850+1,098 = 1,948 $GtCO_2$, or nearly two trillion tons.

This suggests that Hansen et al.'s scenario of returning below 350 ppm CO_2eq by 2100 scenario would entail removing about two-thirds of the CO_2 that humanity will have emitted into the environment between the beginning of the industrial revolution and the mid-21st century. To achieve this cumulative amount of CDR, 1,948 $GtCO_2$, if we assume equal annual CDR volumes between 2050 and 2100, would mean implementing **39 $GtCO_2$ CDR per annum**. It is as yet unclear whether this level of CDR is technically feasible, since no single CDR method has yet been shown unequivocally to scale to more than a few (1 to at most 5) $GtCO_2$ per annum (though it is possible that some, e.g., DACCS or OAE, ocean alkalinity enhancement, may eventually prove scalable in amounts >5 $GtCO_2$). Implementing ca. 40 $GtCO_2$ per annum would certainly be an enormous global challenge. Existing expert reviews of CDR methods, e.g. the UK Royal Society of Chemistry's book "Greenhouse Gas Removal Technologies" or the "State of CDR Report", suggest that even the current (less ambitious) policy target of limiting global warming to 1.5°C by 2100 will require the implementation of several different CDR methods concurrently so that they add up to ca. 17 to 20 $GtCO_2$ per annum during the second half of this century, since no single CDR technology is expected to be scalable enough to be able to do the job alone.

Estimates of potential annual volumes achievable by different CDR methods are provided in section 3 of this report. None of those estimates are definitive or authoritative; currently available estimates of CDR volume potentials of each method vary widely, in part because many CDR methods are at very early technology readiness levels and have not been extensively field-tested.

SECTION 2 CONCLUSIONS: PLAUSIBLE RANGE OF 21ST CENTURY CDR REQUIREMENTS

Existing and proposed global climate policy targets require that total CDR requirements during the decades between now and 2100 can be estimated to lie in the range 850 to 2,000 $GtCO_2$, or about 17 to 40 $GtCO_2$ per annum in the second half of this century, depending on whether the global climate policy target will remain a return to 1.5°C by 2100 as per the UNFCCC Paris Agreement of 2015, or climate policy ambition is increased and a new target is set of returning to 1.0°C by 2100 as has been proposed by some influential climate scientists.

Further atmospheric GHG reductions via CDR may be implemented after 2100, prospectively all the way back down to the pre-industrial CO_2 level of 277 ppm (the level in 1750 CE), if policymakers of future generations decide they prefer to avoid risking the loss of coastal cities and lowlands to sea level rise. Future policymakers may well make that decision, given paleoclimate data suggesting that:

- Eemian interglacial period sea levels were 6 to 9 meters higher than today's (the Eemian, which ran from about 130,000 to 115,000 years before the present, was the most recent interglacial prior to the current Holocene);
- the Eemian interglacial period was just 1.0°C warmer than the pre-industrial Holocene era (today, in 2024, we are 1.2°C warmer than the pre-industrial Holocene), and
- Greenland was largely ice-free around 416,000 years ago, during the MIS11 interglacial that lasted from 388,000 to 427,000 years ago and during which atmospheric CO_2 levels never rose above 280 ppm.
- For comparison, today, in 2024, we are at 423 ppm and rising, not counting the additional CO_2eq impact of non-CO_2 GHGs; if their impact is counted, we are at 472 ppm CO_2eq.

It is plausible that by mid-century, if and when a global CDR industry has been developed and proven itself capable of removing about 20 $GtCO_2$ per year from the active carbon-climate cycle, policymakers may be inclined, if it seems technically feasible to do so, to increase their climate policy ambition, double the CDR industry's scale, and set a trajectory for a return to 277 ppm by the middle of the 22nd century, setting a goal to limit cumulative sea level rise and so conserve civilization's legacy of coastal cities and productive lowlands – including some entire countries, e.g., the Netherlands and Vietnam, which will eventually be lost to sea level rise if the West Antarctic and/or Greenland Ice Sheets melt away in substantial part or in whole.

With this overview of why the world needs to manage atmospheric carbon levels, and estimates of the magnitude of the challenge in billions of tons per year of carbon dioxide removal, we can move on to an overview of the various available or emerging carbon dioxide removal technologies – most of which are in early stages of technical development. We also will take note of estimates of the prospective scalability of each CDR method, recognizing, however, that such estimates are highly uncertain at this early stage.

SECTION 3: A BRIEF OVERVIEW OF CURRENTLY KNOWN CARBON DIOXIDE REMOVAL (CDR) METHODS AND TECHNOLOGIES AND SCALABILITY ESTIMATES FOR EACH; RELEVANCE OF RESULTS-BASED PAYMENTS

A McKinsey report published in December 2023, "Carbon removals: How to scale a new Gigaton industry," briefly surveyed ten existing and prospective CDR technologies. The table below summarizes that report's estimates of the cost per ton of CO_2 removal associated with each of the ten methods, and also the expected durability of each (some durability estimates adjusted by this author; all other numbers as per McKinsey report). The financial and durability numbers should be taken as rough estimates, not as Gospel – such estimates range widely; but the numbers below present a reasonable synthesis of the current state of opinion amongst subject matter experts.

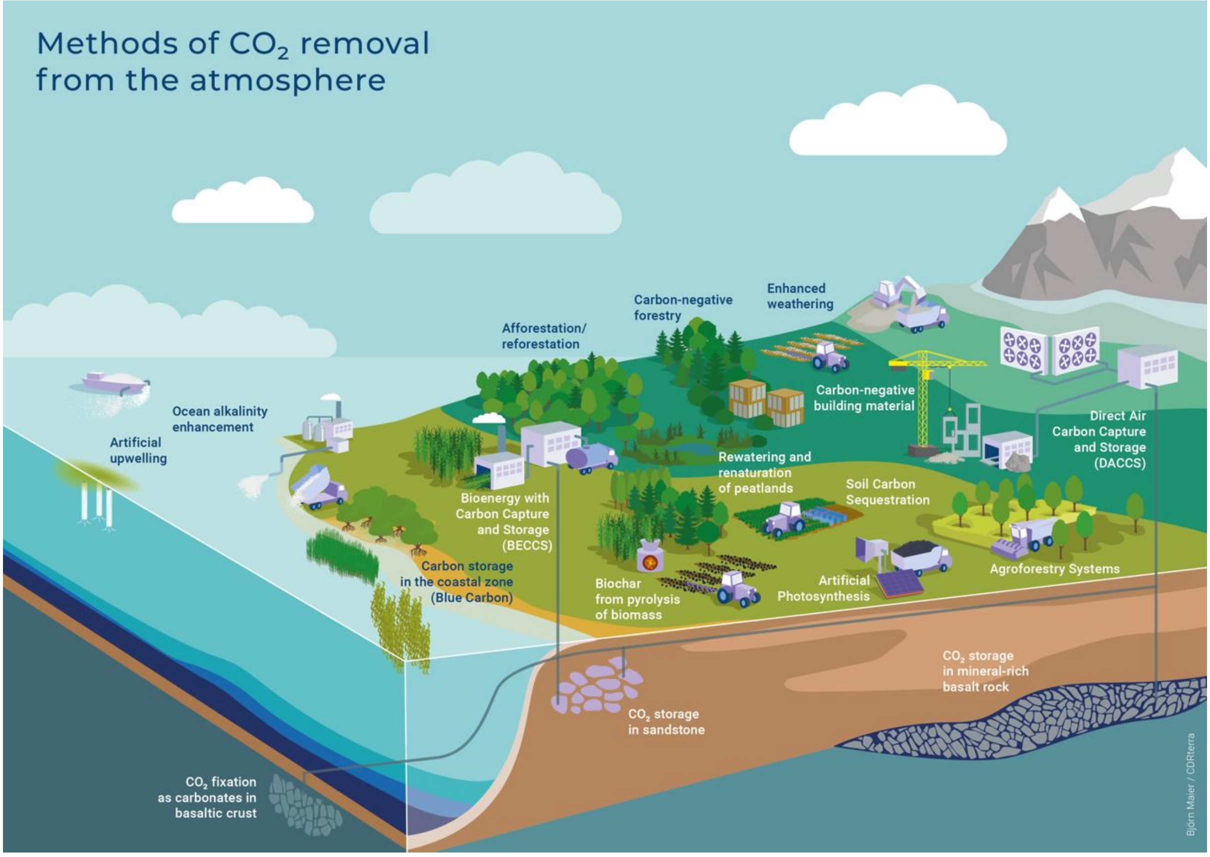
CDR METHOD	**Nature-based or Engineered?**	**$/ton CO_2 (range) as of 2023**	**Durability (years)**
Wetland and peatland restoration	Nb	15-40	<100
Cropland, grassland, and agroforestry	Nb	10-30	<100
Reforestation and afforestation	Nb	10-40	<250
Blue carbon (mangroves, etc.; algae cultiv.)	Nb	25-250	<500
Biochar and bio-oil	Eng	90-220	<500
OAE, Ocean Alkalinity Enhancement	Eng	Uncertain	>1000
ERW, Enhanced Rock Weathering	Eng	120-800	>1000
BECCS, Bio-energy w. carbon capture & storage	Eng	60-270	>1000
DOC, Direct Ocean Capture	Eng	Uncertain	>1000
DACCS Direct air carbon capture & storage	Eng	500-1000	>1000

The McKinsey report (linked here) includes additional information on each of the categories, including notes on potential benefits and potential challenges of each approach. In most cases, especially open-to-environment CDR methods, challenges include measuring, reporting, and verification (MRV) of the specific amounts of CDR achieved by a given project. MRV is not a problem for DACCS and possibly not for BECCS (assuming high quality life-cycle analysis has been carried out). It presents difficulties for most of the others.

McKinsey's list is not fully comprehensive. It doesn't include ocean fertilization, for example, and it doesn't break out OAE into its various subcategories. But it illustrates the overall state of play of the industry in 2023. Note that two promising engineered CDR technologies, OAE and DOC, are so early-stage in their technical development as to be merely experimental, so much so that McKinsey did not see fit to estimate a price per ton of CO_2 for those two technologies.

MOST CDR TECHNOLOGIES ARE EARLY STAGE, WITH UNCERTAIN COSTS AND SCALABILITY

As we saw in Section 2, implementing carbon dioxide removal from the environment, whether by 'nature-based' or 'engineered', 'biological' or 'geochemical', 'marine' or 'terrestrial' methods, will be necessary on a very large scale by the middle of the 21st century to achieve climate goals already agreed in UNFCCC negotiations. Yet the unit cost, energy requirements, and scalability of various CDR methods, and in some cases even their technical feasibility, remains highly uncertain. Most engineered CDR methods are early-stage technologies that will require much more investment and technological innovation before a clear picture of their key numbers can be estimated with confidence – in particular, required energy input per ton of CO_2 removed, cost-effectiveness (dollars per ton of CO_2 removed), and potential scalability.



Source of image: website of CDRterra, the German government funded research program on land-based CDR methods.

Even the most well-known, ‘conventional’ nature-based methods, i.e., afforestation/reforestation, coastal mangrove ecosystem restoration, grasslands restoration, wetlands/peat bog restoration, and soil carbon enhancement, are fraught with uncertainties about their realistically achievable vs. theoretical maximum potential CDR volumes.

The table below provides estimates of the maximum and realistic potential levels of CDR in $GtCO_2$ (billions of tons of CO_2) per year for nine major CDR categories. Relevant sources are linked. Note again that these estimates are provisional, disputable, and not authoritative. Multiple uncertainties influence all of them. At this point, for many CDR methods, we just don’t know what their realistic potential will turn out to be. And for some, notably bio-energy carbon capture and storage (BECCS), as we will argue in a special section in this report, volume estimates set out in some past reports and 2000s- to 2010s-era Integrated Assessment Models are turning out to have been major overestimates. Claims in CDR-related literature about the potential scalability of any given CDR method should, for now, be taken with a large grain of salt.

TABLE: CATEGORIES OF CDR METHOD AND THEIR ESTIMATED SCALABILITY

CDR Method	Est. Max. Potential $GtCO_2$/yr	Realistic Potential $GtCO_2$/yr	Pros	Cons	Sources
Afforestation and Reforestation	3-18	2-4	Biodiversity enhancement& ecosystem restoration	Land use conflicts, permanence issues	Land-based CDR potl.; A/R on abandoned cropland; CarbonBrief; IPCC; IPCC AR6 CDR factsheet

BECCS	3.5-5.9	0.1-1.6	Renewable energy production	High land and water requirements	Potl. scale of BECCS; E.T.C. on Bioresources; Romm; Nature; OneEarth
Ocean Fertilization	1-5	0.1-1	Potential large-scale deployment	Ecological risks, uncertain effectiveness	OceanNETS, OceanVisions; Earth-Science Review; Nature NPJ
Soil Carbon Sequestration	2-5	1-2	Improved soil health and agricultural productivity	Monitoring challenges, potential reversibility	SCS MRV; SCS strategy; SCS scalability; SCS certificates; Grassland C risks
Direct Air Capture (DAC)	5-10	0.5-5	Scalable, can be located near storage sites	High costs, energy-intensive	DAC Roadmap; 50 DAC startups; DAC method overview; IEA on DAC; DAC scalability critique
Enhanced Weathering	2-4	1-2	Utilizes abundant natural materials	Land and energy requirements	EW via croplands; EW limits; Max. theor. potl.; Coastal EW; Sulfuric EW
Ocean Alkalinity Enhancement	2-10	0.5-2	Enhances oceanic CO_2 uptake	Potential ecological impacts, logistics	OAE MRV; OAE regional potentials; OAE review; Nature NPJ; Ocean CDR
Biochar	0.4-2.6	0.1-1	Soil enhancement & waste biomass utilization	Limited scalability, cost variability	Engineered biochar; Book (2024), Biochar in Envir. Mgmt.; Biochar supply-chain; Scale est.
Blue Carbon (Coastal Wetlands)	0.5-1.4	0.2-0.8	Biodiversity benefits, coastal protection	Limited geographic scope, restoration challenges	Frontiers in Climate 2022; Frontiers in Climate 2021; Current Biology; Nature; Blue Carbon Handbook

Some source texts that provide useful overviews of a wide range of known CDR technologies are "Greenhouse Gas Removal Technologies," edited by Mai Bui and Niall Mac Dowell, published by the UK Royal Society of Chemistry in 2022; the online "CDR Primer," edited by J. Wilcox, B. Kolosz, & J. Freeman, published in 2021; and the online State of Carbon Dioxide Removal report (2nd ed., 2024).

Before we dive into details on the various categories of CDR in Sections 4 and 5 of this report, or prospective and existing mechanisms for funding CDR in Sections 6 and 7, let's get a sense of emerging novel engineered CDR industries by looking at three CDR technologies that may come to play significant roles in future decades, and considering **how results-based payments (RBPs) might be deployed to help CDR technologies move up their technology readiness levels, to get them ready for large-scale implementation a decade or so down the road.** We assume, in the rest of Section 3, a near-future, pre-2030 scenario world in which total global funding for CDR remains relatively modest. In this world, the limited funds available for advancing CDR technology advancement and supply chain development must be carefully targeted to push the technologies along their respectively learning curves quickly and effectively.

EXAMPLES OF POSSIBLE DEPLOYMENT OF RESULTS-BASED FINANCE TO ACCELERATE DEVELOPMENT OF EARLY-STAGE NOVEL CDR METHODS

What is the most effective way to deploy limited funds via results-based payments (RBPs) in the face of a many-Gigaton-scale challenge like global atmospheric carbon management for climate safety?

RBPs at this stage in the development of the nascent novel CDR industry may be best deployed toward moving promising, very early-stage, potentially game-changing technologies along their learning curves. Let's consider three examples of CDR technologies and possible application of RBPs to each: Biochar, enhanced weathering of powdered olivine rocks, and electrochemical seawater processing.

BIOCHAR

Biochar is a carbon-rich material produced via pyrolysis of biomass, i.e., thermal decomposition of organic biomass in an oxygen-limited environment. High-quality biochar can best be produced in purpose-built kilns in which temperature, pressure, heating rate, residence time, gas flow rates, and feedstock composition can be controlled.

Biochar production is a fairly well understood technology, but it has not yet been optimized. Biochar production kilns can be made for very different processing scales and different biomass types, e.g., ranging from a size appropriate for a small farmer in Kenya with a hectare of land with mixed crops, to a meso-scale maize farm of perhaps ten hectares, to a large thousand-hectare soybean farm in Brazil, to an industrial-scale facility for processing wood waste from large forestry operations in Uruguay, Brazil, Sweden, or Canada.

Example RBP scenario for biochar (illustrative, not an actual program): One could design a results-based payments scheme to pay for the delivery of, say, 100 small farm-scale biochar production units from each of 5 different suppliers, with carefully specified performance parameters, in a design challenge intended to stimulate the development of manufacturing capacity for efficient and robust small-farm biochar production units. The competition could go through several rapid iterations until major gains were no longer evident in the newest iteration. The best units from amongst the five different suppliers could then be promoted for scaling-up through other distribution channels and financing mechanisms.

RBPs for biochar could also be deployed to incentivize testing of biochar as an input material in a variety of durable products. At present, biochar is predominantly thought of as a soil amendment. Adding biochar often does improve soils, especially tropical soils; however, the permanence of carbon sequestration from adding biochar to soils is limited. Estimates of how much biochar carbon added to soil will remain after 100 years vary widely; one estimate (Rodrigues et al. 2023) suggests that 25%–50% of the carbon originally in the biomass feedstock for pyrolysis remains in the soil after 100 years, depending on the quality of the biochar and soil conditions. Some carbon is emitted during pyrolysis and complicated scientific estimates suggest that perhaps 20 to 40% of biochar carbon is converted, through microbial activity, to CO_2 within 100 years after it has been added to the soil.

Could additional uses for biochar, beyond its use as a soil amendment, offer economic opportunities and greater permanence of carbon sequestration? It would be useful to fund experiments aimed at finding such uses. For example, biochar can be added to asphalt (e.g., 10% by mass of asphalt) or to concrete (5%). Adding biochar to asphalt improves asphalt's temperature resistance in subtropical and tropical climates and increases stiffness and viscosity of asphalt binders, thereby increasing road surfaces' resistance to deformation.

Possibly biochar could also be mixed with a binding agent (e.g. cement or bio-epoxy) to create standard high-strength construction elements (breezeblocks, bricks, wall panels). If so, the permanence of the resulting carbon sequestration could be much greater than is the case when biochar is added to soil. Again considering an iterative design challenge scenario, RBPs could be paid per kiloton of each of a range of different durable biochar-containing products that have potential large-scale uses in construction industries. In this way, RBPs could financially enable product development and experimentation by providing a small-scale guaranteed offtake market. A criterion for success could be the development of products that include as high a percentage by mass of biochar as possible (to sequester as much carbon as possible) whilst also achieving specific targets for strength, durability, composition consistency, etc.

A number of biochar advocacy trade associations exist, including the International Biochar Initiative, the US Biochar Initiative, the European Biochar Industry Consortium, India Biochar and BioResources Network, and several others. Development of a large-scale biochar industry will require a systematic approach toward developing and commercializing biochar kilns sized and optimized for various categories of application, seeding regional supply chains, capacity-building, and providing access to financial incentives.

ENHANCED ROCK WEATHERING

Enhanced weathering of powdered mafic rocks (see Section 4 for more detail on enhanced rock weathering) such as dunite or basalt (among others) could in principle be a moderately scalable method for achieving removal and mineralization of carbon from seawater or agricultural lands. In dunite, for example, carbon from CO_2 reacts with magnesium in olivine, the main component of dunite, to form magnesium carbonate. The challenge is that the mineralization reaction, while exothermic, is very slow. To maximize mineralization of CO_2, powdered rock must be exposed to CO_2 for a long time (one to ten years), preferably in an aqueous environment, such as ocean surface waters or wet agricultural soil. Running dunite, basalt, or some other suitable type of rock through electricity-powered rock crushers and grinders is straightforward, albeit energy intensive. The more difficult technical challenge is working out how to effectively expose the powdered rock to CO_2 for months and years – long enough for the minerals in the rock powder to react with ambient CO_2.

One suggestion has been to spread the powdered rock grains on ocean beaches, where waves and tidal action will roll them around, so that all sides of each rock grain will be exposed to ambient CO_2 (rock powder that gets buried in sediment will not react with much CO_2). However, there are limits on the plausible area of beaches which might be suitable. Unfortunately, if the rock powder is simply dumped into the ocean, it sinks to the bottom too fast to react with much CO_2 in surface waters.

Another approach could be to find a way to make olivine rock dust float on the ocean surface. For example, suppose containers similar to very large tea bags were made of a material with mesh finer than the grain size of the crushed olivine powder. Each tea bag could be suspended from a buoy designed to float for two years before either sinking as a unit along with the bag of powdered rock (at which point it would fall to the seabed) or releasing the 'tea bag' (allowing recovery of the floating buoy). Such a device might achieve a good ratio of carbon mineralization per ton of olivine powder. An iterative design challenge could be launched, with a guaranteed small-scale offtake market offered via results-based payments to qualified participants in a competition. The aim would be to develop rock-dust 'tea bags' and buoys that will be very cheap, rugged enough to last two years, and environmentally benign.

Here again, a results-based payments scheme could be designed to offer contracts to several different suppliers, paying each to supply some number (e.g. 1,000) of 'tea bags' and buoys in each iteration of the competition, each according to their own design, yet all required to meet certain design parameters. (E.g., the contract could specify that each tea bag should contain not less than 2 tons of rock powder and achieve a mineralization efficacy of no less than 200 kg of CO_2 per ton of olivine powder after one year floating in the ocean). This model of funding for a CDR engineering design challenge should lead to a race to the top. One of the five designs would outperform the others in terms of the key technical criteria. Again, such a design challenge could be run iteratively, through three or more rounds of competition, each funded through RBP contracts. Each round of the design competition would lead to improvements in the product's design, technical performance, and unit cost profile.

A special challenge with open-to-environment carbon removal methods like ERW is measurement, reporting, and verification (MRV), i.e., the technical difficulty of estimating how much carbon is actually sequestered as a result of a given action, such as spreading ten tons of powdered rock on a farmer's field. This difficulty could be largely eliminated by using easily quantifiable modular ERW systems such as the 'tea bags' envisioned above.

A nascent trade association, the Enhanced Weathering Alliance, affiliated with the Carbon Business Council, was launched in March 2024.

ELECTROCHEMICAL SEAWATER PROCESSING FOR CDR

Electrochemical seawater processing for CDR involves passing a current through seawater to induce chemical reactions that capture and sequester CO_2 via mineralization in the form of carbonate solids, or in a simpler procedure, it merely separates CO_2 from seawater, allowing the CO_2 to be concentrated and piped away for geological storage.

One version of the process includes the following steps:
1. Electrolysis of seawater, which splits water molecules (H_2O) into hydrogen (H_2) and oxygen (O_2) gases. The hydrogen gas can be captured and stored.
2. CO_2 capture: The electrolysis also generates hydroxide ions (OH-) which react with dissolved CO_2 in seawater to form bicarbonate (HCO_3-) and carbonate (CO_3^{2-}) ions, effectively removing CO_2 from the water and allowing more atmospheric CO_2 to be absorbed.
3. Precipitation: Some bicarbonate or carbonate ions then react with cations like calcium (Ca^{2+}) and magnesium (Mg^{2+}) in seawater to form solid carbonate minerals (e.g., $CaCO_3$, $MgCO_3$), which precipitate out of solution, effectively sequestering CO_2. These reactions are as follows:

$$Mg^{2+} + 2\,HCO_3^{-} \rightarrow MgCO_3\,(s) + CO_2\,(g) + H_2O\,(l)$$
$$Ca^{2+} + 2\,HCO_3^{-} \rightarrow CaCO_3\,(s) + CO_2\,(g) + H_2O\,(l)$$

(Note that the carbonation reaction that combines each Mg^{2+} and Ca^{2+} ion with bicarbonate to form solid magnesium carbonate and calcium carbonate remove one carbon atom from the carbon-climate cycle, but also produce a CO_2 molecule.)

This process is inherently scalable, because it leverages the ocean’s almost unlimited amounts of seawater and its vast amounts of dissolved inorganic carbon. By using renewable electricity to drive the reactions that capture CO_2 by mineralizing carbon in stable, solid forms, it has the benefit of permanence, unlike most terrestrial nature-based CDR methods (afforestation/reforestation, etc.). It also generates a potentially useful byproduct (hydrogen gas). But electrochemical seawater processing requires a lot of energy for pumping water, electrolyzing seawater, and so on. Can an efficient version of the process be designed and refined through field-testing?

Again, results-based payments could be implemented to fund several research groups to deliver some agreed amount of carbon sequestration via electrochemical processing, e.g. 10,000 tons of CO_2 removed, each with machinery of their own design. The team delivering tons of CO_2 at the lowest energy input per ton through a robust, reproducible process could be awarded a cash prize (in addition to the payment per ton agreed at the outset) and the prospect of further R&D funding in a second round. The price per ton would likely have to be high in early iterations of experimental technologies – but at the end of each iteration, progress will have been made, and further rounds of design and field-testing competition can build off the first. Energy and cost efficiencies can be expected to result with each iteration.

Iterative CDR technology design competitions aren’t the only prospective high-value use of limited available public or private funds for advancing CDR technologies. The following subsection proposes a mechanism for efficiently advancing CDR technologies through Open Source research and modeling.

STRATEGIES FOR EFFICIENT USE OF R&D SUBSIDIES FOR EARLY-STAGE NOVEL CDR TECHNOLOGIES: FIELD TRIALS, OPEN-SOURCE MODELS

A further consideration when designing ways to spend limited climate funding on early-stage novel CDR technologies is that owners and employees of startup companies have a vested interest in promoting a perception that *their* method is the best one. It is conceivable that a startup with a better marketing team will win more funding and see their technology achieve greater acceptance than a different startup with better technology but inferior marketing.

One way of reducing the attendant risk of malinvestment would be to fund a research effort at a public institution (such as a university) to simultaneously build and test prototypes of multiple different CDR methods within a given category, e.g., all known designs for electrochemical seawater processing and for marine-based enhanced ultramafic rock powder weathering. If one engineering team tests several methods in parallel, they will have less reason to overpromote a specific technology (compared to a startup company that is focused on just one technology), and they will have an unrivalled basis for making comparative assessments of CDR technology options within a category.

Further gains can be made by funding several such efforts around the world – both to generate a wider sample of engineering data and reduce the risk of idiosyncratic results resulting from the work procedures of any one research group, and also, so as to seed several centers of expertise in different geographic regions, including in developing countries where large-scale deployment of CDR paid from global funding sources may present a future industrial-scale economic development opportunity.

A useful approach for results-based funding of novel CDR methods could be to fund CDR engineering research groups at public institutions to build prototypes and conduct simultaneous, parallel field trials with multiple CDR methods within a given category, with data from the field trials informing highly detailed engineering models of each technology.

Funding contracts of this type could include obligations requiring full disclosure of research data and results and an Open-Source approach to modeling the technologies, so that engineers and economic actors at other institutions, startup companies, and others can benefit from the insights gained. The purpose here is to accelerate the emergence of scalable and cost- and energy-efficient CDR technologies – and prevent malinvestment in inferior technology options – by generating comparisons both between CDR technology categories and within each CDR technology category.

It could be useful to fund a core CDR modeling team tasked with maintaining an Open-Source database of very detailed chemical engineering models of novel CDR methods and their financial, energy, and material input costs per ton of CDR, as well as regional assessments of these methods' environmental impacts (positive and negative) and prospective governance and public support. The core team of model curators would be tasked with recruiting and inviting qualified volunteer contributors to this Open-Source CDR Methods database.

Better scoping of more vs less technically promising CDR approaches would help optimize RDD&D investment targeting and avoid malinvestment. It may be useful to establish and fund a program to develop very detailed Open-Source models of each CDR approach, including both closed-to-environment (e.g. DACCS) and open-to-environment (e.g. ocean fertilization) CDR methods.

Why Open-Source?

- A publicly funded Open-Source approach overcomes the challenge that many CDR startup companies do not disclose the details of their CDR technologies (to maintain a market advantage).
- An Open-Source approach leverages volunteer contributions from qualified and motivated volunteer experts, e.g., retired chemical engineers.

Sophisticated input-output models for open-to-environment CDR methods could enable measuring, reporting, and verification (MRV) of open-to-environment methods, e.g., as per the Carbon to Sea program that seeks to lay a foundation for MRV for open-to-environment Ocean Alkalinity Enhancement methods. Open-to-environment CDR methods pose MRV challenges – but may well prove more cost-effective and energy-efficient because they leverage ambient energy (e.g., from sunshine, wind, and waves) and materials.

The take-away message here is that for any given category of CDR method, **the best use of limited funding for results-based payments is to go upstream in the technology supply chain, targeting opportunities to stimulate and reward game-changing design innovations.**

The three examples in the previous subsection suggested that it could be useful and potentially transformative to pay an agreed amount per well-designed, rugged farm-scale biochar pyrolysis unit produced, or per two-ton durable high-sequestration-efficiency ocean-floating olivine teabag, or per kiloton-per-month, maximally efficient electrochemical seawater processing and hydrogen production unit, or some other engineering quantity for stimulating promising novel CDR technology development. Many additional examples of using results-based payments for funding CDR technology advancements could be adduced.

Results-based financing of this kind will still require pairing with appropriate research and development funding or startup financing. Results-based financing generally only applies when there are existing institutions (companies, research groups, etc.) that are capable of fulfilling an order to deliver some quantity (e.g. tons of carbon removal delivered by a specified method). A key concern with novel CDR methods is that few such supply chains exist yet, especially in developing regions.

Before moving on to a survey of novel terrestrial CDR methods in Section 4, let's make note of concerns that sometimes arise in public discourse around carbon removal and other carbon management technologies (CDR, CCS, CCUS): Public perception – including fears that some types of CDR might cause environmental harm, as well as fear of 'mitigation deterrence.'

SOCIAL LICENSE OF CDR: IMPACT OF FEAR OF MITIGATION DETERRENCE ON PUBLIC PERCEPTIONS OF CDR METHODS

CDR's potential impacts on marine or terrestrial ecosystems could include either positive externalities (such as contributing toward reversing ocean acidification via ocean alkalinity enhancement, or enhancing ecosystem productivity) or negative externalities (e.g., potentially overfertilizing some ecosystems). Concerns about possible negative externalities have been raised by some observers, reflecting sentiments among a significant part of the wider public. Driven by such concerns, the UN via the United Nations Convention on Biological Diversity (CBD) and the London Convention on the Prevention of Marine Pollution have adopted decisions to strictly regulate activities such as ocean fertilization, which constitute *de facto* bans against all forms of commercial deployment. Experience has shown that careful public engagement can win support for CDR operations, and such engagement is appropriate prior to their deployment even when projects are only an experimental scale (e.g., as described in a recent CDR project in the Dominican Republic).

Some experts argue that ocean fertilization is analogous to afforestation/reforestation or soil enhancement, and that if it is done with due care in appropriate regions and quantities, it would likely have strongly positive, not negative, externalities. The Centre for Climate Repair at the University of Cambridge takes this view; it has a research project entitled "Marine Biomass Regeneration" that points out that the amount of biomass in the ocean is greatly diminished compared to the pre-industrial era.

Fear of mitigation deterrence appears to drive the opposition expressed by some groups to carbon removal or other 'geo-engineering' methods. "Mitigation deterrence" is a term used to refer to a risk that policymakers and energy industries might take a position of over-reliance on the prospect that future CDR efforts can 'fix' the climate as a justification to slack off on near-term efforts to mitigate CO_2 emissions by reducing fossil fuels use.

The risk of mitigation deterrence is a real and justified concern in general terms. Lancaster University researcher McLaren (2020) attempted to quantify the potential scale of mitigation deterrence that flawed Integrated Assessment Model assumptions about future CDR volumes could generate, and separately describes the issue in an approachable short text.

However, given that several hundred billion tons of CDR (possibly more than a trillion tons) will have to be implemented over the coming century if dangerous climate disruptions are to be minimized (even if net-zero emissions are achieved by 2060), fear of mitigation deterrence is not a compelling reason to oppose or dismiss promising CDR methods.

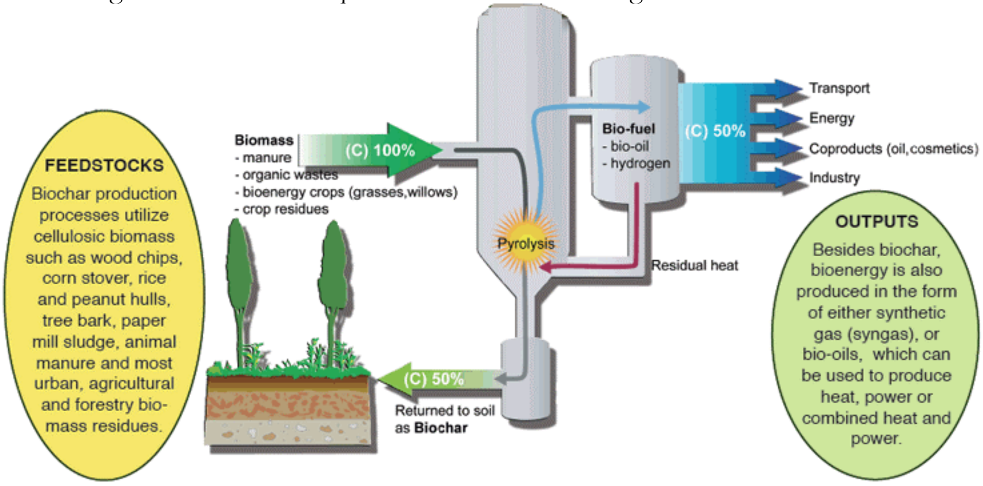
SECTION 4: NOVEL LAND-BASED CDR (TERRESTRIAL CDR) METHODS

This section will look in somewhat more detail at three land-based CDR methods: biochar; CO_2 mineralization, especially via enhanced weathering of ultramafic or mafic rocks (enhanced rock weathering, ERW); and direct air carbon capture and storage (DACCS). The following section (section 5) will look at some promising ocean-based CDR methods. Note however that some CDR methods mix land and sea – for example, biochar is normally considered in relation to agricultural crop residues or wood waste, but it could also be made from seaweed, kelp, or even micro-algae grown in shallow saltwater oceanside ponds (microalgae cultivation for CDR).

The most common large-scale terrestrial CDR methods – afforestation/reforestation and other nature-based methods, e.g., peat bog restoration and soil carbon enrichment – will not be covered here. These methods are at least moderately scalable, often relatively inexpensive, and above all, have many ecological and societal co-benefits. The main difficulty with them, beyond questions of scalability due to limits on available land, is around carbon sequestration *permanence:* because forests can burn and soils can dry out, and droughts will increase as the planet warms, the durability (permanence) of carbon sequestration in living terrestrial biomass is open to question. Nature-based terrestrial CDR methods are thus out-of-scope of this report, which focuses on engineered CDR methods of high carbon sequestration permanence.

BIOCHAR

Biochar, a stable form of carbon, is the solid remainder of biomass decomposition at high temperature in the absence of oxygen. It can be produced from a variety of feedstocks. A closer look at biochar is warranted, because of all CDR methods, it has the most immediate potential for deployment in developing countries in a way that could engage and benefit wide populations of farmers and other land-use managers (see Scholz et al., 2014, “Biochar systems for smallholders in developing countries”). A useful overview of biochar, more detailed than in the present report, can be found starting at p.104 in Ch.3 of the 2019 report published by the US National Academies of Sciences, Engineering, and Medicine, “Negative Emissions Technologies and Reliable Sequestration: A Research Agenda.”



Source: International Biochar Initiative

A strong word of caution is warranted: Biochar added to soils may not be an efficient way of *durably* removing CO_2 from the carbon-climate cycle on a multi-century timescale. A quantitative comparison of CDR methods by Chiquier et al. (2022) entitled “A comparative analysis of the efficiency, timing, and permanence of CO_2 removal pathways” concluded that:

> “Biochar achieves low CDR [biomass carbon feedstock input] efficiency, in the range of 20–39% when it is first integrated with the soil, and that regardless of the biomass feedstock considered.

Moreover, its CO_2 removal efficiency can decrease to −3 to 5% with time, owing to the decay of biochar."

BIOCHAR EQUIPMENT AND MATERIALS

Biochar equipment of suitably rugged and affordable design will be needed for use at different scales, from agricultural smallholder to large industrial scale. The details of biochar pyrolysis unit engineering design are beyond the scope of this report. However, as noted in section 3 above, it may be useful for government or multilateral agencies interested in biochar promotion to deploy funding for the standardization and cost-efficient production of small-scale, meso-scale, and large-scale biochar production units. Results-based payments could be deployed to pay for production of some number of such units at a desired price point, rather than for amounts of biochar produced and utilized by farmers on their own land, or the hard-to-estimate consequent amounts of CO_2 sequestered.

Many different biomass materials can be pyrolyzed, using several different kinds of equipment and process. The numbers in the Table of Biochar Production Methods and Potential Scalability (below) are very rough estimates and not intended to be authoritative. No-one really knows what the realistic range of biochar scalability is. (The same is true for nearly all CDR methods.)

TABLE OF BIOCHAR PRODUCTION METHODS AND POTENTIAL SCALABILITY

Production Method	**Input Biomass**	**Estimated Scalability ($GtCO_2$/year)**
Slow Pyrolysis	Various biomass	0.5 - 1.0
Fast Pyrolysis	Various biomass	0.3 - 0.7
Flash Pyrolysis	Various biomass	0.2 - 0.5
Gasification	Various biomass	0.5 - 1.5
Hydrothermal Carbonization	Various biomass	0.2 - 0.5
Microwave Pyrolysis	Various biomass	0.2 - 0.5
Anaerobic Digestion with Biochar	Organic wastes	0.5 - 1.0
Rotary Kiln Pyrolysis	Various biomass	0.5 - 1.5
Top-Lit Updraft (TLUD) Gasification	Various biomass	0.1 - 0.3
Biochar Ovens	Various biomass	0.05 - 0.2
Wood Gas Stoves	Wood biomass	0.05 - 0.2
Agricultural Waste Pyrolysis	Agricultural residues	0.5 - 1.0
Forestry Residues Pyrolysis	Forestry residues	0.5 - 1.5
Municipal Solid Waste Pyrolysis	Municipal solid waste	0.3 - 0.7
Manure Pyrolysis	Livestock manure	0.5 - 1.0
Crop Waste Pyrolysis	Crop residues	0.5 - 1.0
Bamboo Pyrolysis	Bamboo	0.5 - 1.0
Seaweed Pyrolysis	Seaweed	0.2 - 0.5
Algae Pyrolysis	Algae	0.5 - 1.0
Coconut Shell Pyrolysis	Coconut shells	0.1 - 0.2

BIOCHAR IN SOILS

The estimates in the table below are collated from several sources, including the International Biochar Initiative, Lefebvre et al. 2023: "Biomass residue to carbon dioxide removal: quantifying the global impact of biochar," Tisserant and Cherubini 2019, Tisserant et al 2023. As Tisserant and Cherubini (2019) say in "Potentials, limitations, co-benefits, and trade-offs of biochar applications to soils for climate change mitigation":

> "Biochar is an attractive NET [negative emissions technology] for CDR as it can supply two marketable products, biochar as soil amendment and bioenergy generation via biochar coproducts (bio-oil and syngas). Pyrolysis is a rather simple, known technology that can be deployed in both developed economies and developing countries. More agricultural benefits associated with biochar systems are expected in developing countries with low agricultural inputs and degraded/weathered soils. … Climate change mitigation benefits of biochar are potentially large, but depend on soil interactions, its production conditions, availability of cheap and sustainable feedstocks, and management practices. As another biomass-based NET, biochar supply is constrained by the availability of forest or crop residues or of land to grow dedicated bioenergy crops. Interactions of biochar with the climate system are more complex than just carbon sequestration or reductions in GHG emissions from soils. They include changes in surface albedo, soil water fluxes, and emissions of NTCFs [short-lived near-term climate forcers, e.g. methane, ozone, or aerosols], which are difficult to quantify and affect estimates of net local and global climate effects of biochar systems."

BIOCHAR AND BASALT POWDER CO-APPLICATION TO SOILS

Biochar and crushed basalt powder could be co-applied to agricultural fields, which is expected to result in increased CDR volume per hectare of land and potential increases in agricultural productivity, according to some assessments, e.g. Honvault et al. 2024, although few field experiments have been done yet. By combining biochar and crushed basalt powder into a soil amendment product and mixing it into agricultural soils, farmers would be implementing the outputs of two distinct CDR materials and methods (biochar production and enhanced mafic rock weathering) in a single soil improvement procedure. See the subsection further below on 'enhanced weathering' of mafic and ultramafic rocks. This approach merits experimentation and field-testing.

BIOCHAR FIELD STATIONS, AGRICULTURAL EXTENSION HUBS

A take-away from these considerations is that results-based payments for biochar application (or for co-application of biochar and powdered basalt) could be a useful pathway to engage farmers and land managers in developed and developing countries, and this would be particularly beneficial in tropical regions with acidic or depleted soils.

However, widespread application of biochar and/or basalt powder as soil amendments is unlikely to happen without considerable effort in developing regional and local supply chains. Regional agricultural and agroforestry field stations could serve as hubs for promoting these techniques and the know-how, equipment, and funding required to promote their implementation. Funding to establish and develop such hubs must come before funds for results-based payments per ton of biochar can be paid out.

An additional challenge is that MRV (measuring, reporting, and verification) of the quantities of biochar or biochar-basalt powder mixes added to soils may be logistically difficult. Applying MRV on a basis of payments per ton of carbon removed via biochar/basalt-powder mixes would be even more difficult, given the uncertainties around quantifying the long-term carbon sequestration impacts. Instead, perhaps the distribution of standard biochar-making equipment and the training to make good use of them could be subsidized along with basalt powder, and farmers might continue to make use of it if they observe useful results in terms of agricultural productivity.

BIOCHAR-CEMENT: BIOCHAR AS A CONSTRUCTION MATERIAL ADDITIVE

As briefly explored in Section 3 above, the question arises whether the permanence of carbon sequestration via biochar could be improved by adding biochar to a durable binding matrix, e.g. cement, or bio-based polymers in biochar-polymer blends, rather than mixing it into soil where it will be exposed to water, oxygen, and microbial activity. This merits further investigation. In a review article on "biochar-concrete", Barbhuiya et al. (2024) suggest that the incorporation of biochar in concrete has several benefits: improved strength and durability, enhanced thermal properties, and the potential for carbon sequestration.

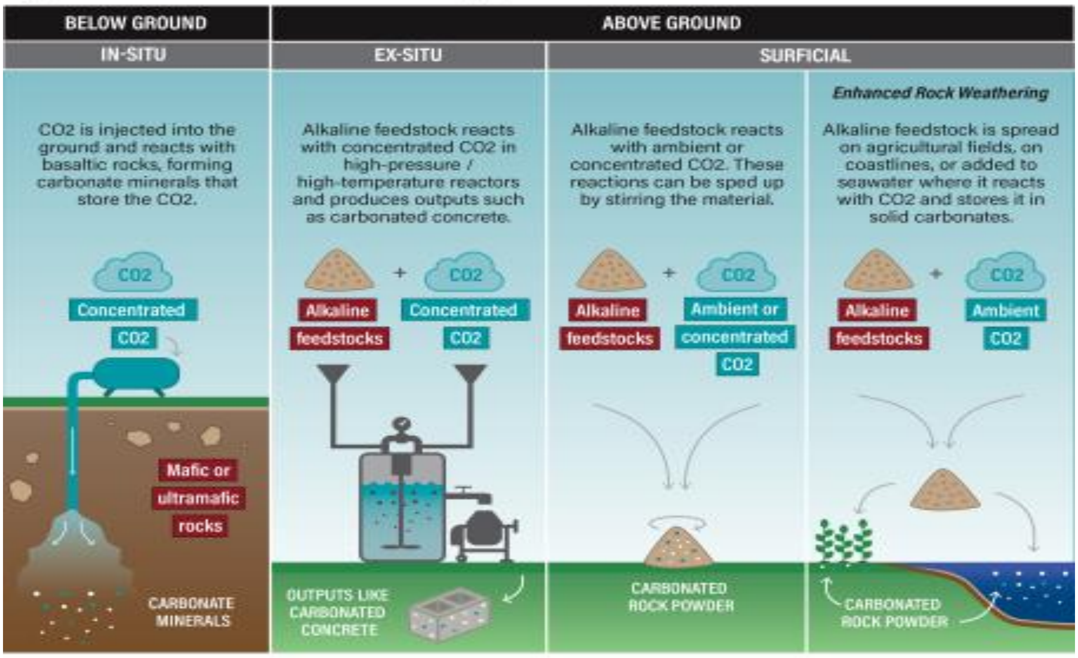
Taking a wider view, we can ask whether large-scale carbon sequestration from dedicated crops grown on marginal lands – e.g. Bana grass plantations – or marine sources, e.g., biochar made from seaweed – could be processed industrially to provide input material for construction industries on a large scale. This might be achieved by crushing biochar into condensed 'carbon black' and mixing it with a binding agent, e.g. 'green' cement or bio-epoxy, for use as building material, e.g., in the form of bricks. If the aim is permanence of carbon sequestration, biochar mixed into a binding material such as cement or epoxy and deployed as building material would seem to be more promising than biochar mixed into soils, given Chiquier et al.'s estimate of low permanence for much of the carbon in soil biochar.

The potential large-scale use of biochar to make standardized construction products such as bricks or mixed into asphalt does not yet appear to have been intensively investigated experimentally and may merit R&D funding or, as described in section 3, results-based funding per ton of biochar-biopolymer or biochar-cement composite. The question is whether uses can be found for biochar-containing composites that combine permanence of carbon sequestration, utility in construction industries, low cost, and gigaton-per-annum potential scale.

GEOCHEMICAL CARBON DIOXIDE REMOVAL METHODS

A number of CDR methods are in development that entail removing CO_2 by promoting reactions between CO_2 (or more precisely, carbonic acid formed when CO_2 is dissolved in water) and various minerals. The general term is 'geochemical CDR methods,' including various 'carbon mineralization' methods. The diagram below shows some of these. They're divided into 'in situ' and 'ex situ' methods.

Types of carbon mineralization approaches



Alkaline feedstock = alkaline mine tailings, some industrial by-products and certain types of mined rock.
Source: WRI

WORLD RESOURCES INSTITUTE

Source of image above: WRI.org, “5 things to know about carbon mineralization.”

An ‘in situ’ approach takes concentrated CO_2 and pumps it underground under pressure, into porous mafic or ultramafic rock formations such as basalt or peridotite that are rich in minerals that naturally combine with CO_2 in the presence of water to form solid carbonate minerals. (Basalt is naturally porous; other rock types may require fracturing to increase their permeability.) The term ‘in situ’ refers to the fact that the reactant rock minerals are left in place – they are not moved or dug up.

If the concentrated CO_2 is derived e.g. from combustion of biomass, then this can be a net negative emissions method. Otherwise, if derived from fossil fuels combustion or another CO_2-emitting industrial process, it is considered a CCS (carbon capture and storage) process, not a net negative emissions process.

The CO_2 is typically injected in a supercritical state, which means it behaves as both a liquid and a gas, making it easier to transport and inject. Supercritical CO_2 is denser than its gaseous form and has properties that allow it to penetrate small rock pores, which is crucial for successful injection into the subsurface.

In some cases, the CO_2 is mixed with water (often referred to as "carbonated water") before or during injection. This mixture helps facilitate the chemical reactions necessary for the permanent storage of CO_2. Once injected into the rock, the CO_2 reacts with silicate minerals in the basalt, such as calcium, magnesium, and iron silicates, to form stable carbonate minerals (e.g., calcite, magnesite). These reactions effectively lock the carbon that was in the CO_2 into solid, stable forms, preventing it from escaping back into the atmosphere. Basalt's porous nature allows the CO_2 to spread out and react with the minerals, leading to permanent sequestration over time.

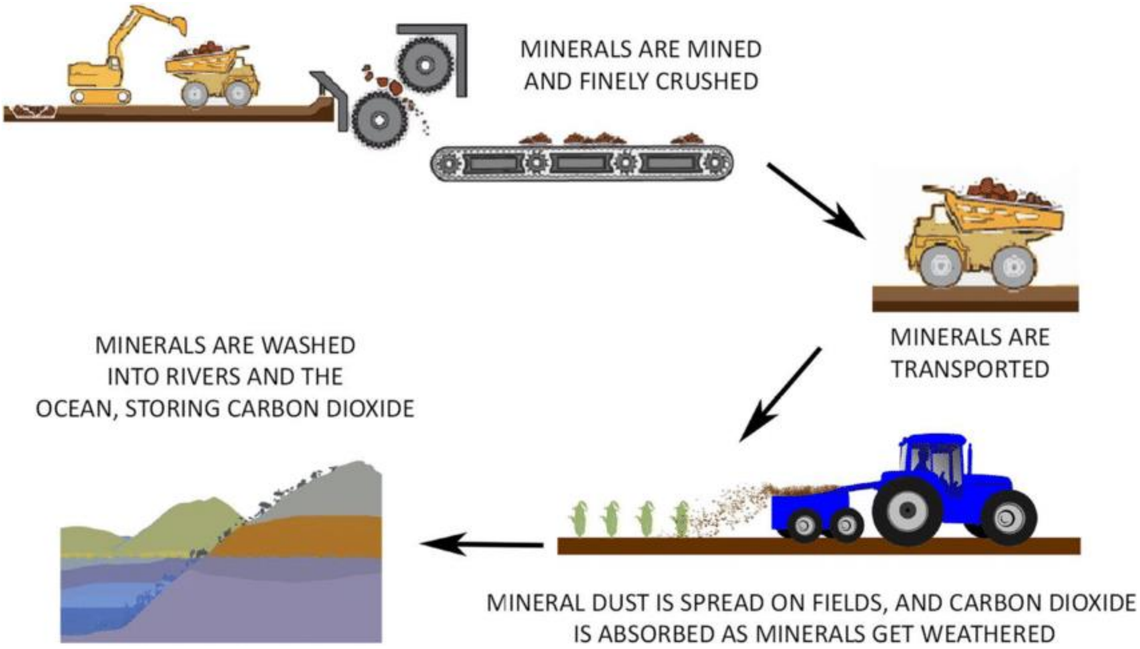
For more details on the ‘in situ’ method, see Matter, J. M., et al. (2016). "Rapid carbon mineralization for permanent disposal of anthropogenic carbon dioxide emissions." *Science*, 352(6291), 1312-1314.

Some forms of ‘ex situ’ carbon mineralization can speed up the carbon mineralization reactions by having them occur in pressure vessels and/or at high temperatures. However, models and experiments have shown that this approach is often expensive (uses too much energy) and is difficult to scale. A review of ex situ methods is found in Romanov et al. (2015), “Mineralization of carbon dioxide: Literature review.” Another is Gadikota (2021), “Carbon mineralization pathways for carbon capture, storage and utilization.”

Finally, there are two major categories of surficial geochemical carbonation operations that do not involve pressure vessels and occur at ambient temperatures, yet over longer timespans (months and years) nevertheless cause CO_2 to combine with suitable minerals and become locked up as solid carbonate minerals, safely away from the carbon-climate cycle. One approach is to use alkaline feedstocks that are byproducts of ongoing or past industrial processes, notably mine tailings or slag from steel production as the reaction substrate and mix CO_2 and water with these to encourage mineral carbonation reactions. The other approach is “enhanced rock weathering,” which was previously mentioned in Section 3 and is the subject of the remainder of this subsection.

ENHANCED ROCK WEATHERING: HARNESSING GEOCHEMISTRY AT SCALE

Enhanced Rock Weathering (ERW) is a carbon dioxide removal (CDR) technique that accelerates the natural process of chemical weathering of silicate rocks, wherein silicate minerals like olivine, $(Mg,Fe)_2SiO_4$, or pyroxene, $(Ca,Mg,Fe)(Si,Al)_2O_6$, react with CO_2 and water to form aqueous solutions of cations (Mg^{2+}, Ca^{2+}, Fe^{2+}, etc.) and stable bicarbonate ions, HCO_3^-; the bicarbonate ions can remain in solution in water indefinitely (e.g., in groundwater or in the ocean), effectively sequestering CO_2 from the atmosphere. Additionally, chemical weathering of silicate rocks can sequester carbon in solid form by generating solid magnesium carbonate and calcium carbonate as the product of reactions involving CO_2, H_2O, and silicate minerals such as olivine.

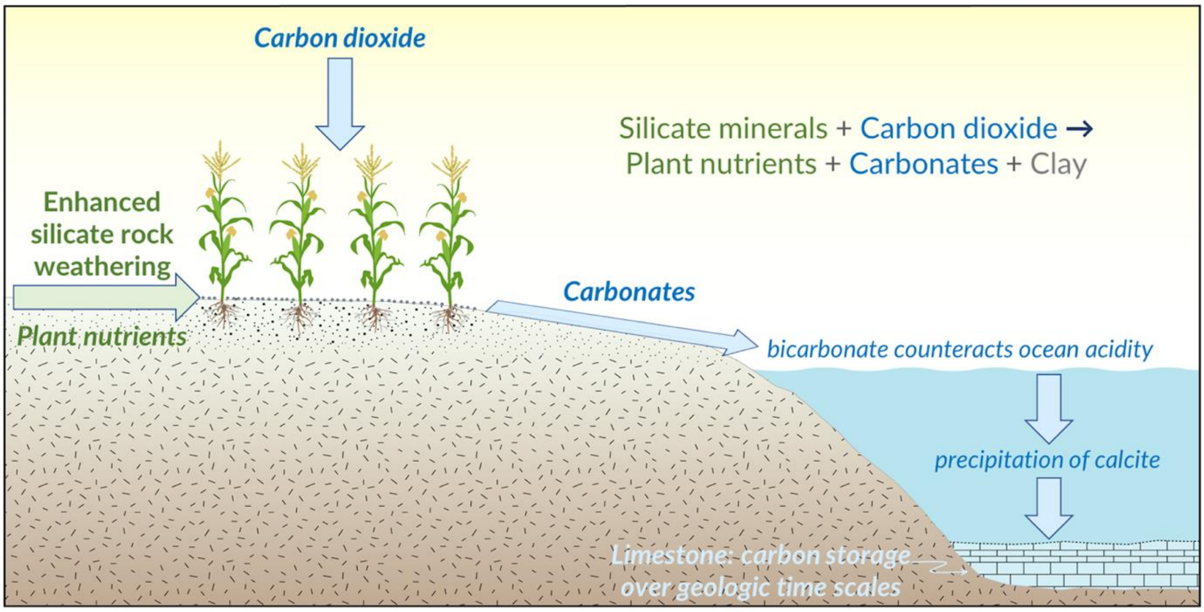


Source: Spence et al. 2021, "Exploring cross-national public support for the use of enhanced weathering as a land-based carbon dioxide removal strategy."

The natural weathering process of silicate rocks (the 'carbonate-silicate cycle') is just one of several key weathering processes, but one which is of special importance to the Earth's homeostatic regulation of global temperature over geological timescales. See Penman et al. (2020), "Silicate weathering as a feedback and forcing in Earth's climate and carbon cycle." The natural rock weathering process slowly removes CO_2 from the atmosphere at a background rate of perhaps 1 billion tons of CO_2 per year (see Table 4 in Gaillardet et al. (1999), "Global silicate weathering and CO_2 consumption rates deduced from the chemistry of large rivers"). Crucially, weathering intensifies (removing more CO_2) when temperatures and rainfall increase or when CO_2 concentrations increase. Without weathering of silicate rocks and consequent CO_2 removal, CO_2 released from volcanoes and vents would accumulate in the atmosphere and eventually turn Earth into a lifeless hothouse planet – something like Venus.

Now that humanity has put more than 2.2 trillion tons of CO_2 into the surface environment (1.6 trillion tons by digging up fossil hydrocarbons and burning them, 0.6 trillion by deforestation and ecosystem degradation), causing a very large and unprecedentedly sudden change in atmospheric CO_2 and CH_4 concentrations and in effect turning up the global thermostat, the question arises whether accelerating the rate of silicate rock weathering could remove some of it from the carbon-climate cycle.

In the land-based version of ERW, finely crushed silicate rock is spread over large areas of land, typically agricultural fields, where it interacts with rainwater and CO_2 absorbed from the air, enhancing the rate of natural weathering processes. ERW can also involve spreading crushed rock powder along ocean beaches. Either way, crushing mafic silicate rocks into powder and dispersing it where CO_2 dissolved in rain can get to it greatly increases the surface area accessible to carbonic acid (carbonic acid forms when CO_2 dissolves in water) and thereby enhances the amount of chemical weathering. The finer-grained the powder, the more quickly and thoroughly will chemical weathering proceed. But this comes at a cost: as the next subsection explains, it costs a lot of energy to crush solid rock into powder, and the finer-grained the powder, the higher the energy cost per ton.



Source of image above: Remineralize the Earth – 'crash course on enhanced rock weathering'

Dumping rock powder into the deeper ocean waters is not effective for carbon sequestration due to a combination of colder temperatures and lower CO_2 availability, with consequently much lower chemical weathering rates. The carbon captured would be minimal compared to enhanced weathering on well-watered land or in shallow coastal areas where conditions are more favorable.

Basalt is the preferred rock for enhanced weathering due to its high reactivity, low toxicity, and abundance of essential nutrients like calcium, magnesium, potassium, and iron, which are released during the weathering process. These nutrients not only facilitate CO_2 sequestration but also improve soil fertility, providing a co-benefit of increased agricultural productivity. Basalt's composition, rich in silicate minerals, makes it particularly effective in binding CO_2 into stable forms over long periods.

Some other types of rock, e.g., dunite, which is composed mainly (80-100%) of olivine, $(Mg,Fe)_2SiO_4$, are even more reactive with CO_2 and better at removing carbon than is basalt. However, dunite tends to contain higher amounts of toxic heavy metals like nickel and chromium, and is therefore more problematic as a source of crushed rock powder for ERW.

According to a much-cited paper by Beerling et al. (2020), "Potential for large-scale CO_2 removal via enhanced rock weathering with croplands":

> Enhanced silicate rock weathering (ERW), deployable with croplands, has potential use for atmospheric carbon dioxide (CO_2) removal (CDR), which is now necessary to mitigate anthropogenic climate change. ERW also has possible co-benefits for improved food and soil security [improvements in agricultural soil quality], and reduced ocean acidification. Here we use an integrated performance modelling approach to make an initial techno-economic assessment for 2050, quantifying how CDR potential and costs vary among nations in relation to business-as-usual energy policies and policies consistent with limiting future warming to 2 degrees Celsius. China, India, the USA, and Brazil have great potential to help achieve average global CDR goals of 0.5 to 2 Gigatons of carbon dioxide (CO_2) per year with extraction costs of approximately US$80–180 per ton of CO_2. These goals and costs are robust, regardless of future energy policies. Deployment within existing croplands offers opportunities to align agriculture and climate policy. However, success will depend upon overcoming political and social inertia to develop regulatory and incentive frameworks. We discuss the challenges and opportunities of ERW deployment, including the potential for excess industrial silicate materials (basalt mine overburden, concrete, and iron and steel slag) to obviate the need for new mining, as well as uncertainties in soil weathering rates and land–ocean transfer of weathered products.

Beerling et al.(2020)'s ERW scenarios correspond to an aggregate total CDR of 25–100 Gt CO_2 if sustained over five decades. Their modelling framework analyzed a baseline application rate of 40 tons per hectare per year (equivalent to a <2 mm layer of rock powder distributed over the croplands), which, they wrote, "falls within the range of basalt amendments shown to improve crop production in field trials" (per Beerling et al. (2018), "Farming with crops and rocks to address global climate, food, and soil security"), in which they write:

> Enhanced weathering aims to accelerate the natural geological process of carbon sequestration with production of alkaline leachate that reduces ocean acidification. It is achieved by amending the soils of intensively managed croplands with crushed calcium (Ca) and magnesium (Mg)-bearing rocks11-13. Besides removing CO_2 from the atmosphere, we discuss how this strategy has the potential to also rejuvenate soils, stabilize soil organic matter, improve crop yields, conserve geological fertilizer resources, and benefit the marine environment.

The amount of land that would have to be covered is enormous – more than half of global croplands. Would that be logistically feasible? Existing equipment for distributing fertilizers and soil amendments could be used to distributed crushed basalt powder (perhaps in combination with crushed biochar (Honvault et al. 2024)). Per Beerling et al. (2018), "The feasibility of mobilizing millions of smallholder communities to adopt ERW practices in China and India will depend both on demonstrating that soil improvements can reverse yield declines and on government subsidies."

A point that Beerling et al. (2020) make is that using existing stockpiles of basaltic mining waste could save a lot of energy that will otherwise have to be applied to crushing and grinding fresh basalt, though these stocks of mining waste will not suffice to meet the whole ERW quantity requirements in the scenarios.

THE CHEMISTRY OF ENHANCED ROCK WEATHERING

For those who are curious about the chemistry of ERW, a brief, simplified exposition follows: When CO_2 dissolves in rainwater, it forms carbonic acid (H_2CO_3), which then dissociates into hydrogen ions (H^+) and bicarbonate ions (HCO_3^-). When these ions encounter minerals in surface rocks – e.g., feldspars, olivine, pyroxenes, calcite, peridotite, or mica – the hydrogen ions attack the chemical bonds in those minerals, leading to dissolution of some of the components of the minerals into aqueous solution, and to formation of new chemical bonds and different minerals.

In the chemical weathering of minerals, H^+ ions (protons) do much of the heavy lifting. H^+ ions are highly reactive; they play a crucial role in the breakdown of silicate minerals through a process known as 'acid hydrolysis.' When an H^+ ion (in rainwater) encounters a mineral, e.g., olivine, $(Mg,Fe)_2SiO_4$, or pyroxene, $(Ca,Mg,Fe)(Si,Al)_2O_6$, or orthoclase ($KAlSi_3O_8$), it can displace cations like Ca^{2+}, Mg^{2+}, Na^+, or K^+ from the mineral structure. This reaction weakens the mineral's crystal lattice, leading to the dissolution of the mineral and the release of these cations into solution.

For example, the olivine weathering reaction can be summarized as follows, using the forsterite variant of olivine. (Olivine is composed of two variants, or 'end-members,' of the 'olivine solid solution series': forsterite (Mg_2SiO_4) and fayalite (Fe_2SiO_4). These two can occur in varying proportions in differing samples of olivine.)

$$Mg_2SiO_4 + 4CO_2 + 4H_2O \rightarrow 2Mg^{2+} + 4HCO_3^- + H_4SiO_4$$

This reaction involves forsterite (Mg_2SiO_4) reacting with hydrogen ions that have been released from carbonic acid (H_2CO_3). Carbonic acid forms when carbon dioxide (CO_2) dissolves in water (H_2O). The carbonic acid dissociates (reversibly) into bicarbonate ions and hydrogen ions according to the reaction:

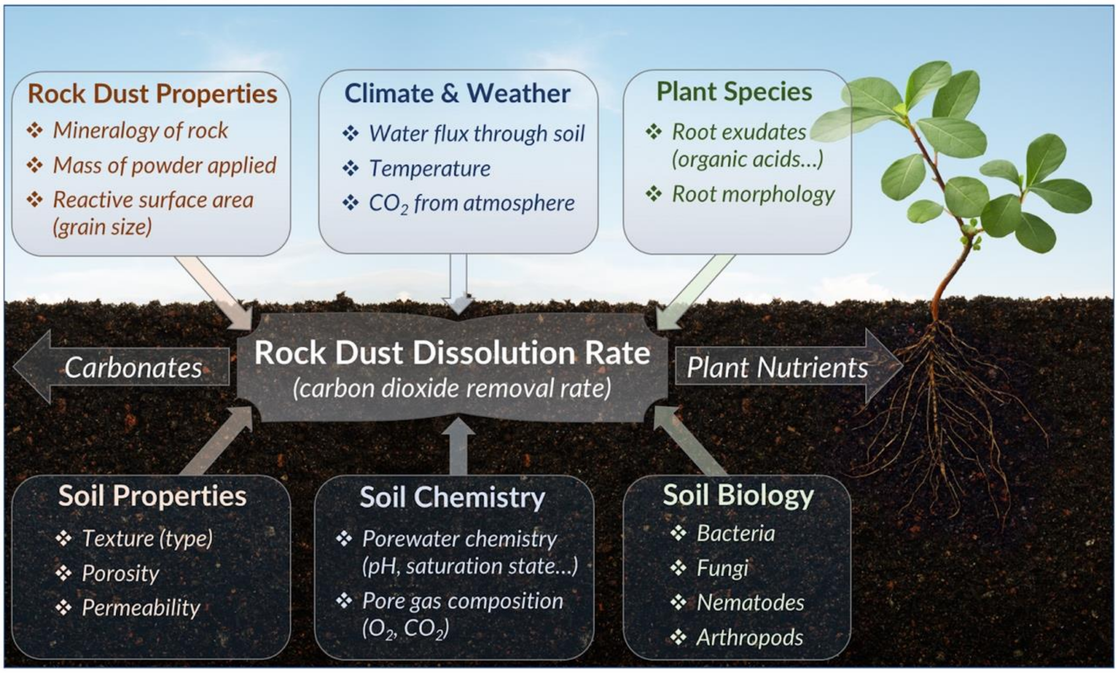
$$H_2CO_3 \rightarrow HCO_3^- + H^+$$

When H^+ ions encounter Mg_2SiO_4, a reaction occurs that produces magnesium ions (Mg^{2+}), bicarbonate ions (HCO_3^-), and silicic acid (H_4SiO_4). H^+ ions attack the mineral structure of mineral molecules by substituting for metal cations within the crystal lattice (e.g., substituting for Ca^{2+} from calcite, ($CaCO_3$), the main component of limestone, or in this example, Mg^{2+} from foresterite). This leads to the dissolution of the mineral, i.e., instead of solid Mg_2SiO_4 we now have Mg^{2+} cations in solution along with more bicarbonate ions and silicic acid. Silicic acid is relatively soluble in water, so it doesn't remain as a solid. Instead, it dissolves and can be carried away by water, contributing to the overall weathering process. Over time, it may precipitate out of solution under certain conditions to form solid silica (SiO_2) or other silicate minerals, but initially, it remains dissolved in the aqueous environment.

Bicarbonate ions (HCO_3^-) can react with dissolved cations (e.g., Ca^{2+}, Mg^{2+}) released during the weathering process to form solid carbonate minerals like calcium carbonate ($CaCO_3$) and magnesium carbonate $MgCO_3$. This is one of the ways in which CO_2 is removed from the atmosphere and from the carbon-climate cycle via natural rock weathering. The other way is through the formation of the bicarbonate ions themselves: many of them do not react with dissolved cations, and instead stay in aqueous solution, sometimes for very long periods. Many eventually travel via groundwater, streams, and rivers to the oceans, where bicarbonate ions can stay in solution indefinitely, thereby contributing to long-term carbon storage.

In the context of enhanced weathering, bicarbonate ion formation is generally considered more important in terms of the total quantity of carbon sequestration, compared to the direct carbonation reactions that form solid carbonate minerals (Penman et al. 2020, Beerling et al. 2020). The reason is that bicarbonate ions (HCO_3^-) produced during the weathering process are stable in aqueous solutions and can be transported to the oceans, where they can store carbon for very long periods, potentially indefinitely. In contrast, the formation of solid carbonate minerals is a more localized process and is often limited by the availability of cations like Ca^{2+} and Mg^{2+} and the specific conditions required for precipitation. The ratio is uncertain, but bicarbonate formation could account for as much as 80-90% of the total carbon sequestered through enhanced weathering, while direct carbonation reactions contribute the remaining 10-20%. This all refers to silicate rock weathering; it is uncertain whether calcite weathering can also lead to net carbon sequestration on a timescale relevant to the current climate emergency (Knapp and Tipper 2022).

There is much more to the ERW process – the foregoing is a simplification – but it would go well beyond the scope of this report to explore the chemistry of ERW in depth. The diagram below gives a taste of how much more complexity is involved – a multitude of site-specific variables affect ERW efficacy.



Source of image above: Remineralize the Earth – "crash course on enhanced rock weathering"

HOW MUCH COMMERCIAL ENERGY INPUT WILL BE NECESSARY TO ACHIEVE GLOBAL CDR TARGETS DURING THE SECOND HALF OF THIS CENTURY, USING ERW AS A MODEL PROCESS?

Key questions that will determine the cost and feasibility of enhanced silicate rock weathering will be:

- What are the main energy inputs required for enhanced silicate rock weathering operations, as shown by life-cycle analysis?
- Taking this into account, what total commercial energy input, expressed in MWh per ton of CO_2 sequestered, is required?
- What does this mean for the total energy input required to achieve a carbon removal target of about 20 $GtCO_2$ per annum in the second half of this century (a number we arrived at in Section 2 of this report as the estimated amount that may be necessary to return global heating back down to 1.5C by 2100 after a highly likely period of overshoot)?

The numbers remain uncertain, but we can offer a sample calculation. In what follows, we assume an average energy consumption figure for each key stage in the ERW process. We assume that we're working with basalt, which is less chemically efficient than some other rock types, such as dunite, for ERW, but also less likely to harbor toxic elements such as heavy metals that could poison agricultural soils. The numbers assumed here are illustrative, not definitive; they aren't based on real data. We use them only to show the steps of the calculation. A detailed study should be separately undertaken to model the actual plausible life-cycle energy inputs of ERW (and every other proposed CDR method). Here, we assume the year is 2050 and only electric machinery is being utilized, including, inter alia, electric mining machinery and rock grinders, electric trucks, tractors, and coastal ships. These technologies all already exist today (e.g., electric Monarch tractors), but have not yet been deployed on a large commercial scale.

- Mining: 0.05 MWh/ton of rock
- Crushing and Grinding: 0.3 MWh/ton of rock
- Transport: 0.05 MWh/ton of rock
- Spreading and Distribution: 0.03 MWh/ton of rock

Total energy input per ton of rock = 0.05 + 0.3 + 0.05 + 0.03 = 0.43 MWh/ton of rock.

If we assume that 1 ton of finely powdered basalt (<10 µm grain size) can sequester about 0.3 tons of CO_2, the commercial energy input per ton of CO_2 sequestered = 0.43 MWh/0.3 tons of CO_2 = 1.43 MWh/ton of CO_2. That would mean that sequestering 1 $GtCO_2$ via this method would require commercial energy inputs of about 1.43 billion MWh, i.e., 1,430 TWh.

To put this number in perspective, let's assume that by about 2060, global energy abundance and net zero GHG emissions have been achieved by full electrification based on clean renewable energy, and that there are 10 billion people in the world, each consuming an average of 20 MWh per person per year (for all purposes together, including indirect consumption of energy via consumer goods manufacturing and transport, etc. as well as energy required for CDR and other carbon management measures). This estimate for average annual energy consumption per capita is arguably a reasonable estimate given a prosperous, energy-abundant economy as proposed by Sustainable Development Goal 7. In that world, 10 billion people consuming 20 MWh per year each would consume a total of 200,000 TWh per year.

If we were to scale up ERW to achieve 10 $GtCO_2$ removal per year – about half of what will be necessary, as per our estimates in Section 2 of this report – then doing so would entail 14,300 TWh per year, or about 7.2% of total global energy demand. If we blithely assume that 1.43 MWh per ton CO_2 is a reasonable estimate for the commercial energy input per ton of any other CDR method we might be willing and able to implement, then to get our target amount of 20 $GtCO_2$ carbon removal per year, we will be devoting about 15% of total global commercial energy to CDR operations. This is not a shocking number – indeed, it is a rather optimistic figure. It will be very fortunate if it turns out that the amount of commercial energy per ton of CO_2 removal is only around 1.5 MWh when a full life-cycle analysis of energy inputs for CDR are taken into account.

DACCS is another CDR technology whose estimated energy input cost per ton of CO_2 removal once it is a mature, optimized technology has been estimated as likely to be in the range of perhaps 1.7 to 3 MWh per ton CO_2, most of which (ca. 80%) takes the form of heat, i.e., $MWh_{thermal}$, but a significant portion must be supplied from electricity (see p.19 in the UKERC report on BECCS and DACCS by Daggash and Fajardy (2019)).

The next subsection provides an overview of DACCS technology.

DIRECT AIR CARBON CAPTURE AND STORAGE (DACCS) VIA CHEMICAL ENGINEERING PLANTS AND EQUIPMENT

Direct air carbon capture and storage (DACCS) is a technology designed to capture carbon dioxide (CO_2) directly from the atmosphere and then either store it permanently deep underground or utilize it in various industrial processes. In most of its current versions, the DACCS process uses fans to draw in large volumes of air and force it past arrays of chemical sorbents that have an affinity for CO_2 to 'capture' some of the passing CO_2 molecules. After they've been saturated with CO_2, the sorbents are heated in a closed environment and the CO_2 is released again, but in a closed vessel so that the CO_2 can be captured and concentrated. The sorbents are then re-used to capture more CO_2.

The extracted CO_2 can either be utilized in industrial processes (such as in the production of fuels, chemicals, or materials) or stored underground in geological formations such as depleted oil and gas fields or deep saline aquifers. Monitoring of underground disposal sites verifies that the captured CO_2 remains securely stored and does not leak back into the atmosphere.

DACCS can in principle be scaled to >5 billion tons of CO_2 per year, perhaps even 10 $GtCO_2$, although doing so would take enormous quantities of energy and probably would be the biggest engineering project in history, involving hundreds of thousands of DACCS plants around the world.

DACCS is further along in terms of technological readiness than other novel CDR methods such as electrochemical seawater processing or enhanced rock weathering, but it is still an early-stage technology, far from technological maturity or economies of scale.

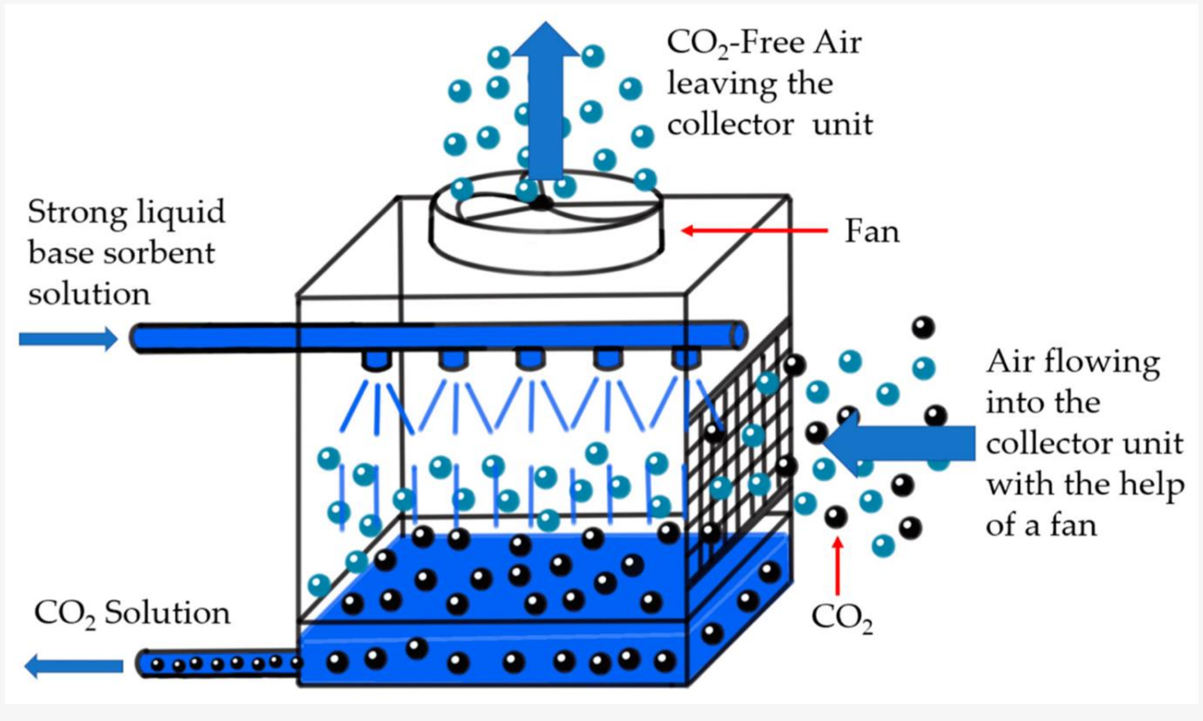
Several companies involved in DACCS technology development have small working DACCS demonstration plants or small modular DAC units for sale. They include Carbon Engineering (Canada/USA), Climeworks (Switzerland/Iceland), Global Thermostat (USA), Heirloom Carbon (USA), Infinitree (UK), Skytree (UK), Soletair Power (Finland), and there is a growing number of other early-stage DAC startups. Many of these startup companies have already been in existence for several years, as evidenced by a 2017 article comparing DACCS technologies. A couple of companies are currently building next-generation, larger demonstration plants. The following brief descriptions of several prominent DACCS CDR technology companies is meant to provide a sense of the industry's current state of development.

- Carbon Engineering, with its demonstration plant in Squamish, British Columbia, Canada, operates a working liquid sorbent-based DAC plant which converts CO_2 into low-carbon fuels or stores it underground. In August 2023, Carbon Engineering was acquired by Occidental, a petroleum production and petrochemicals manufacturing company.
    - This could prove to be an early example of a business model in which CDR startup companies position themselves for investment from oil and gas companies, and perhaps an eventual sale of the startup to one of those oil and gas majors as the CDR company founders' financial 'exit strategy.'
    - There is an argument to be made that the natural evolution of fossil hydrocarbon companies in a world which leaves fossil fuels behind will be to get into the business of

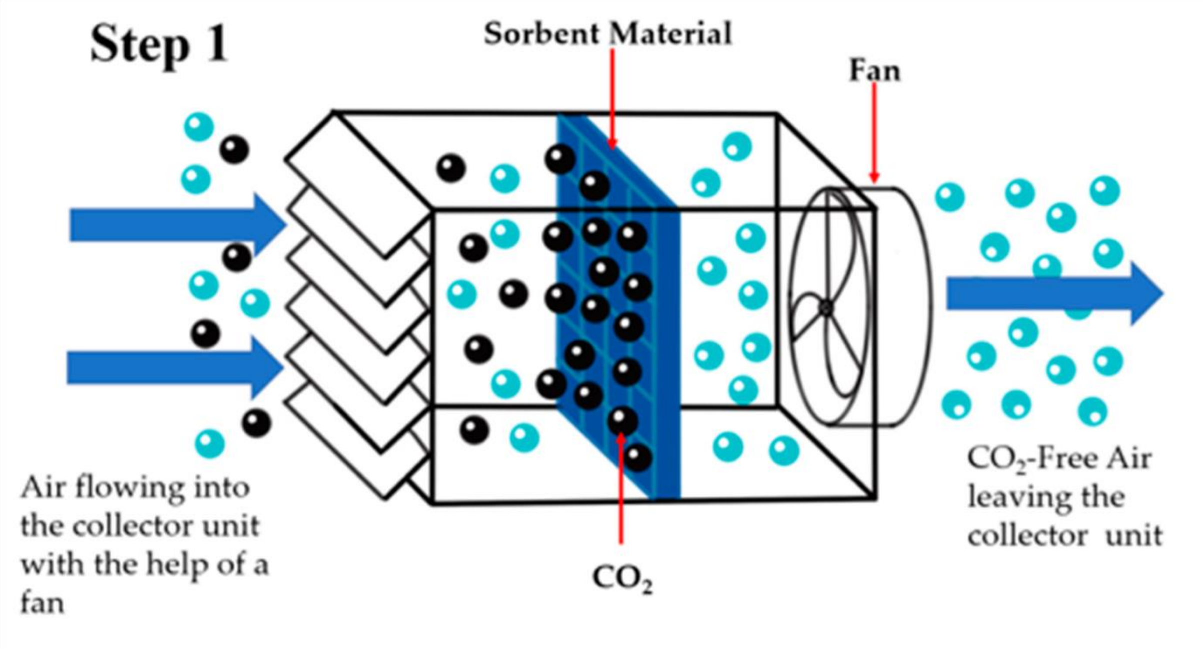
    CDR, reversing the climate impact of their past operations and profiting off both the ramp-up and reversal of atmospheric CO_2.

- Occidental has partnered with its subsidiary 1PointFive, a CCS-specialized engineering project management company, to build a $1 billion, 500,000 tons CO_2 per year DAC plant, based on Carbon Engineering's technology.
    - The DAC plant, to be called 'Stratos,' will be set up in the Permian Basin region of Texas. 'Stratos' is meant to be operational by summer 2025. It will be by far the biggest DAC plant built to date. Given US per capita annual CO_2 emissions of 13 tons, Stratos could offset the emissions of 38,462 Americans.
    - It will be interesting to observe whether Occidental's investment could be an early indicator of a germinating awareness amongst some fossil hydrocarbon corporations that the CCS/CCUS business could be a major opportunity for them – a mid-century future in which capture and storage of past emissions potentially represents a natural segue from a past dominated by mining hydrocarbons.
- Climeworks, a Swiss company, filters CO_2 directly from ambient air through an adsorption-desorption process. At its first commercial direct air capture and storage plant, Orca, in Hellisheidi, Iceland, the air-captured CO_2 is disposed of by storage partner Carbfix, another startup, which injects it deep underground where it eventually mineralizes into solid form via chemical reactions with minerals in basaltic rock.
    - In May 2024, ClimeWorks commenced operations at a 10x larger DAC plant called 'Mammoth,' also in Iceland. 'Mammoth' aims to capture 36,000 tons of CO_2 per year. Given Iceland's estimated per capita CO_2 emissions of 4 tons per year (World Bank data), Mammoth will, once it is fully operational, compensate for the annual emissions of some 9,000 Icelanders.
- Global Thermostat, based in the United States, uses amine-based sorbents to remove CO_2 from the atmosphere at its CDR plant in Huntsville, Alabama.
- Heirloom Carbon of California, USA, uses limestone, heat, and water as inputs to a cyclical process in which calcium hydroxide is generated and exposed to the air to combine with CO_2 to form limestone, then reheated to release the CO_2 in a vessel so that it can be captured and pumped underground into permanent geological storage.
- Soletair Power of Finland, which is backed by a well-established Finnish power generation equipment company, Wärtsilä, scrubs CO_2 from the air forced through building HVAC systems.
- Infinitree is a US-based startup working on direct air capture technology using biomimetic materials to capture CO_2 and recycle them through natural evaporation.
- Skytree, a Netherlands-based company, produces small (20kg/day) and medium sized (600 kg/day) modular units that capture CO_2 from the atmosphere for applications such as supplying controlled-environment greenhouses with CO_2.

The illustrations below show two variations of the basic direct air capture process: one uses liquid sorbents, the other uses solid sorbents.



Contactor unit diagram of a direct air carbon capture system using liquid sorbent. Source: Garza et al. 2023: “A Technological Review of Direct Air Carbon Capture and Storage (DACCS): Global Standing and Potential Application in Australia.”



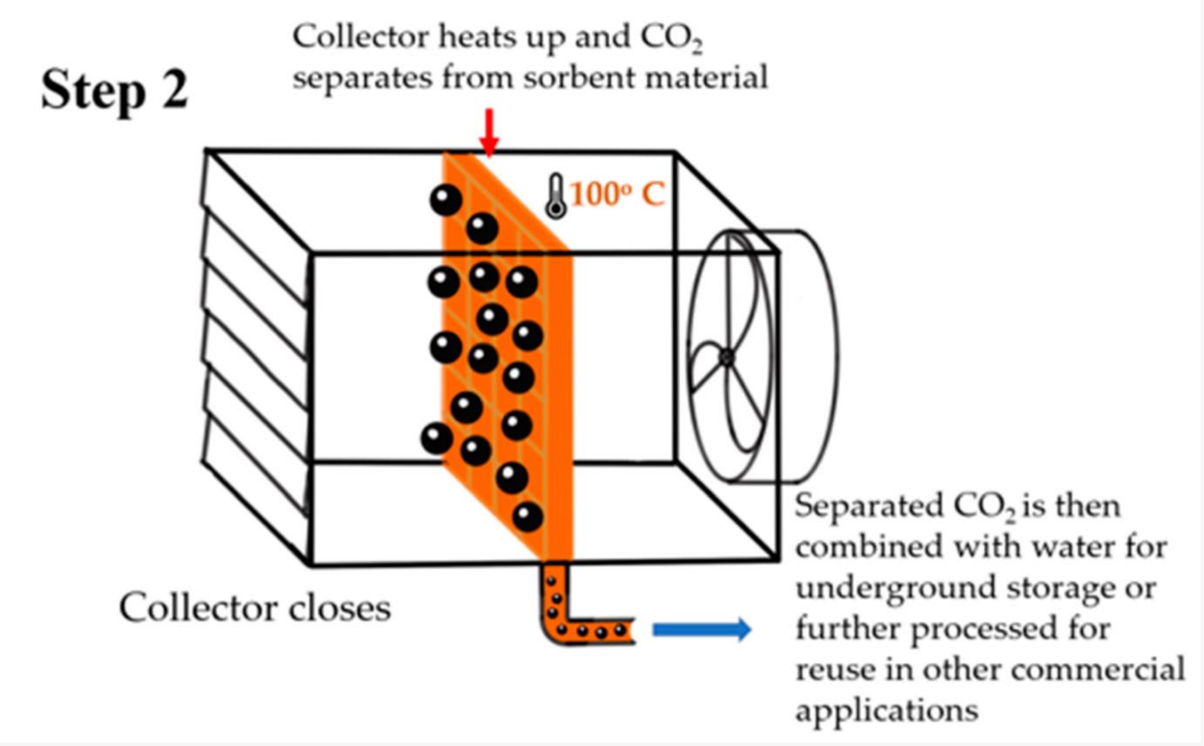


Image: Adsorption using the solid sorbent DACCS process. Source: Garza et al. 2023: “A Technological Review of Direct Air Carbon Capture and Storage (DACCS): Global Standing and Potential Application in Australia.”

Newer, potentially more efficient DAC methods are emerging from chemical engineering laboratories. Existing methods tend to be very energy-intensive due to large heat input requirements. A new approach currently in laboratory-scale development is electrochemical direct air capture, which promises to be significantly more energy efficient (Ozkan et al. 2024). Although it works best when processing flue gases rich in CO_2 rather than ambient air (i.e., in point-source industrial CCS operations), it can also be used for capturing CO_2 from ambient air. Laboratory tests using ‘neutral red’ dye as the recyclable CO_2-absorbing chemical estimated minimum electrochemical energy requirements in continuous flow in the range of 35 kJ_e/mol of CO_2 using 15% CO_2 and 65 kJ_e/mol of CO_2 using air (Seo & Hatton 2023, “Electrochemical direct air capture of CO_2 using neutral red as reversible redox-active material”). A startup, Verdox, an MIT spinoff company, is among the new initiatives exploring electrochemical DAC due to its relatively high energy efficiency.

It is plausible, though not certain, that **within a few years, new, more energy-efficient electrochemical DAC processes** (from companies like Verdox) **may supplant the prior-generation heat-input-demanding DAC processes** (from companies like ClimeWorks).

A possible future use of results-based payments administered by public agencies or corporate groups spending CDR money via voluntary carbon market mechanisms could be to provide ‘advance market commitments’ to early-stage companies developing the new, more energy-efficient DAC approaches.

‘Advance market commitments’ involve paying up-front for future carbon removal deliveries some years later, or alternatively, they can take the form of firm contracts from credible buyers agreeing in advance to buy a specified quantity of carbon removals at a future date, which can make it easier for early-stage companies to raise development money.

‘Advance market commitments’ are the method deployed by the private-sector voluntary carbon market Frontier Climate fund, which is a vehicle for supporting CDR sector development initiated by Stripe, a payments company, with participation from several major corporations (most of the US-based), including Alphabet, Shopify, Meta, and McKinsey.

TERRESTRIAL BIOLOGY-BASED CDR: AFFORESTATION/REFORESTATION, PEATLAND AND BOG RESTORATION, BIOCHAR

Terrestrial nature-based CDR, including afforestation/reforestation (A/R), is not within the scope of this report, which is focused on non-biological 'engineered' CDR methods. However, a quick note on the potential scope of CDR via land-based biological methods is warranted. A key recognition is that while afforestation/reforestation and biochar are valuable CDR methods, and A/R (in first place with 2 billion tons of CO_2) and biochar[3] (in distant second place) are currently by far the largest CDR methods by annual volume (see State of CDR Report), *they will not suffice,* in aggregate, to remove the amounts of CO_2 that will be necessary between the first net-zero year (perhaps around 2060) and the end of the century (2100) if global heating is to be returned to 1.5°C by 2100 after a now probably inevitable period of temperature overshoot above 1.5°C during the second half of the century.

As explained in Section 2 of this report, if global average annual surface air temperatures are to be returned to 1.5°C compared to the pre-industrial average by 2100, potentially well over 1,000 $GtCO_2$ will have to be removed via CDR by 2100 if high fossil fuels use and CO_2 emissions continue for another decade or more through the 2020s and early 2030s. A further 1,000 $GtCO_2$ will have to be removed by 2100 if policymakers shift the goalposts and decide to try to limit global heating in 2100 to 1.0°C instead of 1.5°C. Additional quantities of similar magnitude will likely have to be removed in the decades after 2100, on a path back toward pre-industrial atmospheric CO_2 levels, if limitation of long-term cumulative sea level rise is eventually adopted – as seems plausible – as a key post-2100 goal.

According to IPCC AR6 Working Group III, Ch.3 (2022), an increase of forest cover of about 322 million ha (–67 to 890 million ha) is projected by 2050 in pathways limiting warming to 1.5°C (with >50% probability) with no (or very limited) temperature overshoot above 1.5°C. In contrast, the techno-economic pathways think-tank RethinkX proposes that the replacement of today's agricultural systems, before mid-century, with advanced food production systems, including precision fermentation, cultivated meat (cellular agriculture), and indoor vertical farming, could free up 70% of the land currently used globally for livestock and feed production by mid-century - an area of 1.3 billion hectares, nearly twice the size of Australia. While the proposed *timing* of the obsolescence of the cow- and cattle-based dairy and beef industry in RethinkX's scenario by the mid-2030s seems highly implausible, if cultivated meat eventually does mature as a cost-effective technology and leads to an end to livestock farming (perhaps in the second half of this century), the land-use impacts could indeed be of great scale.

A major consequence of such a change would be that IPCC's estimates of CO_2 and CH_4 fluxes from land, as expressed in IPCC's Special Report on Climate Change and Land, would turn out to be too pessimistic. These scenarios posit 100 to 200 $GtCO_2$ sequestered by 2100 on 300 to 500 million hectares of afforestation/reforestation and peat bog restoration. Under a major reforestation and rewilding program on 1.3 billion hectares made possible by the disappearance of most cattle, AFOLU (agriculture, forestry, land-use) could contribute much more to total CDR volumes by end-of-century than is currently foreseen – perhaps as much as 500 $GtCO_2$.

The take-home message is not that we should believe that the RethinkX scenario of a major technological transformation of the food and agriculture sector is likely to occur in the near future as an inevitable technological (r)evolution, but rather, that policymakers might like to consider two clusters of strategic questions:

(1) Should a shift to new high-tech food production systems as envisaged by RethinkX be encouraged, supported, and enabled via public investments and regulations, given their massive climate and biodiversity benefits? Could results-based payments, e.g., a feed-in tariff per ton of cultivated meat, be helpful in accelerating the emergence of these technologies by supporting them through early-stage development?

(2) What will be the land-use consequences of the obsolescence of beef cattle and dairy cows through cellular agriculture (cultured meat) and precision fermentation (including of milk proteins), if it eventually comes to pass on a large scale, i.e., if it displaces most ungulate-raising? Will this, by itself, suffice to see former pastureland return to a state of nature, i.e. will it result in large-scale rewilding? This may be desirable

from a biodiversity point of view, given that wild animals comprise only 4% of total mammalian biomass on the planet now (domestic livestock comprise 62%, humans 34%) (OurWorldinData). However, it is not obvious that this is what will occur once pastures are no longer needed for cows or sheep. What will happen to privately owned land in a scenario in which most cattle disappear? The landowners will seek new revenue-generating uses for the land. What will they do with it? It isn't obvious.

The ecological context of these considerations is remarkable: again, domesticated livestock and pets currently make up 62% of the world's mammalian biomass; humans account for 34%; and *wild mammals are just 4%*. Returning a substantial portion of the world's land to wilderness will be necessary to avoid wild species' eventual extinction. Recognizing this, a global-scale rewilding target has been proposed by the Half Earth Project (see map). At the same time, returning much of the world's current pastureland to its former state as natural forest or grassland would sequester a great deal of CO_2.

It does seem likely that precision fermentation, cellular agriculture, and other high-tech indoor agriculture methods will *eventually* free up an enormous amount of land. Will new public legal and financial mechanisms be necessary to bring much of the land freed-up by back into the global commons?

This question should be addressed in separate work.

The next section, Section 5, moves from the land to the sea. It provides an overview of marine CDR methods.

SECTION 5: OCEAN-BASED CDR (MARINE CDR) METHODS

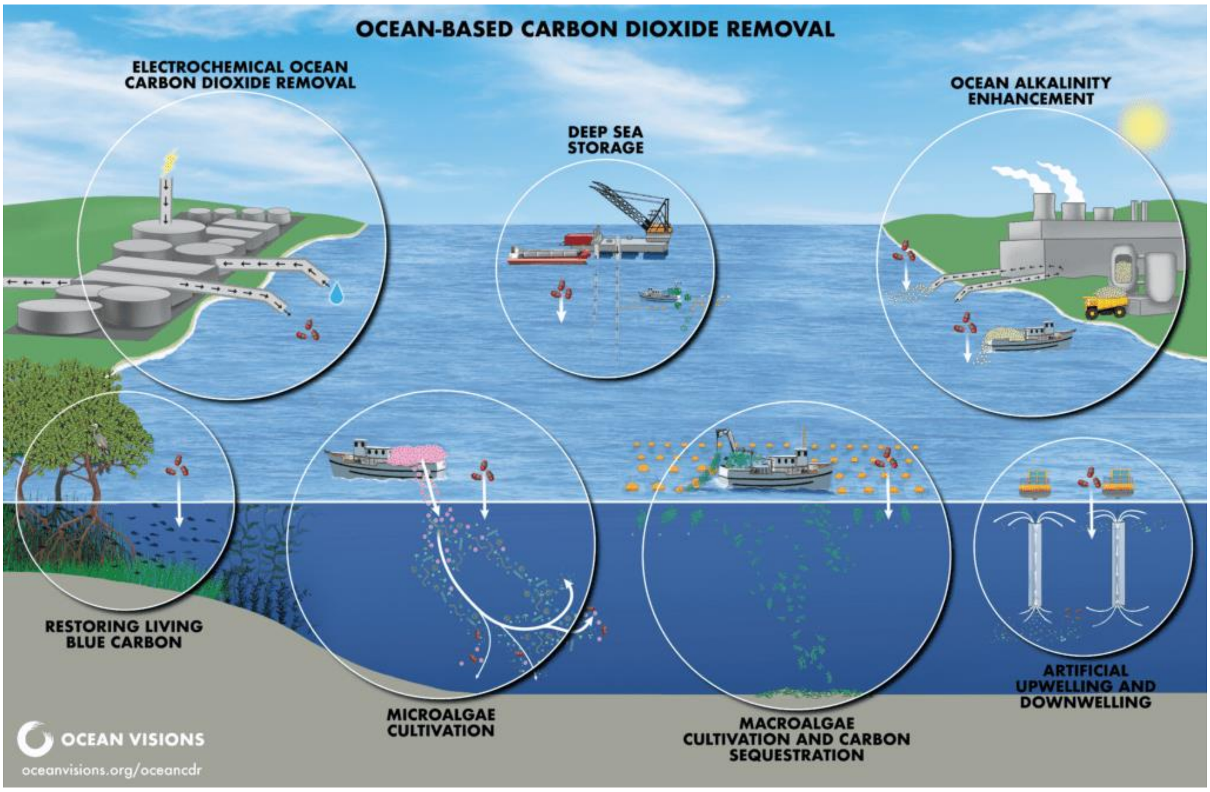
Marine carbon dioxide removal methods – often abbreviated using the acronym mCDR – are a range of techniques aimed at enhancing the ocean's natural ability to absorb and sequester CO_2 from the atmosphere through biological, chemical, and physical processes. mCDR methods include ocean alkalinity enhancement (OAE), artificial upwelling and downwelling (AU), seaweed cultivation and harvesting (SCH), direct ocean capture (DOC) (including electrochemical ocean capture, EOC), and ocean fertilization (OF). The latter is sometimes subdivided into ocean iron fertilization (OIF), ocean nitrogen fertilization (ONF), or ocean phosphorus fertilization (OPF).

A useful review of the risks and potentials of several marine CDR options (both biological and chemical-engineering based mCDR) was published in 2023 by Dutch-Australian ocean and climate scientist Prof. Eelco Rohling, entitled "Marine methods for carbon dioxide removal: fundamentals and myth-busting for the wider community."

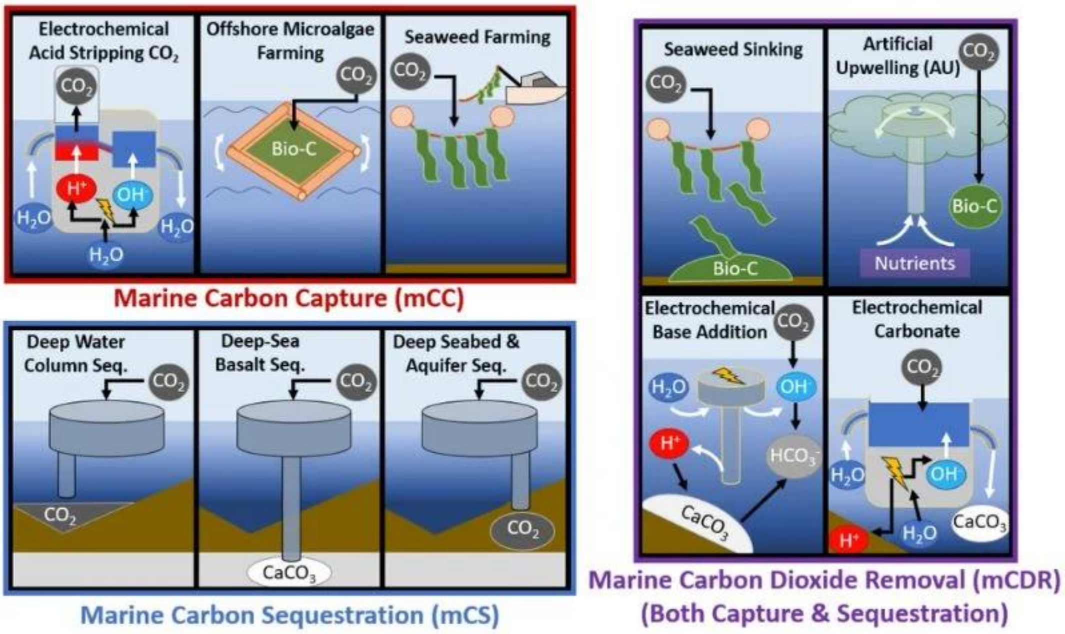
Ocean Visions website is a key source of information presented in this section. Another is the 2022 US National Academies of Sciences, Engineering, and Medicine publication, "A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration."

Ocean Visions is "a nonprofit organization at the center of a robust network of organizations comprised of leading universities and oceanographic institutions [e.g., Scripps, Woods Hole, CMCC, AGU, World Ocean Council, Ocean Networks Canada, the oceanographic research divisions of MIT, Stanford, Georgia Tech, UCSB, and others], and a diverse set of practitioner partners. Ocean Visions works to engage resources across the Network for concerted action, catalyzing collaboration and co-design, development, testing, and evaluation of potential solutions to address the interlocking ocean-climate crisis."
The Ocean Visions website is a useful point of reference for information on ocean CDR methods. The two images below provide an illustration of some known ocean CDR methods – more are likely to emerge.

CDRmare is Germany's government supported network of marine CDR research projects. Germany is at the forefront of ocean CDR research along with USA, Canada, and UK.



Source: EDF

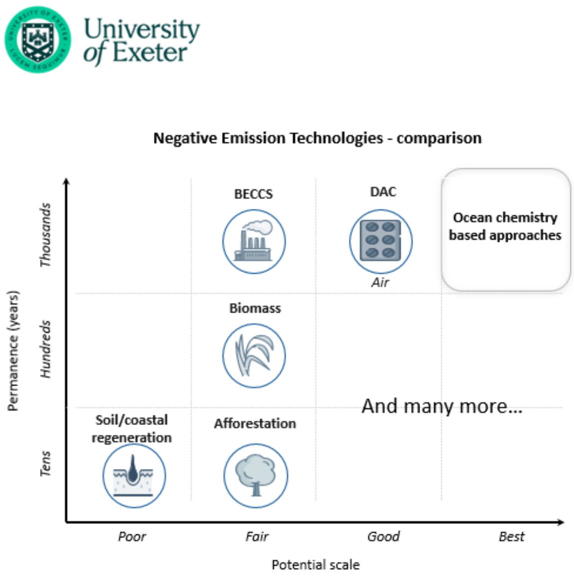


Source of image above: US National Renewable Energy Laboratory (NREL 2023), “Mission Analysis for Marine Renewable Energy to Provide Power for Marine Carbon Dioxide Removal.”

OCEAN CDR METHODS MAY PROVE TO BE MORE SCALABLE THAN MOST LAND-BASED CDR METHODS

The high potential scalability of marine CDR methods has a straightforward reason: nearly 71% of our planet’s surface is covered by oceans. The oceans already absorb about 31% of all the CO_2 human activities emit into the atmosphere each year, although the ability of the ocean to act as a ‘carbon sink’ may decline with time, because warmer water surface waters will not sink as readily. A 2023 NOAA study suggested the decline may already have begun.

The diagram below situates mCDR in the larger CDR technology landscape.



Source of image: Paul Halloran, University of Exeter

A GROWING LIST OF OCEAN CDR METHODS ARE BEING IDENTIFIED AND INVESTIGATED, BUT ALL ARE STILL IN VERY EARLY DEVELOPMENT STAGES

Several research groups are exploring whether the ocean's ability to act as a carbon sink can be enhanced by means of a variety interventions whose effect is to regionally alter the chemistry of the upper surface waters slightly, e.g., ocean fertilization, ocean alkalinity enhancement, or electrochemical processing of seawater to directly remove CO_2 and put it in deep geological storage (an ocean-based analog to DACCS, sometimes termed 'direct ocean capture', DOC, or 'electrochemical ocean capture,' EOC). Others have looked at options for growing biomass in the oceans – whether macroalgae or microalgae – and finding ways to ensure that some of the carbon soaked up in that biomass is subsequently removed from the active carbon/climate cycle.

A 2022 report by scientists at EDF, NRDC, and the Ocean Conservancy entitled "Ocean Carbon Dioxide Removal Methods" surveys the options for ocean-based carbon removal. The options identified in that report are: 'Blue carbon' (coastal ecosystem restoration, especially mangroves), macroalgal open-ocean mariculture and sinking, ocean fertilization, ocean alkalinity enhancement, electrochemical seawater processing, and injection of liquified CO_2 in deep ocean waters or sub-seafloor burial of captured CO_2.

See OceanVision's mCDR Roadmaps for a detailed overview of marine CDR options, or a concise four-page factsheet pdf giving an overview of OceanVision's perspective on mCDR.

OCEAN ALKALINITY ENHANCEMENT (OAE)

Ocean alkalinity enhancement (OAE) involves increasing the ocean's capacity to absorb and sequester carbon dioxide (CO_2) either by adding alkaline materials, such as ground silicate or carbonate minerals, or by removing acids from seawater, thereby enhancing chemical weathering and carbonate formation processes.

OAE can be implemented in several very different versions. In one, dispersing slaked lime (calcium hydroxide) into seawater can increase alkalinity and promote the formation and precipitation of chemically stable calcium carbonate minerals (but first, slaked lime has to be made from limestone, and the CO_2 emissions from that process must be disposed of in geological storage). In another, adding powdered silicate minerals such as olivine to seawater promotes the formation of carbonate minerals when the olivine dissolves and releases Fe^{2+} and Mg^{2+} cations, which can react with carbonate ions to form solid carbonates; this is a form of directly ocean-based enhanced rock weathering (but the challenge is to keep the silicate minerals in shallow water long enough to allow their dissolution, which is a slow process). In another approach, electrochemical OAE applies an electrical current to seawater to remove hydrogen and reduce the water's acidity.

A key point in favor of OAE is that – in principle – it is highly scalable. Given enough cheap renewable electricity and beachfront ocean access, and a supportive regional population and government, huge volumes of seawater could be processed, and a cumulative total of perhaps hundreds of $GtCO_2$ removed from the carbon/climate cycle (plausibly more than could be removed via enhanced rock weathering achieved via spreading basalt rock powder on agricultural lands, given limitations on available land area).

A co-benefit of ocean alkalinity enhancement is that it directly counteracts ocean acidification caused by CO_2 dissolved in seawater. Ocean acidification is a rising threat to the ocean biosphere; the acidity of ocean surface waters has already increased by about 30% over the past two centuries, with more than half of the change having occurred just since 1990.

A deep dive into the technical minutiae of ocean alkalinity enhancement methods is beyond the scope of this report. The comprehensive 2023 Guide to Best Practices in OAE Research and the 2023 Eisaman et al. paper "Assessing the technical aspects of ocean-alkalinity-enhancement approaches" provide an abundance of detailed information for readers who would like to learn more. Additional papers on technical aspects of OAE can be found via embedded links in what follows, which makes note of several research projects and research groups.

OAE can be combined with other mCDR methods in integrated approaches. For example, electrochemical OAE and ocean iron fertilization (OIF) can be combined into an approach called electrochemical ocean iron fertilization, OEIF (Taquieddin et al. 2024).

Some research groups working on electrochemical OAE experiments are a based in Kiel, Germany; and the "Ocean Alk-align" research program at Dalhousie University, Canada, which is supported by the Carbon to Sea Initiative, a private philanthropic network.

Some forms of chemical engineering based marine CDR could potentially generate marketable co-benefits as an inherent part of the process, although the overall cost picture will determine marketability and profitable CCUS products cannot be assumed. An example is UCLA spinoff Equatic (Principal Investigator: Gaurav Sant), whose prototype electrochemical CDR equipment produces H_2 gas from electrolysis of seawater in an integrated step with mineralization of CO_2 as dissolved bicarbonate ions (in water) and solid mineral carbonates.

Future combined-benefit electrochemical CDR operations that generate hydrogen gas as well as CO_2 sequestration outcomes could be paired with on-site modular Haber-Bosch ammonia (NH_3) production facilities to generate a relatively easily transportable and marketable product (instead of trying to ship H_2 via pipeline or as a compressed gas, which is more expensive than transporting ammonia). This would be an expensive way to make ammonia if taken out of the context of CDR, but within that context, producing marketable ammonia might partially offset the cost of electrochemical seawater CDR operations.

In the remaining subsections of Section 5, we will briefly look at three additional categories of mCDR beyond OAE: direct CO_2 capture from seawater, followed by its disposal/storage (the marine equivalent of DACCS); ocean fertilization; and marine plant biomass cultivation and processing methods.

DIRECT OCEAN CAPTURE, DOC: DIRECT CO2 CAPTURE FROM SEAWATER

This method involves directly capturing CO_2 from seawater and storing it. One research group working on this is Project SeaCURE at the UK's University of Exeter (Principal Investigator: Paul Halloran). The US government funding agency ARPA-E is also supporting research in this direction.

Direct ocean capture is the marine analog to DAC, direct air capture. Both DAC and DOC are, in principle, readily scalable, but both are also rather energy intensive. Open questions are whether DAC or DOC will prove more vs. less energy efficient per ton of CDR, more vs. less bulky and costly in terms of capital equipment, more vs. less maintenance-intensive, and at the end of the day, which will prove more cost-effective. The current state of knowledge is insufficient to settle these questions. Further R&D, detailed technical modeling, and experimentation with prototypes will be needed to determine the answers.

OCEAN FERTILIZATION

Ocean fertilization is a geoengineering technique aimed at enhancing the growth of marine phytoplankton to increase the ocean's capacity to sequester carbon dioxide. In various ocean regions, biomass growth is limited by a dearth of one or more nutrients – usually iron, nitrogen, phosphorus, and/or silica. A list of scientific experiments and research in this area is found on the Woods Hole Oceanographic Institute's website, here. In 2022, the US National Academies Press published a "Research Strategy for Ocean-Based Carbon Dioxide Removal and Sequestration." Ocean fertilization is controversial but cannot yet be dismissed; it requires further research as a possible large-scale, relatively inexpensive mCDR method.

Following is a brief overview of the most-discussed ocean fertilization method, ocean iron fertilization, followed by links to associated research groups and their principal investigators:

IRON FERTILIZATION: This involves adding iron to ocean regions where it is a limiting nutrient to stimulate phytoplankton growth, which can enhance CO_2 uptake. The best ocean regions for ocean iron fertilization (OIF) are typically high-nutrient, low-chlorophyll (HNLC) areas. These regions are characterized by abundant macronutrients like nitrogen and phosphorus, but are limited in iron, and this restricts phytoplankton growth. The main HNLC regions suitable for OIF are:

i. The Southern Ocean surrounding Antarctica, particularly between 40°S and 60°S. The Southern Ocean is the largest HNLC region, with extensive areas where iron is a limiting factor for phytoplankton growth. It has strong potential for carbon sequestration due to its vast size and the efficiency of the biological pump in transporting carbon to deep waters.
ii. The Equatorial Pacific Ocean, primarily between 140°W and 180°W. This region has upwelling currents that bring nutrient-rich deep water to the surface, but it is iron-limited. Adding iron here can stimulate large phytoplankton blooms, enhancing carbon uptake.
iii. The Subarctic Pacific Ocean, particularly between 40°N and 60°N. This area is iron-limited and has high levels of macronutrients. It is a key area for studying the effects of OIF due to its responsiveness to iron additions and potential for carbon sequestration.

An important OIF research group was Germany's Alfred Wegener Institute, P.I.: Victor Smetacek (emeritus), leader of the EIFEX experiment of 2004. Opposition to OIF by environmental NGOs has largely put a stop to ocean field trials of OIF since then. Some teams are trying to resurrect it, e.g. the scientists proposing KIFES, an OIF experiment similar to EIFEX off Korea (Yoon et al. 2018).

NITROGEN, PHOSPHORUS, AND/OR SILICA FERTILIZATION: Iron is not the only limiting nutrient. Some ocean regions are deficient in one or more of these others: nitrogen, phosphorus, and/or silica. Fertilizing the ocean with missing nutrients leads to biomass increases. For example, nitrogen compounds such as urea or ammonia can be added to the ocean to stimulate phytoplankton growth.

Some leading researchers in ocean fertilization are Philip Boyd, University of Tasmania, Australia; Mark Wells, University of Maine, USA; Ken Buesseler, Woods Hole Oceanographic Institute, Massachusetts, USA; David Emerson, Bigelow Laboratory for Ocean Sciences, Maine, USA; Joo-Eun Yoon, Centre for Climate Repair at Cambridge; Atsushi Tsuda, University of Tokyo; and Anthony Michaels, Proteus Environmental Technologies, co-author of a 2023 New York Times opinion piece, "Iron dust could reverse the course of climate change."

NATURE-BASED MARINE CDR METHODS: REGIONAL HUBS REQUIRED

Ocean Visions presents accessible overviews of nature-based mCDR methods such as kelp farming, saltwater micro-algae farming, and shallow-water coastal ecosystem restoration (blue carbon), in which mangroves and seagrasses, among other things, are restored to some of the many regions where they have been degraded or eliminated.

More and larger field trials of all biomass cultivation-based marine CDR methods will be needed to test their scalability and economic viability. This could entail funding the development of coastal field stations in EMDEs (emerging markets and developing economies) and once they are established and running well, using results-based payments in long-term support. In some cases, this could entail payments per ton of carbon produced from biomass delivered to a biochar facility, for example. But in other cases, it might not be appropriate to try to pay for tons of carbon sequestered, since for some methods, especially 'open to the environment' methods, that can be difficult to measure. Other quantities could be used for measuring 'results' instead, e.g. area of mangrove or seagrass restored.

Experimental field stations will require long-term, stable, and sufficient funding to test marine biomass cultivation CDR approaches empirically, with careful tracking of the quantitative results and environmental costs and benefits. A key goal will be to find ways to produce marketable products using marine biomass. Kelp farming and seaside saltwater algal ponds are two possible sources of fast-growing biomass. Seaside experimental CDR field stations could host both approaches.

SECTION 6: CDR FUNDING – FUTURE POSSIBILITIES

Today's engineered CDR industry (i.e., CDR other than afforestation/reforestation and other nature-based CDR methods) is in its infancy. According to the State of CDR Report, the global engineered CDR market in 2023 saw 0.1 million tons of CO_2 delivered and pre-orders made for 4.5 million tons (to be delivered in future years). By mid-century, just 25 years from now, CDR deliveries will have to scale by >100,000x to >10 billion tons per year to put the world on track for 1.5˚C by 2100 (which will likely require CDR of about 20 $GtCO_2$ per year during the second half of this century, as we saw in Section 2). Whatever the precise numbers, what is clear is that if climate safety continues to grow in importance as a global policy goal, CDR is likely to gain enormously in scale and importance over the coming years and decades.

THE CDR FUNDING GAP

At the beginning of Section 3, we made note of a recent McKinsey Sustainability report, "Carbon removals: How to scale a new Gigaton industry," and summarized that report's estimate of the cost per ton and the durability of each of ten CDR methods. That McKinsey report also offers interesting estimates of CDR funding requirements by 2050, assuming the CDR industry is scaled up to 6 to 10 $GtCO_2$ annually by then, and the funding gap between 2024 and 2030.

McKinsey estimated that the CDR industry might grow to about $1.2 trillion dollars in annual revenue by 2050 to achieve the net-zero scale foreseen in recent IPCC scenarios. Cogently, the McKinsey report's authors worry that far too little investment is flowing into CDR to get on track to attain climate goals (assuming, as per IPCC scenarios, that 6 to 10 $GtCO_2$ per year CDR will be needed by 2050 on the road to net zero CO_2 emissions). Excerpt:

> "Investment would be needed to support innovation to drive down costs and to support project development. Analysis in [the McKinsey] report estimates **the cumulative investment in CDR required to deliver net zero in 2050 at $6 trillion to $16 trillion.** The investment need would depend on the volume of removals needed as well as the range of available CDR solutions. Estimates based on the current trajectory for investment, however, suggest investment could fall considerably short of these levels. In fact, **the gap between estimated investment and what is estimated to be needed by 2030 to put CDR on track to meet 2050 targets is between $400 billion and $1.6 trillion**."

Note their estimate for money required for CDR development and deployment already by 2030, i.e., five and a half years from the time of writing of the present report: $400 bn to $1,600 bn. As of this writing, no mechanism exists yet for raising more than about 2% of that cumulative volume of money for CDR by 2030.

It is beyond the scope of this report to explore in depth the question of how to raise the missing $400 bn to $1,600 bn to spend on CDR by 2030. What seems clear is that a consultation and co-design process with key stakeholders will be necessary to address this enormous gap in global climate policy, and should be embarked upon with due urgency.

Here in Section 3, we will briefly look at how a limited amount of money for CDR technology development could be usefully spent, but not at the question of where the money might come from.

CAN CDR PARTIALLY PAY FOR ITSELF VIA CCUS APPLICATIONS?

We've seen that billions of tons per year of CDR will be needed in coming decades to meet the challenge of absorbing and disposing of vast quantities of previously emitted CO_2, and to compensate for hard-to-abate emissions of CO_2 and other GHGs from distributed sources (e.g. jet aircraft and some farming operations). In addition, CO_2 harvested via CDR and CCS operations can serve as inputs to a future bio-economy, in which plastics, liquid fuels, and other materials currently made using fossil fuels will be made using fresh biomass or synthesized using CO_2, water, and renewable energy. CCU (carbon capture and use) and CCUS (carbon capture, use, and storage) are the terms of art for such applications.

CCUS applications are conceptually crucial, even if their details are largely beyond the scope of this brief report. The key point is that **CCUS applications that produce marketable products alongside permanent storage of tons of CO_2 could partially offset the cost per unit of sequestering each ton of CO_2.**

Efforts to identify marketable high-volume Gigaton-per-annum-scale products that achieve net CO_2 sequestration are warranted, as is ample funding to accelerate their development. For example, could biochar produced from large-scale kelp farming, or magnesium carbonates produced via enhanced weathering of crushed olivine, serve as high-volume inputs to the construction industry? For the answer to emerge as 'yes,' new building materials would have to be engineered and tested. In this way, **some of the excess hundreds of billions of tons of CO_2 in the environment could become useful inputs for production processes rather than merely a waste management problem.**

EARLY-STAGE CDR DEVELOPMENT FUNDING

Most novel CDR technologies are in early-stage development, and currently reliant on discretionary donations of public, corporate, or philanthropic money for R&D and demonstration projects.

- In recent years, modest amounts of venture capital money have been flowing into the CDR technology space from sustainability-focused VC funds. Investor Casper Bjarnason has written a primer offering a VC perspective on investing in CDR.
- Several major corporations are donors to the Frontier Climate fund. which provides non-equity funding to CDR startups in the form of advance market commitments to buy future CDR deliveries from CDR startups. Frontier Climate was initiated by Stripe, a payments company. Corporate donors include, among others, Stripe, Alphabet, Meta, Shopify, and McKinsey. The fund has so far (as of May 2024) committed $925 million to buying carbon credits from CDR startups some years ahead of the eventual delivery of the contracted carbon removal volumes. Frontier Climate can be understood as a stand-alone voluntary carbon market mechanism.
- Microsoft has funded CDR efforts via its Climate Innovation Fund investments and its Carbon Removal procurement program.
- The Bezos Earth Fund announced a $1 million prize for new GHG removal technology solutions in January 2024.
- In April 2022, Elon Musk sponsored a $100 million Carbon Removal X Prize.

Venture capitalists invested in the CDR space require a long-term view, since CDR is, as things now stand, fundamentally a waste management business funded by voluntary donations, and the **funding mechanisms to scale up CDR beyond a modest voluntary carbon market scale have not yet been established**. However, patient venture capital investors investing in CDR startups are aware that **by mid-century, CDR could become a trillion-dollar global business driven by compliance markets** and possibly also by legislated nationally determined contributions (NDCs) to global warming target limits set by large countries or blocs (e.g., the European Union).

Political will and international cooperation will be necessary to set up robust financial mechanisms to pay for billions of tons of carbon removal per year. CDR can become a multi-trillion-dollar global business only if financial mechanisms are established to routinely allocate about one to three trillion dollars annually to pay for CDR. Such mechanisms do not yet exist.

The CDR industry as it now stands is very small and largely dependent on the goodwill of a few technology-corporation CEOs who have allocated some money to voluntary carbon markets and some modestly funded government RD&D project subsidy programs. **Donations will not be sufficient in the long term**. The scale of funding and investment in CDR, at around $1.3 billion in 2023, is at a surprisingly modest level at this point in the global climate disruption dynamic. If global climate policy targets are to be met, including the Paris Agreement targets, increased efforts will be needed to accelerate the development and scaling of novel CDR technologies – to support research and development, fund small-scale pilot projects, fund meso- and large-scale demonstration projects, and ultimately establish large-scale, enduring CDR supply chains in regions around the world.

FOUR ENABLING CONDITIONS MUST BE PUT IN PLACE TO GROW THE GLOBAL CDR INDUSTRY FROM A TINY SEED INTO ONE OF THE WORLD'S LARGEST INDUSTRIES BY MID-CENTURY

To build sustainable and scalable CDR supply chains, CDR hubs must be seeded, funded, and nurtured in many regions, and each must have access to scalable, enduring financial mechanisms willing and able to pay out money for large quantities of the CDR industry's product: tons of carbon dioxide removed. All this must be embedded in a context of well-crafted policies and regulations designed to support the emergence of a robust, rapidly growing CDR industry. None of this exists yet – not even in North America or Europe, and certainly not in developing countries.

Four enabling conditions must be implemented for CDR to scale to a level of tens of billions of tons of CO_2 removal per year by mid-century: accelerated RD&D; seeding and development of regional supply chains; supportive national and global regulatory frameworks; and large-scale funding – preferably a globally integrated source of funding for payments per verified ton of CO_2 removed, so that money can be raised in metropolitan regions and spent in remote regions where land and resources are relatively cheap.

In slightly more detail, development of CDR deployment at a scale of several $GtCO_2$ per year by mid-century (or preferably well before that) would require:

1. **Technical development of highly scalable, cost-effective CDR methods.** This would require major investment in accelerated CDR technology research, development, and field testing, supported by detailed financial, chemical, physical, and environmental process models of every CDR method under consideration, available on an Open-Source basis, to help guide investment efficiently and minimize malinvestments.
2. A well-funded, sustained push to **seed and develop regional CDR supply chains centered on nodes of CDR industry expertise and capacity in every global region.** Creation of CDR supply chains can be seen as economic development opportunities by EMDEs (emerging market and developing economies) if a global CDR funding system is put in place to enable money to flow from wealthy developed regions of the world to less-developed regions where CDR money can be spent cost-effectively.
3. **Effective regulatory frameworks and supportive government policies** to enable the emergence of a CDR industry in each region.
4. **Stable, predictable sources of large-scale funding**, e.g., >$200 billion per year by 2030 or soon thereafter, to fund the emergence of >1 $GtCO_2$ per year CDR deliveries, and >$1 trillion per year by 2050 to pay for >10 $GtCO_2$ per year CDR, with the payouts channeled through competitive CDR markets to enable viable business models, attract entrepreneurs, and reward cost-efficient solutions.

GHG USER PAYMENTS INTO A CDR DEVELOPMENT FUND?

In principle, a 'user pays' financial mechanism to pay for future CDR could be fit for purpose. This could entail **charging GHG emitters** – especially in industrialized countries – **an affordable fee per ton of CO_2eq emitted and channeling the revenues through a global CDR development fund (or a set of regional CDR development funds),** to be spent wherever lowest-cost CDR providers can be found. The user fee amount charged to GHG emitters could be calculated on the basis of estimates of the mid-century price per ton of CDR (rather than today's much higher price per ton) to prevent price shocks.

The establishment of CDR compliance market funding agreements will take time to negotiate. In the meantime, absent a CDR compliance market, a way forward could be to set up a Global CDR Fund and request voluntary donations from the world's wealthiest oil-and-gas producing nations, in proportion to their means.

As the McKinsey report mentioned above recognized, funding volumes totaling several hundred billion dollars by 2030 (or soon thereafter) will be needed to pay for a comprehensive learn-by-doing exploration and scale-up of CDR technology options to the >1 $GtCO_2$ scale. There is no other way to advance CDR technologies along their learning curves and reduce the cost per ton of carbon removed. At >$100 per ton of engineered CDR as at present, it will require >$100 billion a year to achieve 1 $GtCO_2$ engineered CDR per year. This funding volume could be an appropriate initial goal (by, e.g., 2028-2030), since if there are (say) 40 different CDR technologies, and each must be scaled up sufficiently to begin to achieve economies of scale, $100 billion is only $2.5 billion per year per CDR technology.

In the longer run, CDR compliance markets will be necessary, given that >$1 trillion per year will likely be required to achieve >10 $GtCO_2$ per year CDR volumes.

One way to set up a routine carbon levy collection system to supply money to a regional or global CDR development fund could be to set up a first-mover CDR compliance market mechanism in a major jurisdiction. Many possible formats of such a system could exist. A simple example would be to require all companies that sell oil, gas, or coal into a market to buy certified CDR credits in a volume corresponding to the company's total sales as measured in barrels of oil or tons of coal or gas – e.g., initially, in a first program year, enough to compensate just 5% of physical emissions associated with the sales (taking into account life cycle supply chain emissions), then 10% in the second year, 20% in the third, and rising to 100% by e.g. the tenth or 15th year (these numbers are purely illustrative and are not meant to be taken as proposals). Techno-economic modeling will be necessary to evaluate the pace of CDR ramp-up that is physically, technically, and socio-economically feasible.

To build an off-ramp from today's fossil-fueled civilization, we must ensure that we first build an on-ramp onto a prosperous and affordable post-fossil-fuels civilization. Any jurisdiction implementing a compliance market or rising GHG emissions fee scheme must invest in accelerating the rollout of non-fossil-based 'green' alternative technologies – to drive down their unit costs, expand their market availability, enable low-friction technology substitution away from fossil-fuels-based infrastructure and equipment, and so prevent avoidable inflationary pressures.

Some of the revenues from carbon border adjustment mechanism fees and other carbon levies could be appropriately spent on green technology acceleration portfolios. A case in point is the European Union's Innovation Fund for climate-relevant innovative technology deployment, which is funded by revenues from sales (by auction) of the EU's Emissions Trading System (ETS) allowances.

CDR FUNDING MECHANISM DESIGN POSSIBILITIES

Sebastian Manhart (2024) has provided a brief overview of some of the possible designs for a CDR funding mechanism in "Government as Catalyst: Strategic financing paths for scaling carbon dioxide removal." Manhart's short article identifies several categories of policy options for funding CDR. In his words: **"Funding policy for CDR can be broadly categorized into three main buckets: compliance markets, public procurement, and fiscal incentives.** Each of these categories encompasses specific mechanisms designed to support the development and deployment of CDR technologies by leveraging different aspects of market and governmental forces."

Funding CDR via Compliance Markets

Let's consider CDR compliance markets first. Manhart defines Compliance Markets as follows:

"A carbon compliance market is a regulatory system that establishes a cap on admitted carbon dioxide emissions, requiring specific companies to either reduce their emissions to meet these caps, buy emissions allowances, or receive a limited number of free allowances to comply with the regulations. There are two main approaches:

> **Emission Trading System (ETS)** Integration foresees the integration of CDR within an ETS, allowing for the direct inclusion of removal credits within an existing carbon market. This enables entities to offset their emissions by purchasing CDR credits, thus providing a financial

> incentive for carbon removal. [Example: the European Emission Trading System (EU ETS) could in future be modified to include carbon removals.]
> **Removal Trading System (RTS)** involves creating a dedicated compliance market where removal credits can be traded. It imposes an obligation on certain sectors to achieve a specific level of CO_2 removal, thereby incentivizing the development and use of CDR technologies through market dynamics." [No example of an RTS exists yet anywhere in the world.]

Setting up a Removal Trading System would be preferable to integrating carbon removals directly into an ETS, according to Meyer-Ohlendorf (2023), "Making Carbon Removals a Real Climate Solution," and Manhart (2023). Including CDR in ETS markets has the disadvantage that it could make it possible for companies to avoid reducing emissions even where reducing emissions is relatively technically straightforward, e.g., in power generation markets, and instead buy carbon removal credits. Enabling such substitutions may be undesirable, because it could absorb the limited supply of lowest-cost CDR opportunities that are better deployed for achievement of net negative emissions, i.e. for lowering global temperatures, rather than offsetting continuing, relatively easily avoidable emissions.

Eventually, CDR funding at the very large scale that will be required to achieve Paris Agreement climate targets (billions of tons of CO_2 removal annually beginning as soon as possible, with about 20 $GtCO_2$ per annum on average in the second half of this century, as explained in Section 2 of this report) will necessarily rely either on compliance markets, or on public procurement funded via obligatory levies on some economic quantity or quantities (e.g., fossil fuels), or both.

Funding CDR via Public Procurement

Let's now consider the second of Manhart's three CDR funding categories: public procurement. The money raised from levies on fossil fuels could be channeled to CDR suppliers through public CDR funding vehicles, e.g., a global CDR development and deployment fund, or a set of regional CDR deployment funds, via feed-in tariffs or other results-based payment schemes to reward suppliers of tons of removed carbon.

Payments per ton of CO_2 for CDR will require solving MRV challenges (monitoring, reporting, and verification) to reliably confirm volumes of CDR deliveries. MRV will be especially difficult to implement accurately for open-to-environment CDR methods, e.g., OAE (Ocean Alkalinity Enhancement) or OF (Ocean Fertilization). Given that some open-to-environment CDR methods may eventually prove significantly more cost-effective than closed-system CDR methods like DACCS, the MRV challenge is well worth solving.

Funding CDR via Tax Incentives

Alongside compliance markets and public procurement, the third option for paying for CDR, tax incentives, is the principal instrument being used by the United States to fund CDR efforts at present (see Section 7 for details). In the long run, however, tax incentives may face inefficiencies and constraints on scope that can arise when CDR payments are routed through tax deductions.

RFF, Resources for the Future (2024), examined the policy challenges in a US context in "Policy Incentives to Scale Carbon Dioxide Removal: Analysis and Recommendations," subtitled: "This report surveys the challenges to scaling carbon dioxide removal efforts in the United States and details short-term solutions and long-run policy frameworks."

That concludes our overview of Manhart's three main CDR funding categories. We now turn to the question of how to go about designing CDR funding mechanisms of whatever kind. Such policies will inevitably draw the lively interest of many stakeholders. Some form of co-design process tends to emerge. What criteria should a CDR funding mechanism fulfill to be considered successful?

CDR funding mechanism policy design process targets and methods

Honegger et al. (2021), in "Who is paying for carbon dioxide removal? Designing policy instruments for mobilizing negative emissions technologies," suggest that:

> “CDR characteristics point to the need for up-front capital, continuous funding for scaling, and long-term operating funding streams, as well as differentiation based on permanence of [carbon] storage that should influence the design of policy instruments.
>
> Transparency and early public deliberation are essential for charting a politically stable course of action on CDR, while specific policy designs are ... developed in a way that ensures effectiveness, prevents rent-seeking at public expense, and allows for iterative course corrections.
>
> [One could consider] a stepwise approach whereby various CDR approaches initially need differentiated treatment based on their differing maturity and cost through R&D pilot activity subsidies. In the longer term, CDR increasingly ought to be funded through mitigation results-oriented financing and included in broader policy instruments.
>
> We conclude that CDR needs to become a regularly provided public service like public waste management has become over the past century.”

In the short run, funds in a potential CDR technologies development fund should be invested in accelerating the technological and economic development of cost-effective CDR methods and processes. As these technologies reach higher technology readiness levels and become more ready for large scale deployment, the fees would increasingly flow toward seeding and expanding regional CDR hubs where a confluence of funding, CDR expertise, infrastructure, supportive regulatory environments, and supportive regional populations will have been established.

As noted earlier in this section, a ‘user pays’ mechanism to pay for future CDR could entail charging emitters – especially in industrialized countries – an affordable fee per ton of CO_2 released and channeling the revenues from such a fee through a Global CDR Development Fund, with the amount charged calculated on the basis of estimates of the mid-century price per ton of CDR (rather than today’s much higher price per ton). This would constitute a carbon emissions levy.

In the longer run, as fossil fuel use declines toward mid-century, the fossil fuels tax base will shrink, so at some point, perhaps starting in the early 2040s, the world will no longer be able to rely on carbon fees to pay for continuing CDR operations. Restoring safe atmospheric CO_2 levels via net negative emissions could require collecting >$1 trillion in annual revenues (possibly as much as $5 trillion/yr) to pay for >10 billion tons CDR per year (possibly as much as 50 billion tons/yr). **Forms of CDR levy may be required by or before mid-century that can raise and dispense trillions of dollars a year through global CDR funding vehicles *without relying primarily on carbon emissions fees.***

Possibilities for funding CDR that do not rely on carbon emissions levies include, for example, an increment on value-added taxes; land use or financial transaction fees; or energy taxes (taxes on all energy, including clean non-fossil energy, with a higher tax per MWh on less clean energy and a lower tax per MWh on clean energy).

Whatever the CDR funding channels eventually implemented, if global policy target limits to global heating are to be met, then by the second half of the century, even assuming – very optimistically – a low average price of $50 per ton CDR, $1 to $2.5 trillion dollars per year will have to be hypothecated to some form of global CDR fund or a basket of regional CDR funds to remove 20 to 50 $GtCO_2$. Given a $100 trillion GDP 2024 global economy, and assuming a 2% real annual GDP growth rate, GDP would be $164 trillion in 2050, $260 trillion in 2075, and $432 trillion in 2100. In that context, $2.5 trillion a year does not seem too large a figure. It will, however, require CDR compliance markets or obligatory levies to fund the level of effort required. Voluntary donations will not suffice.

SUMMARY OF MID- TO LONGER-TERM CDR FUNDING TARGETS

Increased efforts are needed for CDR technology R&D and to establish and develop regional CDR technology hubs and supply chains, especially in developing countries.

Short run, medium term, and long run CDR funding strategies will be needed:

- Short run (2024-29): Countries whose wealth has come from oil & gas revenues could contribute to an initial donations-based iteration of a Global CDR Development Fund.
    - Financial goal: raise $tens of billions/yr. A reasonable approach could ask each oil-and-gas-rich nation to contribute in proportion to the volume of oil and gas produced, e.g. at a rate of $1 per bbl of oil. This would raise about $90 billion from oil sales alone, if all oil-producing nations contributed. If only half of the top 10 wealthiest oil producing nations contribute, it would still add up to ca. $30 to 40 billion annually. A small fee per ton of coal could likewise be levied, adding to the total size of the CDR Development Fund.
    - CDR volume goal: achieve CDR volumes of at least 1 billion tons CDR/yr by 2030 or soon thereafter.
- Short to Medium term (2024-2040): A coalition of countries willing to apply a modest surcharge on bulk sales of fossil fuels could fund a Global CDR Development Fund (or a basket of regional CDR Funds) to implement CDR via public procurement in competitive-bid CDR markets. Participating countries could complement this by putting in place compliance markets in their own jurisdictions, requiring oil, gas, and coal users to buy offset credits from CDR suppliers.
    - Financial goal: raise $hundreds of billions/yr.
    - CDR volume goal: >5 billion tons CDR/yr.
- Longer run (by 2050): Beginning in the 2020s, convene co-design processes amongst stakeholders to build consensus on a long-term funding system to pay for ca. 20 $GtCO_2$ of CDR annually. Ensure a robust system is agreed and in place well before 2050.
    - Financial goal: >$1 trillion/yr by 2050.
    - CDR volume goal: Tens of billions of tons CDR/yr by 2050 or soon thereafter.

COULD SOME COUNTRIES IN THE GLOBAL SOUTH DEVELOP CDR AS A NEW INDUSTRIAL SECTOR AND BUSINESS MODEL?

Most of the carbon emitted into the atmosphere has been put there by highly industrialized countries. Yet it seems likely that many of the best opportunities to build large-scale carbon removal operations will be found in remote locations in the Global South, where large quantities of barely populated desert or semi-desert land can host large solar parks to power $GtCO_2$-scale CDR operations, amongst other things. CDR could emerge as a significant new industrial sector and a welcome business opportunity for developing countries.

For the emergence of large-scale CDR industries in EMDEs to be feasible, a mechanism will be needed that can raise money in the global metropoles (where much of the excess CO_2 was emitted over the past century) and spend it in the global South. As we noted above, a **Global CDR Development Fund**, or perhaps several such funds, would be appropriate for this purpose. Beyond this, however, developing countries will need to take capacity-building measures to get ready for the prospective global industrial CDR deployment opportunity.

A model for how developing countries can explore opportunities to develop CDR industries as a new industrial sector and national business opportunity is presented by the International Renewable Energy Agency's Renewables Readiness Assessments (RRAs), which have been prepared for many countries, e.g. Senegal, Mozambique, and Jordan. Some RRAs were prepared in the early 2010s, and renewable energy technologies have advanced dramatically since then. Prices per MW have come down by an order of magnitude, and continue to decline. RRAs must be occasionally updated to reflect technological progress.

In the same way, County Carbon Removal Readiness Assessments, CCRRAs, could be generated for countries to explore their opportunities and constraints, considering geophysical, social, environmental, and economic factors, and updated regularly as new CDR technologies emerge and mature.

Carbon Gap, a philanthropy-funded non-profit organization focusing on "scaling up just effective carbon dioxide removals (CDR) in the EU," has recently taken IRENA's Renewable Readiness Assessments as a model to prepare Country Carbon Removal Readiness Assessments for Norway, the United Arab Emirates, and France in the context of the first phase of deployment of Carbon Gap's CCRRA methodology (which was inspired by IRENA's RRA methodology). These CCRRAs take a perspective which approaches carbon removal as a potential economic opportunity for a country.

ESTABLISHING REGIONAL CDR INDUSTRY HUBS IN DEVELOPING COUNTRIES

Only a few efforts have been made to date toward seeding regional CDR industry hubs in developing countries.

Kenya's Great Carbon Valley initiative is an example of such an effort. This is an attempt to attract investment in CDR projects to the Great Rift Valley, which boasts a superabundance of geothermal energy and basaltic rock availability, making the region suitable for a variety of energy-demanding CDR project types. Companies promoting this initiative include Africa Climate Ventures and Great Carbon Valley.

Another CDR development effort, also in Kenya, is Bio-Logical, a small company active in promoting smallholder (farmer) biochar-making.

Oxford University's Institute for Science, Innovation, and Society is working to develop an international network in which "policymakers and researchers collaborate to develop portfolios of climate action which include the maximum responsible contribution of greenhouse gas removals." This network initiative – focused primarily on engaging EMDEs in developing technological capacities and supply chains for deployment of engineered CDR methods – so far has identified prospective partners in India, Tanzania, and Argentina.

An initiative called the Carbon Removal Partnership hosted by Arizona State University (USA) also seeks to advance carbon removal in the Global South. See its list of participating organizations here. Its non-US-based partners appear to be in Kenya and Colombia.

Much greater efforts will be needed – including efforts to help EMDEs understand CDR as a business model in which many of them may well have a comparative advantage compared to industrialized countries, due to the availability of thinly populated high-insolation lands and extensive coastlines, some of which are not densely populated. Again, this presupposes cross-border or global funding mechanisms, so that money can be raised for CDR in metropolitan regions of wealthier countries that emit large quantities of GHGs (currently and/or historically), and used to pay for CDR projects in EMDEs, where opportunities to spend that money on cost-effective CDR projects may be particularly abundant.

The Country Carbon Removal Readiness Assessment process pioneered by Carbon Gap (mentioned above) may offer a useful tool in making progress in identifying regions which are environmentally, technically, and socioeconomically especially suitable for CDR (and keen to deploy CDR).

In Section 6 of this report, we have estimated the CDR funding gap to 2030 and to 2050, and considered, in outline, theoretically possible funding mechanisms that could be developed to fill the funding gap. We've also noted that a future global CDR industry may offer an extraordinary new large-scale industrial economic development opportunity for EMDEs. In the remainder of Section 6, we look at two existing and emerging national and international frameworks for supporting CDR – one via the UNFCCC, and one for EU members (only).

ARTICLE 6 OF THE UNFCCC PARIS AGREEMENT

A beginning has been made in the direction of allowing money to flow from the industrialized countries to developing countries for CDR with Article 6 of the Paris Agreement, which sets out how countries can pursue voluntary cooperation to reach their climate targets. Article 6.2 will enable bilateral carbon trading between countries. Article 6.4 establishes a new international carbon crediting mechanism and a supervisory body. The following paragraphs provide a brief outline of key points on Article 6 carbon crediting mechanisms; to learn more, one option is to read the useful 'explainer' on Article 6 published by The Nature Conservancy (TNC) in February 2024.

Article 6.2 creates the basis for trading in greenhouse gas emission reductions and removals (mitigation outcomes) bilaterally across countries. Article 6.4 will create a global carbon market overseen by a United Nations (UN) Supervisory Body. Articles 6.2 and 6.4 enable international cooperation by allowing money to flow across borders and, in effect, allow emissions reduction projects done by entities in one country to be sold to entities in another country. The entities in the second country that purchased such cross-border carbon credits may use the credits to comply with its own emission reduction obligations, or help it meet voluntary net-zero targets, or for other purposes.

Cross-border carbon credits issued under Article 6.2 are called Internationally Traded Mitigation Outcomes, ITMOs, in UNFCCC parlance. ITMOs can be transferred bilaterally between countries, allowing the buying country to count the emission reductions towards its NDC (Nationally Determined Contribution, i.e., emissions mitigation target). This mechanism is meant to promote flexibility and cost efficiency in meeting climate targets.

To avoid double counting of emission reductions, corresponding adjustments must be made. This means that when an ITMO is transferred, the country transferring the ITMO deducts the corresponding amount from its emissions inventory, and the receiving country adds it to its inventory. This ensures that the emission reduction is counted only once across participating countries.

Key quality goals for ITMOs are that they must uphold environmental integrity by ensuring real, measurable, and long-term benefits related to the mitigation of climate change. This means including stringent verification and monitoring processes to maintain credibility and effectiveness. Also, the implementation of ITMOs should contribute to sustainable development – ITMO projects must comply with the sustainable development goals of the involved countries. This involves integrating social, economic, and environmental considerations into the projects generating ITMOs.

ITMOs are a new mechanism, still under development, and only one ITMO has been issued and traded so far (as of mid-2024) – see UNEP's Article 6 pipeline database.

The Article 6.4 mechanism, also known as the Paris Agreement Crediting Mechanism, is an international (global) carbon credit trading mechanism with a central clearing-house. Article 6.4 has a Supervisory Body tasked with developing and supervising the requirements and processes needed to operationalize the mechanism. This includes developing and/or approving methodologies, registering activities, accrediting third-party verification bodies, and managing the Article 6.4 Registry.

The Article 6.4 Supervisory Body is responsible for establishing guidance and procedures, approving methodologies, registering projects, issuing credits, and more. Methodologies may be developed by project participants, host countries, stakeholders, or the Supervisory Body.

Credits that will be issued under Article 6.4 are called the Article 6.4 Emission Reductions (A6.4ERs). These will be used for both emission reductions and carbon removals. The host country will have to authorize A6.4ERs and account for these by applying corresponding adjustments – unless the A6.4 ERs contribute to the national target in the host country (mitigation contribution A6.4ERs). The A6.4ER mechanism allocates credits for emission reductions and removals by both public and private sector actors.

2% of Article 6.4 credits are subject to cancellation ("Overall Mitigation in Global Emissions" clause); 5% of credits are dedicated to the Adaptation Fund ("Share of Proceeds for Adaptation"). Other fees for registration, inclusion, issuance, renewal, and post-registration apply as well ("Share of Proceeds for Administrative Expenses"). As of July 2024, many other details are yet to be ironed out. Article 6 is not yet in active implementation. It is possible (though not certain) that the first credits under Article 6.4 will be issued in 2025.

EU CARBON REMOVALS AND CARBON FARMING CERTIFICATION (CRCF) REGULATORY FRAMEWORK

In early 2024, the European Union adopted a new certification framework for carbon removals. which created the first EU-wide voluntary framework for certifying carbon removals, carbon farming, and carbon storage in products across Europe. The certifications only apply within the European Union. Details here. An EU Expert Group on carbon removals, consisting of about 70 people, advises the EU on technical specifications. There was a multi-year negotiation process leading up to the adoption of the new framework.

The EU's Carbon Removals and Carbon Farming (CRCF) Certification Regulation is formally a "provisional" agreement, and further deliberation is in progress within the European Commission, in consultation with stakeholders. The CRCF is not yet operational and the process of developing detailed rules and procedures for the CRCF certification methodologies continues. As of May 2024, the European Commission had prepared several Technical Assessment papers on aspects of the CRCF.

The Clean Air Task Force (CATF) is a well-resourced non-government organization that is a member of the European Commission's Expert Group on Carbon Removals; as such, CATF technically assists and helps oversee the work of the Expert Group. On 15-17 April 2024, the EU Expert Group on Carbon Removals held its fourth meeting as a part of the continuing process of developing the Carbon Removal Certification Framework, with CATF participation. The three-day meeting focused on exchanging views and discussing the certification process, best practices for verification and registries, and the prioritization and development of the upcoming certification methodologies.

In a detailed blog post on its website, CATF reported 'key takeaways' on CRCF certification methodology development progress and noted there are many open questions and technical concerns. CATF noted that: "Resolving important details and being clear and open as to how certain approaches will be chosen, such as the length of monitoring period, baseline setting, defining eligible activities, and identifying appropriate data sources, will be foundational to moving forward with developing robust methodologies. As the CRCF is likely to set a global standard, getting these elements right will be crucial for building trust in carbon removals across categories."

CATF also noted that: "Many questions remain. The challenge that lies ahead is enormous, with numerous open questions related both to the highest levels of how the initiative will be operationalized, to key technical details, such as the duration of the monitoring period for removals, and the appointment and training of certification bodies, which are all critical underpinnings to a robust certification program."

With much work yet to do, European Commission officials at the April meeting expressed the view that in the best-case scenario, the CRCF certification will be up and running at the end of 2026, but realistically 2027 is more likely.

Section 6 has looked at some theoretically desirable financial support mechanisms for CDR, and some emerging international carbon crediting mechanisms (UNFCCC Article 6 and European Union Carbon Removals Certification Framework) that have been in development for several years and will be operational soon. In the next section (Section 7), we provide a very brief overview of some existing, already operational financial support mechanisms for CDR. The overview given in Section 7 is not comprehensive – among other limitations, it lacks detailed information from China, Japan, India, and Russia. It primarily lists program supports in the US and Europe, where much of the world's CDR development efforts have taken place in recent years, driven mostly by voluntary CDR markets, European and US research funding programs, and since 2022, the landmark US Inflation Reduction Act.

SECTION 7: STATUS OF EXISTING CDR FUNDING SUPPORT FROM KEY COUNTRIES, MULTILATERAL FINANCIAL INSTITUTIONS, AND PHILANTHROPIES

FISCAL INCENTIVES, STATE SUBSIDIES, AND PRIVATE CORPORATE OR FOUNDATION FUNDS FOR ADVANCING CDR

Fiscal incentives, public R&D funding, government or multilateral trust funds, and private foundation funding play critical roles in advancing carbon dioxide removal (CDR) projects and investments across several global jurisdictions. This section includes a list of several regions where such incentives are in play, followed by a list of some global/multilateral funding sources. This list covers many of the main sources, but should not be considered comprehensive.

1. UNITED STATES

US PUBLIC FUNDING SOURCES FOR CLIMATE-RELATED PURPOSES, INCLUDING CCS AND CDR

- 45Q Tax Credit: Provides significant financial incentives for carbon capture and storage, including CDR technologies.
- Inflation Reduction Act: Includes enhanced 45Q tax credits, direct payments for non-taxable entities, and substantial funding for DAC hubs and other CDR initiatives.
- Bipartisan Infrastructure Law: Allocates $3.7 billion for CDR-related programs.
- The US federal government's Department of Energy has an Office of Fossil Energy and Carbon Management and a $35 million advance offtake agreements-based CDR purchase program, plus $100 million for funding pilot scale CDR technologies via its "carbon negative shot" program. The Congressional Research Service summarized information on DoE's CCS and CDR funding programs (2024).

US FEDERAL 45Q TAX CREDIT: OVERVIEW AND APPLICATION TO CDR

The 45Q tax credit is a U.S. federal tax incentive designed to promote carbon capture, utilization, and storage (CCUS) by providing financial incentives to companies that capture and sequester carbon dioxide (CO2) from industrial sources or directly from the atmosphere. The tax credit was initially introduced in 2008 and has since been expanded and enhanced to support the growing need for carbon management technologies. **The 45Q tax credit system is essentially a Results-Based Payments scheme.**

KEY FEATURES OF THE 45Q TAX CREDIT

1. Credit Amounts: The amounts are calculated per ton of carbon oxide (i.e., carbon dioxide or monoxide) that can be verified as having been captured and sequestered in geological storage (CCS) or captured and utilized as an input into a product (CCU/CCUS). The specific amounts paid out via the 45Q tax credit system are described here. The amounts vary depending on several factors, including, among others, whether or not 'prevailing wages' and registered apprenticeship programs were offered; and whether the captured carbon was used for enhanced oil recovery (EOR) or not.
2. Eligibility: Applies to industrial facilities and power plants that capture CO_2. Includes direct air capture (DAC) facilities, which capture CO_2 directly from the atmosphere. The captured CO_2 must be securely stored or used in a manner that prevents its release into the atmosphere.
3. Minimum Capture Requirements: Power plants must capture at least 18,750 tons CO_2 per year to qualify for the credit. Industrial facilities must capture at least 12,750 metric tons of CO_2 annually to qualify. Direct air capture facilities must capture at least 1,000 metric tons of CO_2 annually. See Congressional Research Service (CRS) document IF11455 v.5.
4. Duration: The credit is available for up to 12 years after the facility begins capturing CO_2. To qualify, construction of a carbon capture facility must have begun before the end of 2032.

More detail on 45Q credit amounts (as updated in 2023 via the Inflation Reduction Act):

- For geologically sequestered CO_2, the base credit is $17 per metric ton of CO_2 ($36 for DAC), increased to $85 ($180 for DAC) for facilities that pay prevailing wages during the construction phase and during the first 12 years of operation and meet registered apprenticeship requirements. Amounts adjusted for inflation after 2026.
- For geologically sequestered CO_2, with EOR, the base credit is $12 ($26 for DAC), increased to $60 ($130) for facilities that pay prevailing wages during the construction phase and during the first 12 years of operation and meet registered apprenticeship requirements.
- For 'other qualified uses' of CO_2, i.e., incorporation of CO_2 in products (CCU), the base credit is $12 ($26 for DAC), increased to $60 ($130) for facilities that pay prevailing wages during the construction phase and during the first 12 years of operation and meet registered apprenticeship requirements.

45Q'S IMPACT ON THE CDR INDUSTRY

The 45Q tax credit is a crucial policy tool for advancing carbon dioxide removal technologies in the United States. By providing substantial financial incentives, it helps to:
- Lower the cost barriers for new and existing CDR projects.
- Stimulate private sector investment in carbon capture and storage technologies.
- Accelerate the deployment of DAC and other CDR solutions at scale.
- Foster innovation in carbon utilization, leading to the development of new products and markets for captured CO_2.

More detailed information can be found in the following sources (among others):

- Congressional Research Service overview of 45Q tax credit.
- Internal Revenue Service (IRS) overview of 45Q tax credit.
- IEA overview of 45Q.
- Carbon Capture Coalition overview of 45Q.
- NETL Guidance on Life Cycle Analysis for 45Q tax credit calculations.

THE US INFLATION REDUCTION ACT OF 2022 AND BIPARTISAN INFRASTRUCTURE LAW OF 2021

The US federal Inflation Reduction Act (IRA) of 2022 provides a comprehensive set of fiscal incentives aimed at supporting carbon dioxide removal (CDR) technologies and broader carbon management efforts. The **US Bipartisan Infrastructure Law of 2021** allocates significant funding for carbon dioxide removal (CDR) technologies. (Both laws also provide funding for a wide range of other types of infrastructure and technology unrelated to carbon management.) Here are the key components and incentives provided by the IRA and BIL for CDR:

Key fiscal incentives for CDR in the Inflation Reduction Act of 2022 and the Bipartisan Infrastructure Law of 2021:

1. ENHANCED 45Q TAX CREDIT.

Increased Credit Amounts: As noted above, the IRA significantly increased the value of the 45Q tax credit.
Eligibility Expansion: The IRA reduced the minimum capture requirement for direct air capture (DAC) facilities to 1,000 metric tons of CO_2 annually, making it easier for smaller projects to qualify.
Direct Payment Option: Non-taxable entities, such as non-profits and municipal utilities, can receive direct payments in lieu of tax credits, broadening the accessibility of the incentives.

2. INVESTMENT IN DAC HUBS.

Funding Allocation: The Bipartisan Infrastructure Law of 2022 allocates $3.5 billion for the creation of four regional DAC hubs. These hubs will demonstrate and scale DAC technologies, capturing at least one million metric tons of CO_2 annually per hub. This funding is intended to jumpstart large-scale deployment of DAC technologies across different regions in the United States.

3. SUPPORT FOR CARBON UTILIZATION PROJECTS.

Carbon Utilization: The IRA provides expanded grants and funding opportunities for projects that utilize captured CO_2 in various industrial processes (on a larger scale than the pre-2023 45Q provisions). This includes the production of low-carbon fuels, chemicals, and building materials.

Technology Commercialization: Additional funding is allocated to the commercialization of carbon utilization technologies, to help innovations move from R&D to market deployment.

4. OTHER RELEVANT PROVISIONS.

Clean Energy and Manufacturing: The IRA supports the broader clean energy transition, which indirectly benefits CDR technologies by promoting an ecosystem conducive to carbon management. This includes incentives for renewable energy projects, which can provide the necessary energy inputs for CDR processes like DAC.

Research and Development: Funding is allocated for research and development in advanced energy technologies, including CDR. This includes grants for universities, research institutions, and private companies to advance CDR technologies.

2. EUROPEAN UNION

- Horizon Europe: The EU's primary R&D funding program supports, inter alia, climate science and climate restoration projects, including CDR. Examples: UPTAKE, RESCUE, CDR Approaches.
- Innovation Fund: Provides substantial funding for innovative low-carbon technologies, including CDR projects.
- LIFE Programme: EU funding instrument for environmental and climate action, for which, inter alia, CDR initiatives may qualify.
- European Green Deal: Includes policies and funding aimed at achieving net-zero emissions by 2050, supporting CDR technologies as part of broader climate strategies.

3. UNITED KINGDOM

- Carbon Contracts for Difference (CCfD): Provides long-term price stabilization for carbon removal projects. Similar schemes exist in the Netherlands and Denmark (although in its current format as of mid-2024, the Dutch scheme does not yet cover CDR projects). CCfDs can be a powerful tool for encouraging investment in renewable energy projects and in carbon removal projects, by significantly reducing financial risks and making long-term cash flows more predictable. CCfDs may merit adoption in additional jurisdictions.
- Net Zero Strategy: Includes funding for CDR technologies as part of the UK's plan to achieve net-zero emissions by 2050.
- UK Research and Innovation (UKRI): Funds research and innovation in all domains (it is the UK's equivalent to the EU's Horizon program). *Inter alia,* UKRI funds CO2RE, the UK's Greenhouse Gas Removal Hub, and CDR and CCS R&D.

4. CANADA

- Canadian Net-Zero Emissions Accountability Act: Supports various climate action initiatives, including CDR.
- Natural Resources Canada, a Canadian government ministry, has a Carbon Management Strategy.
- NGO and private sector actors: Energy and environment think-tank Pembina Institute published a 2023 report: "Engineered carbon dioxide removal in a net-zero Canada." Canadian venture capital fund bdc has a CDN $400 million Climate Tech Fund.

- The Canadian federal government also offers an Investment Tax Credit for Carbon Capture, Utilization, and Storage. From 2022 through 2030, the CCUS investment tax credit (ITC) offers a refundable ITC of up to: 60% on capture equipment using direct ambient air, 50% on other capture equipment, and 37.5% on qualified carbon transportation, storage, or usage equipment. From 2031 to 2040, the investment tax credit rates will be halved. The ITC will be fully phased out after 2040. Eligible jurisdictions include Alberta, Saskatchewan, and British Columbia.

5. AUSTRALIA

- Carbon Capture Use and Storage (CCUS) Development Fund: Provided grants to support the development and deployment of carbon capture and storage technologies. This grant program is currently closed to further applications; it is unclear whether it will be funded anew or extended in a further iteration.
- Emissions Reduction Fund (ERF): Encourages businesses to reduce emissions through various methods, including CDR. Connected to Australian Carbon Credit Units (ACCU) scheme.

6. NORWAY

- Northern Lights Project: Part of Norway's effort to become a leader in CCS, Northern Lights provides funding for the transport and storage of CO_2 from clients to a storage site offshore. Northern Lights will offer carbon storage to third parties, as part of Longship, the Norwegian Government's carbon capture and storage program: "Northern Lights will be the first cross-border, open-source CO_2 transport and storage infrastructure network, offering companies across Europe the opportunity to store their CO_2 permanently underground. Phase one of the project will be ready to receive CO_2 in 2024 with a storage capacity of up to 1.5 million tons of CO2 per year." While the Longship program is primarily for CCS, not for CDR, Northern Lights could potentially enter into carbon storage agreements with upstream CDR value chain clients such as bioenergy project operators.
- Relatedly, Norway's CLIMIT Program provides funding for the development and implementation of CCS technologies.

7. JAPAN

- Green Innovation Fund: Aims to support innovative technologies for decarbonization, including CDR.
- Carbon Recycling Fund, private sector, aims to advance CCU.
- On CCS (not CDR), Japan CCS Co. Ltd. is a public-private initiative providing funding and support for CCS projects in Japan, in particular, Tomakomai CCS Demonstration Project.

8. CHINA

- National Key R&D Program of China: Supports high-priority projects, including those related to CCUS and CDR technologies.
- China's Carbon Neutrality 2060 Plan: Includes investment in CDR technologies as part of a broader goal to achieve carbon neutrality by 2060. Climate Action Tracker rates the plan as 'poor.'

9. PRIVATE

The following three private sector instruments directly target CDR and have a global scope, although all three are US-based:

- Frontier Climate is a private sector initiative spearheaded by e-payments company Stripe (Stripe Climate): "Frontier is an advance market commitment to buy an initial $925M of permanent carbon removal between 2022 and 2030. It is funded by Stripe, Alphabet, Shopify, Meta, McKinsey, and tens of thousands of businesses using Stripe Climate."
- X Prize / Musk Foundation: $100 million prize fund for carbon removal technology advances.
- Bezos Earth Fund: multiple partly CDR-related funding streams, including for a CDR Ideation Prize, carbon-absorbing crops, 'next' technologies, and decarbonizing energy & industry.

SECTION 8: CURRENT STATE AND FUTURE POSSIBILITIES FOR CARBON CAPTURE AND STORAGE (CCS)

Although engineered CDR methods are the principal focus of this report, a survey of CCS technologies and prospects is provided in this section.

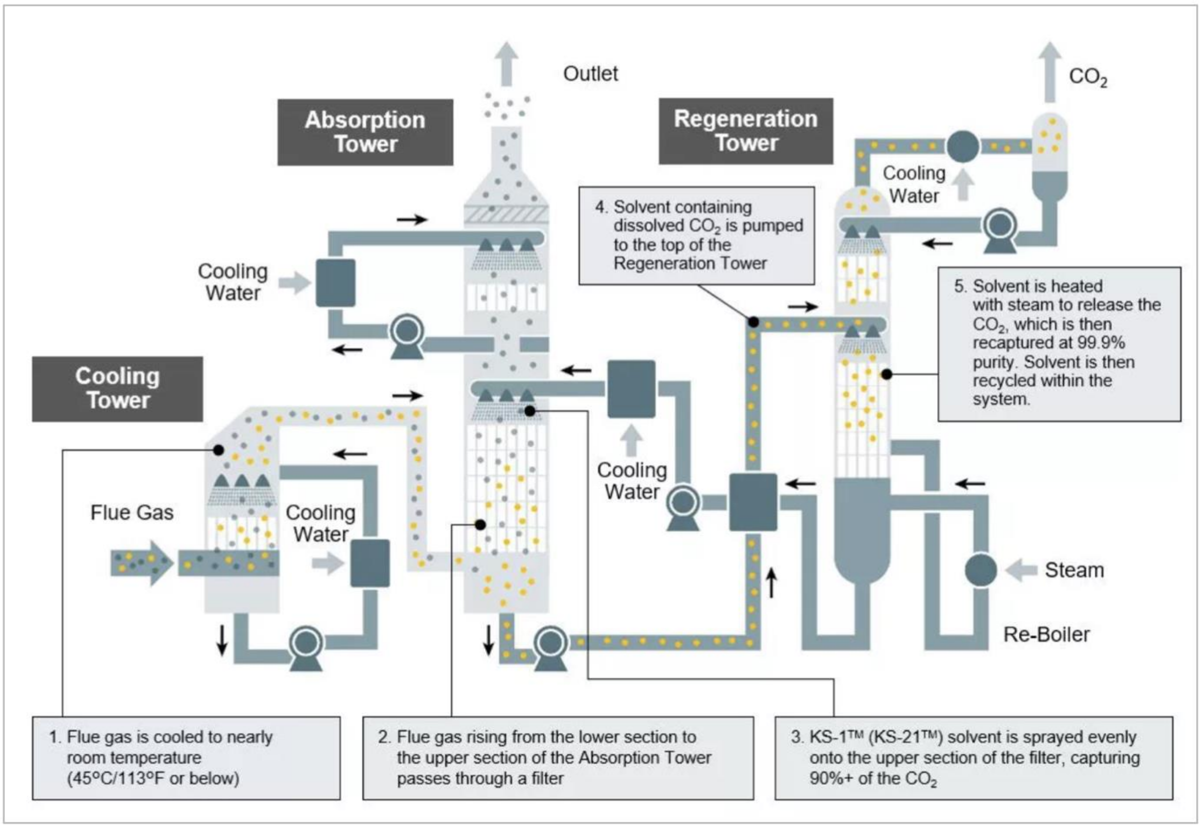
POINT SOURCE CARBON CAPTURE AND STORAGE (CCS)

Capture and removal of CO_2 from industrial waste gas streams and subsequent storage of the captured CO_2, generally from large emitters, is often referred to as point-source CCS (carbon capture and storage). CCS was first applied to flue gases from natural gas processing in 1972 at the Val Verde Natural Gas Plants in Texas, USA, where the captured CO_2 was used for enhanced oil recovery (EOR) in nearby oil fields.

Point source CCS is a well-understood process in which CO_2 is separated from flue gases of an industrial source, concentrated, transported to a disposal site (often by pipeline), and then pumped under pressure down a well pipe for permanent disposal deep underground, in "geological storage." Since the 1970s, the predominant application of carbon captured from CCS operations has been for enhanced oil recovery, i.e., CO_2 is pumped below ground into aging oil fields to restore pressure and force out more crude oil. Between 1972 and 2023, primarily at several different sites in the USA, Canada, and Australia, upwards of 200 million tons of CO_2 had been captured and injected underground, according to the CCS Institute.

CCS can be applied to point sources such as natural gas processing or ethanol production plants, in which CO_2 is in very high concentration (up to 90%), or at coal or gas power plants, where flue gas CO_2 is in somewhat lower concentration (often in the range of 3% to 18% CO_2 by volume), or from other industrial facilities, e.g., in the steel, cement, and chemicals production industries, where the flue gas CO_2 concentration can range from about 10 to 25%. The lower the concentration of CO_2 in a flue gas stream, the more expensive and energy-intensive the carbon capture process tends to be.

The image below shows one example of a carbon capture process from industrial plant flue gases.



1. Flue gas is cooled to nearly room temperature (45°C/113°F or below)

2. Flue gas rising from the lower section to the upper section of the Absorption Tower passes through a filter

3. KS-1™ (KS-21™) solvent is sprayed evenly onto the upper section of the filter, capturing 90%+ of the CO_2

4. Solvent containing dissolved CO_2 is pumped to the top of the Regeneration Tower

5. Solvent is heated with steam to release the CO_2, which is then recaptured at 99.9% purity. Solvent is then recycled within the system.

Source of image above: Mitsubishi Heavy Industries.

Once captured, CO_2 can either be used for EOR, or as an input to some other industrial process (see CCU and CCUS subsection below), or it can be treated as a waste product and permanently disposed of where it cannot impact the climate, e.g., by pumping it under pressure into saline aquifers or other underground rock formations capped by rock layers that are impermeable to gases. Preferred formations include porous basalts or peridotites and other 'mafic' or 'ultramafic' rock types, which chemically react with CO_2 over time and mineralize it more quickly than do other rock types such as sedimentary rocks.

Alternatively, the carbon can be 'mineralized,' or converted into solid form, above-ground by chemically reacting CO_2 with silicate minerals to generate stable carbonate minerals, a process known as mineral carbonation or carbon mineralization. In principle, carbonate minerals can then be used industrially, e.g., as construction material, as was noted in Sections 3 and 4.

Note that CO_2 concentration in outdoor air is, at present, 420 parts per million by volume (ppmv), or 0.042%, so all other things being equal, capture of carbon dioxide from the air (instead of from industrial point source flue gases) will be more difficult and energy intensive per ton of CO_2 captured.

FUTURE SCALE OF CCS: AN OPEN QUESTION

There is an extensive literature of technical reports and scientific articles on CCS methods and their possible implementation in a wide range of industries (surveyed further below in this section), ranging from fossil fueled thermal power generation to biomass fueled thermal power generation (see the section on bio-energy carbon capture and storage, BECCS, in this report), to steelmaking, cement-making, chemical and agri-foods industries.

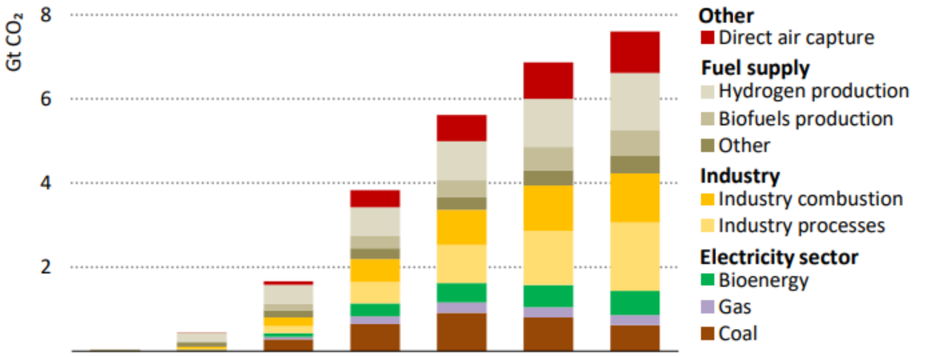
The range of industries in which carbon dioxide capture and storage from flue gas streams is a technically feasible way to avoid climate impacts of CO_2 is very wide. This suggests that CCS may have a very large role to play in a future climate policy constrained world. Recent estimates by IPCC and IEA of the possible future scale of CCS by 2050 underline this point.

The Intergovernmental Panel on Climate Change Assessment Report 6, Working Group III, relying on a paper by Budinis et al. (2018) entitled "An assessment of CCS costs, barriers, and potential," estimated the medium to high volume range of annual carbon capture and storage from fossil hydrocarbons use in the year 2050 will likely be in a range from 3.8 (medium) to 8.8 (high) billion tons of CO_2 ($GtCO_2$); see Table 8 in Annex III of the AR6 WGIII report.

The International Energy Agency (IEA), for its part, in recent years modeled two scenarios projecting the state of the energy system and global carbon management in a climate policy constrained world in the year 2050: a 'Sustainable Development Scenario' (SDS) which assumed net-zero would be achieved by 2070, and a 'Net Zero Emissions by 2050' scenario (NZE2050). The SDS scenario estimated a CCS volume of 5.64 $GtCO_2$ in 2050, of which 0.96 from biomass (i.e., BECCS) and 0.11 $GtCO_2$ from DAC, with the rest, 4.57 $GtCO_2$, from fossil fuels and industrial processes. The NZE2050 scenario estimated a CCS volume of 7.6 $GtCO_2$ in 2050, of which 1.38 was captured from bioenergy (i.e., BECCS) and 0.99 $GtCO_2$ via DAC, and the rest, 5.25 $GtCO_2$, from fossil fuels and industrial processes.

For the SDS scenario numbers cited above, see Table 6, p.48, in the 2020 IEA report 'CCUS in clean energy transitions.' For the NZE2050 scenario numbers, see Fig. 2.21 in the NZE report, reproduced below, and Table 2.9, p.80, in the 2021 IEA report 'Net zero by 2050: A roadmap for the global energy sector.'

Figure 2.21 ▹ Global CO_2 capture by source in the NZE



IEA. All rights reserved.

The magnitudes of CCS/CCUS (5.6 to 7.6 billion tons of CO_2 per annum in 2050) in the IEA's SDS and NZE2050 scenarios are very large. However, in comparison to 2023's global CO_2 emissions, they are relatively small. 2023 saw emissions of 36.8 $GtCO_2$ from fossil fuels combustion (see Friedlingstein et al., Global Carbon Budget 2023), plus another 4.1 $GtCO_2$ from deforestation, wildfires, and other land use changes – and these emissions numbers do not include the further global warming impact of other anthropogenic greenhouse gases such as methane and nitrous oxide; converting these to CO_2-equivalent amounts and adding them gives a total for 2023 of about 53 $GtCO_2eq$. This means that even under the high-CCS NZE2050 scenario of 7.6 $GtCO_2$ CCS/CCUS in 2050, the reduction in GHG emissions by 2050 compared to 2023's will be composed largely of shifts to cleaner technologies that do not use fossil fuels at all. For comparison, in relation to 2023 emissions, the amount of GHGs dealt with in 2050 via CCUS or CDR (7.6 $GtCO_2$) would only constitute 14% of 2023's total CO_2eq emissions.

Any estimates of the possible or plausible volumes of CCS/CCUS in 2050 are highly contingent on both policy context and technological evolution. How large a role CCS/CCUS will play in the future global economy, how many billions of tons of CO_2 will be captured each year from flue gases, processed, and sequestered away from the carbon-climate cycle, is an open question. In a climate policy constrained future, i.e., a future in which policymakers and engineers take serious action to put the world back on a path to 1.5°C (or less) by 2100, CCS may well play a very large role, as the IPCC and IEA scenarios mentioned above suggest. On the other hand, non-fossil-fuels-based 'green' industrial technology alternatives may exist by then that offer cheaper ways to avoid emissions even in industrial sectors currently deemed 'hard-to-abate,' in which case CCS deployment may turn out to be smaller in volume than recent IPCC and IEA scenarios have projected. It is too early to say.

The primary basis for uncertainty on the future scale of CCS is cost: Prospective CCS infrastructure investments are destined to compete with alternative technical approaches to mitigating GHG emissions in each industrial sector in which CCS is an option.

For the purposes of the discussion here in Section 8, we will assume decision-makers are operating in a future climate policy constrained world in which GHG emissions are either against the law or made prohibitively expensive. Managers of industrial plants will be faced with the unequivocal need to avoid emissions. In that context, financial criteria will drive decisions on technology solutions for achieving emissions avoidance. Three types of emissions avoidance technology solutions will generally be available for consideration:

(1) Add CCS/CCUS systems to the industrial facility to capture emissions, or
(2) pay for CDR volumes sufficient to offset the emissions, or
(3) replace the CO_2-emitting source of the problem (in general: coal, oil, or natural gas-using equipment) with non-fossil-fuels-using 'green' technology alternatives.

As time goes on, those alternatives (options 2 and 3 above) are likely to become cheaper. Option 3 solutions, i.e. non-fossil-hydrocarbons-based 'green' technologies, may tend to increasingly outcompete CCS on cost in a growing number of use cases, *unless* CCS systems themselves get cheaper at a faster rate than competing 'green' technologies.

CCS will also have to compete with carbon dioxide removal, CDR, on price per ton, and CDR methods are also likely to get cheaper over time, although it would be surprising if they were to get cheaper than capturing CO_2 from flue gas. It is, however, possible that in some special cases, where local geological storage of captured CO_2 from flue gases is not feasible, the additional costs of transporting captured carbon over long distances could add so much to the total cost of flue-gas CCS that it might be cheaper, per ton of CO_2, to purchase an equivalent amount of CDR to offset ongoing emissions.

Another key financial consideration will be sunk costs in existing equipment. Let's imagine it is 2040, and a government decrees that steel mills will no longer be allowed to emit CO_2. A steel mill owner with a recent billion-dollar investment in a nearly new conventional coking-coal-using steel mill built three years ago will be much more likely to invest in a CCS retrofit than a steel mill owner with a 35 year old steel mill whose fixed costs were long ago amortized and which is nearing the end of its service life anyway. The latter owner will be less likely to invest in CCS and more likely to invest in replacing the old steel mill with a new-technology H_2 DRI (Hydrogen Direct Reduced Iron) steel mill or a Direct Electrolysis steel mill, neither of which use coal, and both of which will probably have attained technological maturity by 2040.

An additional criterion beyond comparative cost considerations will be important in some cases when investment decisions are made in a future climate policy constrained world about how best to reduce emissions from industrial sources: **'Social license to operate'** (SLO). It would go beyond the scope of this brief to review SLO, and it is, in any case, too early to evaluate how much NIMBY (not in my backyard) opposition may arise to CO_2 pipelines and disposal sites in different regions of the world (Global North vs South, urban vs rural, etc.). However, a growing academic literature is reporting on the SLO of CCS infrastructure and on methods for engaging communities to minimize NIMBYism, e.g. a review paper by Nielsen et al (2022), or a paper summarizing opinion survey and focus group results by Scott-Buechler et al. (2024).

With the foregoing in mind, we can make several observations that affect whether CCS will be implemented to reduce CO_2 emissions from steel mills – and similar considerations will apply to other sectors, e.g., thermal power stations, cement-making, or chemicals production:

- **Policy drives CCS/CCUS demand.** There is no business case for adding CCS to steel mills in the absence of policy drivers or subsidies. CCS systems are expensive to build and operate. Steelmakers cannot implement CCS on a voluntary basis, because doing so would incur a severe competitive disadvantage. Absent a policy environment creating a level playing field requiring all steelmakers with access to a given market to limit or eliminate their CO_2 emissions, no steelmaker can afford to implement CCS *unless* an external subsidy is granted (e.g., by the national government) to fully offset the additional cost of CCS.

- **Technology options for avoiding emissions include CCS/CCUS, CDR offsets, and non-fossil-fuels-based alternative 'green' technologies; these options will compete on price, sector-by-sector and case-by-case.** The relative costs and affordability of the three types of emissions-avoidance solution will shift over time.

- **Sunk costs in existing infrastructure will influence whether CCS/CCUS, CDR offsets, or non-fossil-fuels-using 'green' alternative technologies are selected, case-by-case, as the solution to a given emissions avoidance challenge.** The sunk costs associated with existing steel plants must be considered on a case-by-case basis when assessments are made whether it is cheaper to add CCS to existing steel mills or, instead, to build new 'green' steel mills.

- **CCS projects that cost more per ton of CO_2 than the typical price per ton of CDR offsets likely won't be built.** In a regulatory regime in which tons of CDR can be purchased to offset ongoing emissions, the average price per ton of readily available, scalable CDR operations may set a long-term ceiling on CCS deployment costs.

- **Regulatory regimes and public acceptance ('social license to operate') will influence choices between CCS/CCUS investments, CDR offset purchases, and non-fossil-fuels-based alternative technologies like 'green' steel.** These factors also will tend to change over time. NIMBYism may work against a given technology choice in some cases – and not in others.

In the long run, as 'green' industrial production and energy supply technologies that are currently new continue to evolve and mature over coming decades, the window of opportunity for CCS seems more likely to narrow rather than widen. CCS equipment is expensive to retrofit onto industrial or power generation facilities and expensive to operate, requires large amounts of energy input per ton of CO_2 captured and sequestered, and entails building and operating heavy infrastructure (chemical processing plants, pipelines, disposal wells). A conventional coal-burning steel mill that is not constrained by climate policy compliance regulations will always be cheaper to operate than the same mill burdened with CCS equipment.

In contrast, there is no *a priori* reason to assume that steel made in 'green' steel mills, whether they're new-generation H_2 DRI (Hydrogen Direct Reduced Iron) or Direct Electrolysis mills, will remain permanently more expensive than conventional coal-burning steel mills – even in the absence of a carbon price. In the same way that large solar power arrays are now delivering power more cheaply than coal-fired power stations in some EMDEs even in the absence of carbon prices or CO_2 emissions restrictions, because solar panels have simply become the cheapest way to generate a MWh of electricity (IEEFA study, 2004), it is possible, in principle, that when they reach technological maturity a decade or two from now, Direct Electrolysis steel mills could eventually become the cheapest way to make a ton of steel.

It seems plausible that all these technologies – CCUS technologies, CDR technologies, and non-fossil-hydrocarbons-based, electrically powered 'green' technologies – will improve and get more efficient and cheaper (in $ per ton CO_2 emissions avoided). It also seems plausible (though far from certain) that the *rate of improvement* in cost-efficiency of CCS technologies may prove somewhat lower than the rate of cost-efficiency improvement in new green technologies, given that CCS technologies have been around for 50 years and are already fairly mature, whereas many 'green' technologies are earlier in their technology evolution trajectory and still have plenty of runway for improvement.

In CCUS applications, i.e., cases where the CO_2 captured from flue gases can be utilized as a valuable marketable input material for another industrial process (thereby generating revenues offsetting the cost of carbon capture operations), the net financial feasibility of carbon capture improves relative to CCS implementations where the CO_2 captured is simply a waste product that must be disposed of, with no market value. This is an additional financial factor that might influence CFOs deciding on the best option, in financial terms, for meeting their company's emissions avoidance obligation in a climate policy constrained world.

With these caveats in mind on the prospective evolution in relative future cost-effectiveness of CCS compared to the next best alternative technology solutions, which will determine the eventual scope and scale of CCS/CCUS deployment in 2040, 2050, or 2060 to an extent that we cannot yet forecast, we can venture an overview of CCS, CCU, and CCUS technologies as applied to various industrial sectors.

CCU AND CCUS

Carbon Capture and Utilization (CCU) involves capturing carbon dioxide emissions and converting them into valuable products, such as fuels, chemicals, and building materials. Unlike Carbon Capture and Storage (CCS), where CO_2 is treated as waste and generally disposed of underground, CCU operations make economic use of the captured CO_2. CCU applications are those in which the carbon is subsequently re-

released into the atmosphere, rather than stored away from the carbon-climate cycle. A 2011 estimate of the global market for CO_2 can be found in this NETL report.

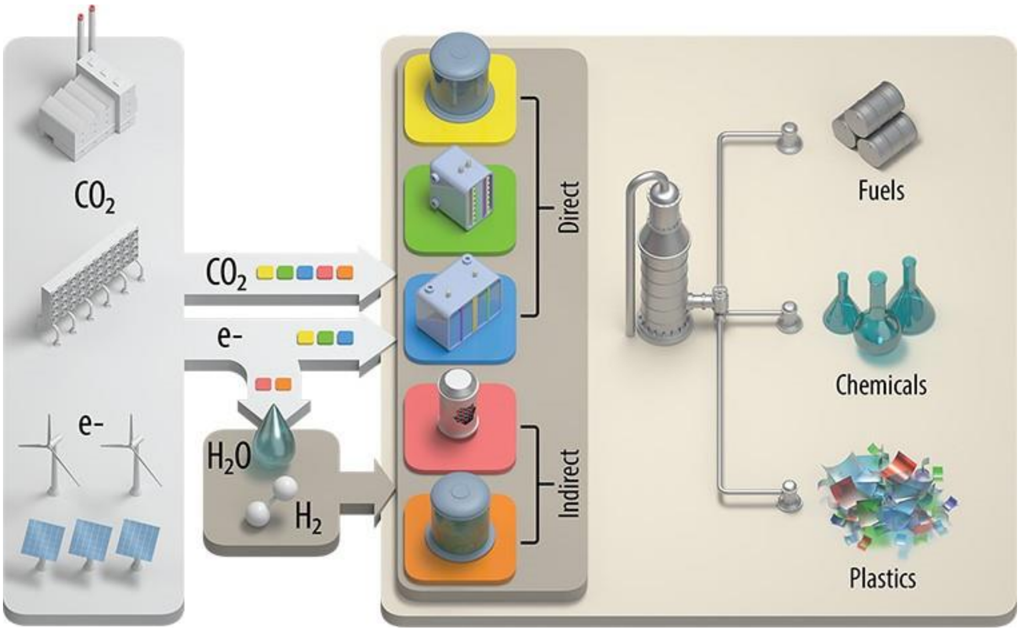
Carbon Capture, Utilization, and Storage (CCUS) combines aspects of both CCS and CCU: utilization *and* storage of carbon. Whether the source of CO_2 is flue gases from industrial point sources or capture of CO_2 from the environment via CDR methods, CCUS entails the capture of CO_2 emissions and their utilization in various applications, but in ways that do not re-release the CO_2 into the active carbon-climate cycle.

A prospective future CCU use case is to make synthetic jet fuel. A smaller-volume existing CCU use case for CO_2 is in the beverage industry, where CO_2 is added to liquids under pressure to make carbonated (fizzy) drinks.

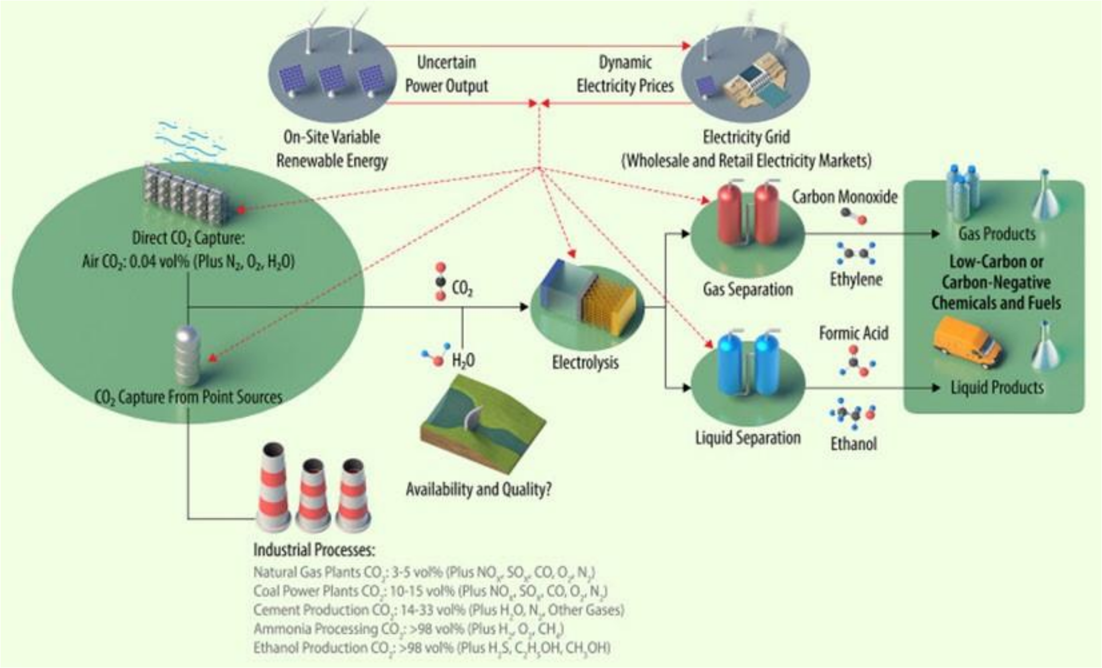
As for CCUS use cases, CO_2 can be used as an input to make a range of durable products that do not involve releasing more carbon into the atmosphere, and instead sequester the carbon away from the carbon-climate cycle. For example, startup companies like Seratech and Myno Carbon are developing ways to use captured CO_2 in the production of concrete, bricks, artificial stone, and other building materials. Captured CO_2 can also be made into carbon fiber or polymers and plastics.

One classic CCUS use case – the most important one until now – has been Enhanced Oil Recovery (EOR) using CO_2, usually referred to as CO_2-EOR, in which CO_2 is injected under pressure into aging oil fields to increase pressure and force out more crude oil. (There are several ways of increasing pressure in aging oil fields, within three main categories: gas injection, thermal injection, and chemical injection. CO2-EORis a gas injection technique. Thermal injection can involve injecting steam, and chemical injection takes various forms, including injection of water mixed with surfactant chemicals. According to IEA, as of 2023, about 20% of the world's EOR-produced oil was produced via CO_2-EOR, and 80% via other EOR techniques.) CO_2-EOR is covered in detail further below, in the next subsection.

Note that the use of captured carbon as an input into products can apply regardless of the source of CO_2. CO_2 can be obtained from CDR via direct air capture plants or from the biosphere, for example, rather than from the flue gases of fossil fuels burning industrial plants. The two illustrations below show this.



Source: NREL, US National Renewable Energy Laboratory



Source: NREL, US National Renewable Energy Laboratory

SECTORAL APPLICATIONS OF CCS

Carbon capture from flue gas is relevant for several major industries, each with various subcategories that entail different CCS procedures and equipment. Each entails specific challenges and opportunities for CCS, influencing the choice of capture technology and integration into existing processes. The different CO_2 concentrations, gas flow rates, and operational conditions require tailored solutions for effective CO_2 capture and subsequent storage or utilization.

To give an impression of the breadth of potential application of carbon capture and storage technology, in this subsection, we list different types of industrial point sources and link to articles that provide some details on each. After that, we list types of industrial point sources and the typical range of flue gas CO_2 concentrations, average CO_2 emissions (in tons) per unit of product, and some examples of projects of each kind. That list is illustrative, and not intended to be definitive or comprehensive.

Power Generation
Coal-Fired Power Plants:
- Conventional Pulverized Coal (PC) Plants: Standard boilers that burn coal to generate steam for turbines. CCS systems on PC plants are typically post-combustion, capturing CO_2 from flue gas using solvents.
- Integrated Gasification Combined Cycle (IGCC) Plants convert coal into syngas (a mixture of CO and H_2) before combustion. IGCC CCS systems can be pre-combustion, i.e., capture CO_2 before combustion.
- Circulating Fluidized Bed (CFB) Plants utilize a different combustion process that can handle varied fuels. CCS procedures for CFB are similar to those of conventional PC plants.

Natural Gas-Fired Power Plants:
- Open Cycle Gas Turbines (OCGT) use natural gas directly in turbines. CCS is usually post-combustion.
- Combined Cycle Gas Turbines (CCGT) combine gas turbines and steam turbines for higher efficiency. CCS for CCGT is typically post-combustion but integrated into both turbine stages.

Cement Production
- Overviews of possible CCS role in cement production here (with global map) and here (IEA overview).

- Global Cement and Concrete Association industry roadmap to net zero CO_2 emissions by 2050 here.
- Rotary Kiln Cement Plants: Large cylindrical kilns for clinker production. CCS is generally post-combustion due to the high CO_2 concentration in exhaust gases.
- Vertical Shaft Kiln (VSK) Plants: Smaller, simpler kiln systems. Post-combustion CCS is possible.
- Dry Process Plants: More energy-efficient than wet process, more easily integrated with modern CCS technologies.
- Wet Process Plants: Older technology with higher energy use, more challenging but possible to retrofit with CCS.

Iron and Steel Production

- Blast Furnace (BF) Plants: Large, conventional plants that use coke to reduce iron ore. CCS systems for BF plants are typically post-combustion or integrated with top gas recycling.
- Direct Reduction Iron (DRI) Plants use natural gas or syngas to reduce iron ore. CCS can be pre-combustion or post-combustion.
- Electric Arc Furnace (EAF) Plants melt scrap steel using electricity. Less CO_2-intensive.
- Basic Oxygen Furnace (BOF) Plants use molten iron and scrap steel inputs. CCS is post-combustion, capturing CO_2 from the exhaust.
- World Steel Association overview of CCS potential and challenges for steel sector here.

Petrochemicals and Refining

- Ethylene Production: Crackers produce ethylene from hydrocarbons. CCS in ethylene production can be post-combustion or pre-combustion.
- Ammonia Production uses natural gas or coal to produce ammonia (though it could instead use ‘green’ hydrogen). CCS can be integrated with the reforming process.
- Blue Hydrogen Production: Steam methane reforming (SMR) or autothermal reforming (ATR) with CCS. CCS is pre-combustion, capturing CO_2 from the hydrogen production process. Cost estimates here.
- Turquoise Hydrogen: pyrolysis of methane to produce hydrogen gas and solid carbon black. This report includes a section on this potentially significant energy-efficient low-emissions hydrogen production route, which may prove more cost-effective than ‘green’ hydrogen produced via electrolysis of water.

Natural Gas Processing

- Sweetening Units: Remove H_2S and CO_2 from natural gas. CCS can capture CO_2 from the process.
- Liquefied Natural Gas (LNG) plants produce LNG for transport. CCS can capture CO_2 during the liquefaction process.

Chemical Production

- Methanol Production: Converts CO_2 and H_2 into methanol. CCS can capture CO_2 from reforming stages.
- Ethylene Oxide Production from CO_2 and renewable energy. CCS captures CO_2 from oxidation reactions.

Waste-to-Energy Plants

- Municipal Solid Waste (MSW) Incineration: Burns waste to generate energy. MSW CCS is post-combustion.
- Biomass Combustion – BECCS: CCS can be post-combustion, capturing biogenic CO_2.

Pulp and Paper Industry

- Kraft Pulping uses chemicals to pulp wood. KP CCS can capture CO_2 from recovery boilers.
- Mechanical Pulping: Mechanical methods to produce pulp. Less CO_2-intensive but still viable for CCS.
- Overview of possible CCS pathways in the sector.

Other Industrial Processes

- Glass Manufacturing: Melts raw materials to produce glass. CCS can capture CO_2 from furnaces.
- Aluminum Production: Electrolysis of alumina. CCS captures CO_2 from anode reactions.

Now let’s look at the typical flue gas concentration of CO_2 in each of several types of industrial or power plant, and make note of some ongoing projects or projects in development.

Coal-Fired Power Plants
- CO_2 Concentration in Flue Gas: 10-15%
- Average CO_2 Emissions: 820-1050 kg/MWh
- Existing Projects: Petra Nova (USA), Boundary Dam (Canada) (evaluation)- CCS
- Projects in Development: San Juan Generating Station (USA) – planned CCS refit project (abandoned)

Natural Gas-Fired Power Plants
- CO_2 Concentration in Flue Gas: 3-4%
- Average CO_2 Emissions: 370-470 kg/MWh
- Existing Projects: Sleipner (Norway), Snøhvit (Norway)
- Projects in Development: CalCapture (USA), Peterhead CCS Project (UK) – CCS, offshore geo-storage

Type of Plant: Biomass Power Plants (BECCS)
- CO_2 Concentration in Flue Gas: 8-14%
- Average CO_2 Emissions: Variable
- Existing Projects: Drax BECCS (UK, in pilot phase) – wood pellets – BECCS
- Projects in Development: Arkalon Ethanol Plant (USA) - CCUS: CO_2 for EOR

Type of Plant: Cement Plants
- CO_2 Concentration in Flue Gas: 14-33%
- Average CO_2 Emissions: 600-900 kg/ton of cement
- Existing Projects: Norcem (Norway): HeidelbergCement's Brevik Plant (Norway) with CCS

Type of Plant: Steel Plants
- CO_2 Concentration in Flue Gas: 15-25%
- Average CO_2 Emissions: 1.8-2.3 tons/ton of steel
- Existing Projects: Emirates Steel Industries (UAE) – Arkan plant – CCUS: CO_2 for EOR
- Projects in Development: HIsarna (Netherlands) – DRI steel; Carbon2Chem (Germany) - CCUS

Type of Plant: Refineries
- CO_2 Concentration in Flue Gas: 8-12%
- Average CO_2 Emissions: 0.2-0.5 tons/barrel
- Existing Projects: Alberta Carbon Trunk Line (Canada) – CCS pipeline
- Projects in Development: Porthos Project (Netherlands), Humber Zero (UK)

Type of Plant: Ammonia Plants
- CO_2 Concentration in Flue Gas: 10-20%
- Average CO_2 Emissions: 1.6-2.2 tons/ton of ammonia
- Existing Projects: Nutrien Redwater Fertilizer Facility (Canada) – CCUS: CO_2 for EOR
- Projects in Development: Yara International (Norway) – deal with Northern Lights CCS unit

Type of Plant: Ethanol Plants
- CO_2 Concentration in Flue Gas: 90-100%
- Average CO_2 Emissions: 0.8-1.0 tons/ton of ethanol
- Existing Projects: ADM Decatur (USA) – CCS of ca. 10% of plant emissions
- Projects in Development: Carbon Clean Solutions (India)

Type of Plant: Petrochemical Plants
- CO_2 Concentration in Flue Gas: 3-5%
- Average CO_2 Emissions: 1.2-3.0 tons/ton of petrochemicals
- Existing Projects: Shell Quest (Canada)
- Projects in Development: Houston CCS Alliance, Houston CCS Innovation Zone (USA)

PROMISING EXAMPLES OF CCU AND CCUS APPLICATIONS: CAPTURED CARBON CAN BE USED AS AN INPUT MATERIAL FOR INDUSTRIAL PRODUCTS AND PROCESSES

Enhanced Oil Recovery (EOR): In this process, captured CO_2 is injected into aging oil fields to repressurize them and thereby increase the amount of crude oil that can be extracted. EOR is widely regarded as a scalable and cost-effective application of CCUS.

In CO_2-EOR, some portion of the injected CO_2 remains below the ground, and some mixes with the crude oil and is pumped back up to the surface. If the CO_2 that returns to the surface is separated and reinjected to form a closed loop, this can result in permanent CO_2 storage. According to IEA data, as per a 2019 IEA assessment, between 300 kg CO_2 and 600 kg CO_2 is injected in EOR processes per barrel of oil produced in the United States (although this varies significantly between fields and across the life of projects).

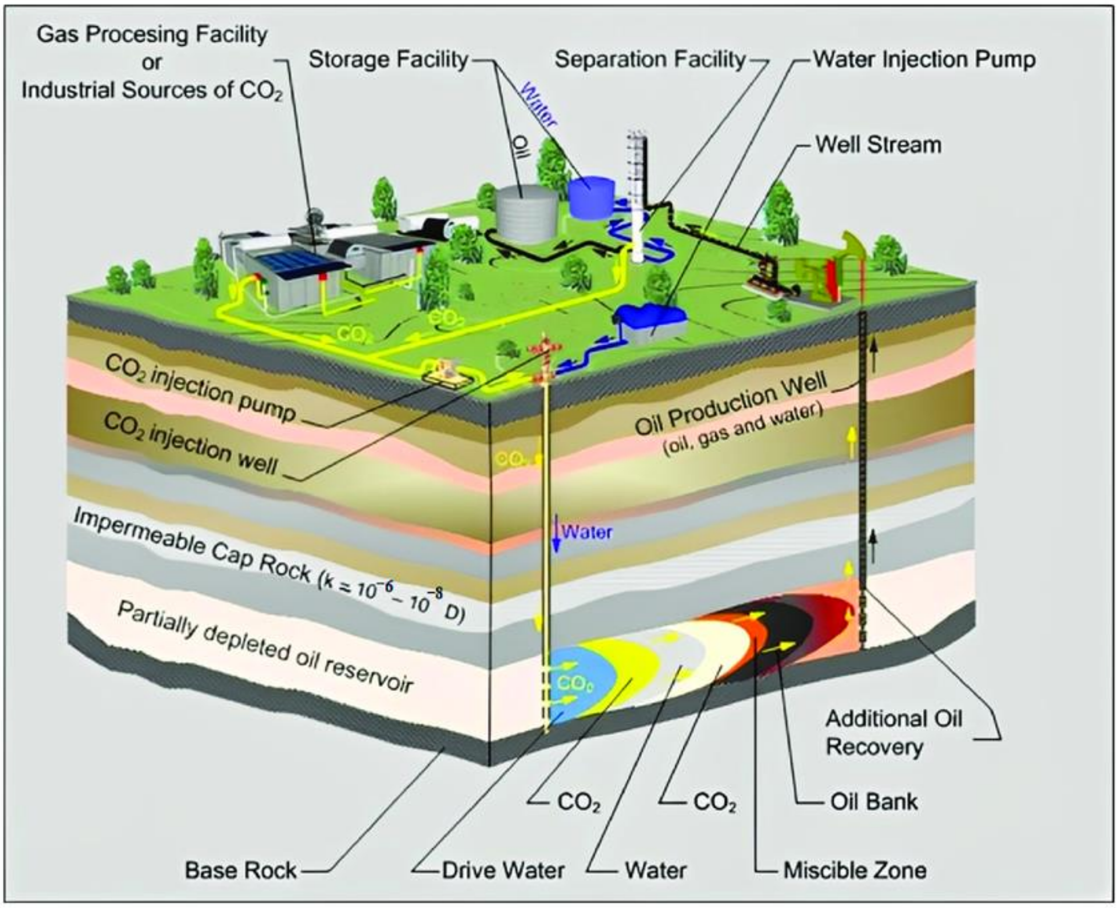
The use of CO_2 for enhanced oil recovery has an obvious corollary: the climate benefits of CO_2 sequestration are offset by the increase in oil production, with its consequent climate impact on combustion. For example, according to a 2014 article by Michael Godec in 'American Oil & Gas Reporter, the U.S. Department of Energy's National Energy Technology Laboratory has estimated that "next-generation" CO_2 EOR can provide 135 billion barrels of incremental technically recoverable oil in the United States, with about half of that total (66 billion barrels) economically recoverable at a West Texas Intermediate oil price of $85 a barrel, a CO_2 market price of $40 a metric ton, and a 20 percent return on investment before tax. How much CO_2 would be emitted in the course of producing that additional amount of oil?

According to a May 2023 IEA report, "Emissions from Oil and Gas Operations in Net Zero Transitions," burning a barrel of crude oil (or products made from it) releases about 405 kg CO_2 in direct emissions from the carbon content of the oil (according to IEA), with about another 20% on top of that in indirect emissions associated with extraction and refining, including combustion of oil products during refining and release of methane at various points of the crude oil extraction and refining supply chain, adding another 105 kg CO_2eq in emissions. This adds up in total to around 510 kg CO_2 per barrel of life-cycle emissions (i.e., 0.51 ton CO_2eq). However, CATF, citing IEA, suggests that the geological storage of CO_2 associated with CO_2-EOR (if carried out in a way that results in permanent CO_2 sequestration) can offset 37% of life-cycle emissions from a barrel of oil; if we accept this figure, then 66 billion bbl of crude oil produced with CO_2-EOR would cause emissions of about (0.63*0.51*66 bn) = 21.2 billion tons of CO_2, i.e., 21.2 $GtCO_2$, which would, for comparison, be an amount as large as 39% of total global annual GHG emissions in 2023 of 54.3 $GtCO_2$ (and 57% as large as total annual CO_2-only emissions from from fossil fuels combustion, estimated as 37 $GtCO_2$ in 2023); for data on CO_2 and GHG emissions, see OurWorldinData.org.

The foregoing calculations are illustrative, not definitive; more recent studies might provide even higher estimates of recoverable oil via CO_2-EOR. The estimate of an average 37% offset of the GHG impact of a barrel of oil from CO_2-EOR operations is likewise not definitive; significant uncertainty is built into such estimates. A further consideration is the source of the CO_2 in CO_2-EOR, in a given case. If the source is, for example, CO_2 emissions from the flue gas of a biomass-burning power plant, then using that CO_2 for EOR operations might be considered to present a genuine offset (though life-cycle emissions associated with transporting the gas to the EOR site, compressing it, and injecting it would all have to be considered). If, however, the source of the CO_2 was flue gas from fossil fuels combustion, e.g., from a natural gas-fired power plant, then it would be important to assign carbon removal credits either to the gas power plant or to the CO_2-EOR operation, not both (otherwise this would be double-counting).

How much CO_2 used in CO_2-EOR is permanently sequestered depends strongly on the details of the EOR techniques used. Vanessa Núñez-López et al. (2019) assessed that the best CO_2 sequestration performance can be achieved via 'stacked saline carbon storage,' an EOR/storage combination strategy where excess CO_2 from the recycling facility is injected into an underlying saline aquifer for long-term carbon storage.

In a separate commentary article, Núñez-López and Moskal (2019) suggested that this opens up the possibility for the emissions intensity of oil to be neutral or even "carbon-negative," but as they acknowledge, the notion of putative "carbon-negative" oil critically depends on the boundaries of the analysis and the origin of the CO_2. If stacked saline carbon storage can be implemented in a way that sequesters more CO_2 than results from combusting the additional oil produced via CO_2-EOR, this does not necessarily mean the life-cycle CO_2 emissions assessment of the project is negative. The source of the CO_2 and the LCA emissions impact of transporting the CO_2 to the injection site and then injecting it all have to be taken into account.



Source of image above: NREL, US National Renewable Energy Laboratory

Green Concrete Production: Captured CO_2 can be used to cure concrete, improving its strength and reducing the carbon footprint of traditional cement manufacturing. Companies like CarbonCure are pioneering this technology, which has significant potential for widespread adoption in the construction industry. Accelerating the deployment of 'green' concrete-making methods, driving down its unit price so that it becomes cost-competitive with conventional cement (IEA 2023), and scaling the production of 'green' concrete is a significant priority for climate policy: About 4% of global CO_2 emissions are caused by cement-making using current, high-emissions methods (CarbonBrief 2022).

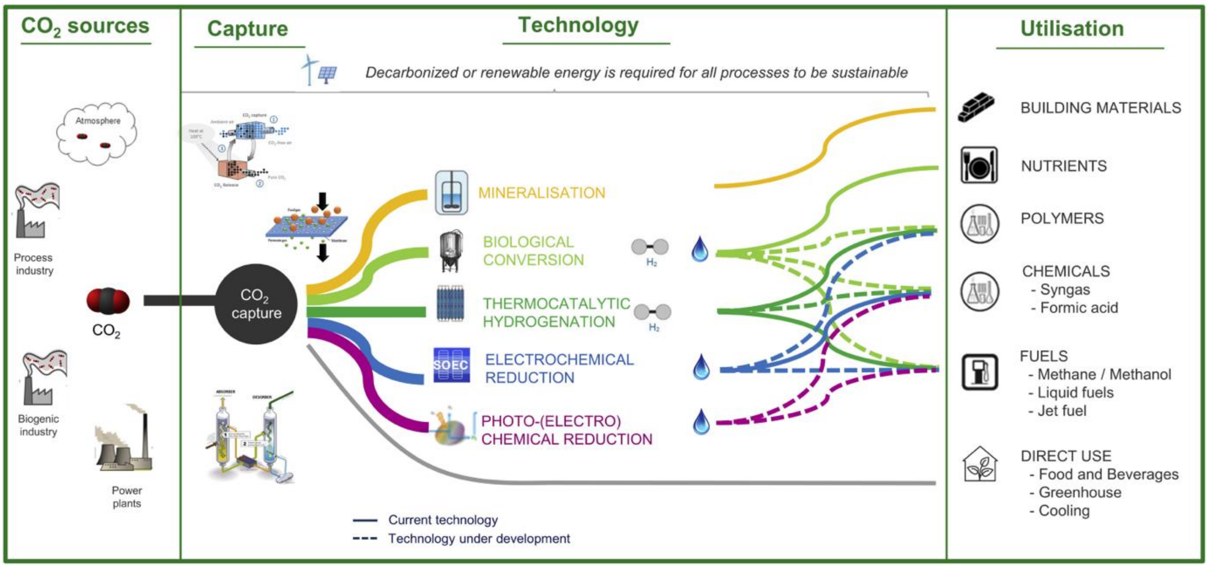
One useful application of the principle of results-based payments could be to make advance market commitments to the purchase of 'green' concrete. For example, this could entail a contractual commitment to buy 100,000 tons of 'green' concrete at a specified price, for future delivery within five years, from a cement manufacturer willing to convert a cement-making facility from conventional (high-emissions) concrete to low- or negative-emissions 'green' concrete. Going one step further, an advance market commitment scheme could pay for the green concrete years in advance of delivery, thereby shifting financial risk from the producer to the buyer.

Synthetic Fuels: Utilizing captured CO_2 to produce synthetic fuels, such as methanol to power cargo ships (as shipping giant Maersk intends) or synthetic aviation fuel (ICAO 2021), offers a promising pathway for reducing emissions from the transportation sector. These fuels can be used in existing engines and infrastructure, making them a practical and scalable solution. However, the life-cycle energy cost and the financial cost of synthetic fuels may limit their deployment. Energy system futurist Michael Barnard has made calculations suggesting that batteries and biofuels, not synthetic fuels, will power aviation in the latter part of this century, and that biofuels and batteries would also be a more efficient choice than synthetic ('green') methanol for shipping. It is also possible, however, that the quantities of biofuel that would be necessary to power these two sectors (aviation and maritime shipping) would outstrip plausibly available supply. Moreover, in the aviation sector, it is possible that offsetting emissions from aircraft powered by fossil kerosene via CDR will be more cost-effective than replacing kerosene with aviation biofuels. In any case, the CO_2 emitted from burning jet fuel during flights only contributes about 20% of climate impacts associated with aviation, according to Sacchi et al. (2023), and so 3.4 $GtCO_2$ CDR per year may be necessary to compensate for aviation's non-CO_2 global warming impact even if most aviation fuel is synthetic or biofuels-based by mid-century, according to Bergero et al. (2023).

Chemicals Production: CO_2 from CCS or CDR sources can be converted into valuable chemicals like urea, fertilizers, and polymers for plastics (Galimova et al. 2022). This approach provides a dual benefit of producing essential industrial products that would otherwise be made from fossil fuels in high-emissions processes.

In summary: by integrating CCU and CCUS technologies, it is possible to create a more circular economy where CO_2 emissions are not merely a waste product but a valuable resource. This approach can contribute to global emission reduction goals while fostering economic value through new market opportunities. **A focus of research and development worth supporting intensively is a search of the technological possibility space for highly scalable CCUS methods and applications.**

The question of what proportion of the very large future volumes of carbon captured and processed via CDR and CCS can plausibly be used as inputs into industrial processes remains open. **If cost-efficient CCUS uses for the captured carbon can be identified and scaled up, this will help offset the cost of capturing the carbon.**



Source of image: Mertens et al. (2023).

CLIMATE POLICY DRIVERS ARE NECESSARY TO MOTIVATE CCUS DEVELOPMENT AND DEPLOYMENT

Note that although CO_2 captured via CCS or CDR methods can be used as an input in making valuable industrial products, **robust climate policy drivers are required to motivate the implementation of CCUS – because in the absence of restrictions on CO_2 emissions (in the form of regulations or high**

carbon emissions prices), fossil fuels will almost invariably be cheaper sources of carbon inputs to industrial processes than carbon captured via CCS or CDR processes.

The underlying reason for this is that fossil hydrocarbons are highly concentrated forms of carbon that have the added advantage that valuable energy is released when hydrocarbons are processed to obtain their carbon content. By contrast, carbon contained in CO_2 is generally present in the environment (and certainly in the atmosphere) in much more dilute forms than the carbon in fossil hydrocarbons, and processes for removing CO_2 from the environment and concentrating it for subsequent use as an industrial input material involve spending energy, rather than harvesting it – all the more so if the C must be separated from CO_2 for a given application (e.g., in creating synthetic jet fuel or plastics), as distinct from uses such as CO_2-EOR in which CO_2 is used as-is.

THE CURRENT STATE AND SCALE OF CCS

A great deal of attention has been paid over the past 25 years to the promise and prospects of carbon capture and storage systems for enabling the continuing use of fossil fuels by equipping fossil-fuels-using industrial and thermal power plants with CCS. Many reports and detailed engineering studies have been written in support. CCS technology has existed and been deployed since the 1970s and is well understood. Yet due to an absence of strong policy drivers, few CCS projects have been implemented to date. According to the Global CCS Institute, there are 41 operating CCS projects in the world today; 26 under construction; and 326 in "advanced or early development." It also notes that: "We are now seeing a rapid escalation in the development of new CCS projects, although relatively few have yet advanced to operation. Given projects typically take 7 years or more to develop, the lag is not surprising."

For a quantitative perspective, 49 million tons of CO_2 were processed in the world's 41 operating CCS facilities in 2023, while global energy-related emissions reached a new historical high of 37.4 billion tons (IEA). Unlike CDR, the business of removing hundreds of billions of tons of previously emitted CO_2 from the environment so as to meet climate policy targets, CCS in the sense of carbon captured from industrial point sources faces welcome competition from other ways of reducing emissions: As noted earlier in Section 8, while CCS is likely to grow, its overall deployment volume in a future climate policy constrained world depends on whether CCS projects prove to be more financially viable ways of achieving mandated CO_2 emissions reduction targets from industrial sources than the best available alternative non-fossil-fuels-using technology options that can achieve similar emissions reductions. In the next (and last) subsection of Section 8, we examine this price-competition question in a bit more detail, even if it remains the case that no definitive assessment can be made – future cost projections of CCS vs. non-fossil-based alternative emissions avoidance strategies remain too uncertain.

CCS SYSTEMS DEPLOYMENT COSTS MUST BE COMPARED WITH AVAILABLE CLEANTECH ALTERNATIVES ON A CASE-BY-CASE BASIS

For many technologies – AI (Artificial Intelligence), solar PV, wind turbines, batteries, electric vehicles – seven years is a long time in our era of rapid technology evolution. CCS systems, in contrast, have evolved relatively slowly. The engineering designs and operation protocols of equipment for separating and removing carbon dioxide gas from the flue gas streams of industrial plants or thermal power generation stations, pressurizing the gas, piping or trucking it to a disposal site, and pressing it down a deep well into a depleted oil field or saline aquifer, comprise a fairly mature technology set that has been around for 50 years. Further gains in efficiency are likely, but they are unlikely to be dramatic; there are basic thermodynamic realities involved in moving materials around that cannot be finessed with technology.

A key consequence is that CCS has proven stubbornly expensive in capex and opex, energy requirements, and financial cost per ton of CO_2 removed. A 2023 Oxford/Grantham study compared high-CCS to low-CCS pathways to 1.5°C by 2100 and reported that **"assessing data from the past 40 years, no evidence is found for technological learning or associated cost reductions to date in any part of the CCS process – capture, transport, or storage."** The study concluded that **"from 2021 to 2050, taking a low-CCS pathway to net zero emissions will cost at least USD $30 trillion less than taking a high-CCS**

route – saving approximately a trillion dollars per year." This might suggest that 'green' non-fossil alternative technology solutions for emissions avoidance could decline in cost at a faster rate than CCS systems, and eventually will likely displace them in cost-competitiveness in most industries.

However, it should be noted that the Oxford/Grantham High CCS versus Low CCS study was criticized for working from a range year 2050 "High CCS" model scenarios that are well above what most energy transition experts are projecting or calling for. For reference, as seen in Table 7, p. 51 of the Oxford/Grantham report, the high-CCS model scenarios cover a range of 14.85 $GtCO_2$/year to 25.82 $GtCO_2$/year in 2050, while the low-CCS model scenarios range from 2.51 to 6.16 $GtCO_2$/year. In contrast, IEA's World Energy Outlook 2023 (see Fig.3.37, p.153 of the 2023 IEA WEO) provides a central estimate of 6.1 $GtCO_2$/year CCS in 2050 for the IEA's NZE (net zero emissions) scenario or 3.7 $GtCO_2$/year CCS in 2050 for the APS (Announced Pledges Scenario), both of which are less than the WITCH 5.0 EN-NPi2020_450 scenario value that is classified as the highest of the "low" range values in Table 7 of the Oxford/Grantham study. This suggests that the CCS community and IEA are expecting and planning for a relatively "low-CCS" route that will, as the Oxford/Grantham study notes, cost some USD $30 trillion less than their very-high-CCS scenario range.

In any case, all such scenarios must be understood as hypotheses, not as projections. No firm projections of the future scale of CCS/CCUS can be made at this time, because the future comparative cost of CCS/CCUS vs. best available non-fossil-fuels-using technology options is very difficult to project with confidence. While those 26 new CCS systems identified by the Global CCS Institute are under development for the next 7 years, and the 326 that are not yet under development but which are being considered for future development are being discussed, the performance of CCS systems, but also of solar panels, wind turbines, batteries, electric vehicles, 'green' steelmaking equipment, novel CO_2-absorbing cement-making processes, and many other clean technologies will continue to improve, and their unit prices will continue to decline (IEA 2023).

As for bio-energy CCS (BECCS), it plays almost no economic role today, and according to IEA projections suggest it seems likely to play only a modest role in the future (see the Special Section on BECCS of this report). The reasons are that BECCS is an expensive way to generate electricity that relies on large-scale inputs of land and biomass that have multiple higher-value uses; moreover, life-cycle analyses as well as opportunity cost analyses show that BECCS projects can have dubious net carbon sequestration outcomes (Romm 2023, WWF/RSPB 2023, ETC 2021).

The IEA's World Energy Outlook 2023 scenario projected total global electricity generation in 2050 (see Table A.3c on p.279 in the 2023 WEO) at 76,838 TWh in 2050, of which 68,430 TWh from renewables (89% of the total), mostly from solar, wind, and hydro power, alongside 996 TWh from fossil fuels with CCUS (just 1.3% of the total). Of the 68,430 TWh renewable electricity, only 3,056 TWh is bioenergy (4% of total electricity generation in 2050), and of that, just 644 TWh is BECCS electricity (0.8% of total electricity, 21% of bio-energy electricity).

GOVERNMENTS ARE INVESTING IN CLEAN TECHNOLOGY TRANSITIONS

The prospect of accelerating new 'green' technologies that do not utilize fossil fuels, and that could in future provide low-emissions energy and low-emissions commodities like steel, cement, and chemicals at a price that could eventually – with sufficient technical development – be comparable to today's fossil fuels dependent production technologies, is why the European Union, in addition to investing in CCS infrastructure, is investing in 'green' technology, including via transition assistance packages for operators of fossil-fuels-powered industrial plants. The EU is deploying a variety of financial and policy instruments in support of this goal (often in combination with other goals, including economic development), such as the EU's Innovation Fund, the Green Deal Industrial Plan, the Just Transition Mechanism, Green Steel for Europe, the EU Chemical Industry Transition Pathway, the Net-Zero Industry Act (establishing the Net-Zero Europe Platform), the Strategic Energy Technology Plan (launched in 2007, updated in 2023), the Clean Energy Transition Partnership, and aspects of the RePower EU program, among others. Some of these instruments, e.g., the EU's Innovation Fund, offer prospective funding support for CCS/CCUS projects as well as non-fossil-fuels based 'green' technologies.

Other jurisdictions, e.g., the US and Canada, are developing their own policy and financial support frameworks for green technology development and deployment, including Inflation Reduction Act support for CCS/CCUS as well as non-fossil-fuels using 'green' technologies. Multilateral financial agencies are likewise intent on advancing realistic climate-friendly solutions compatible with economic growth.

Some non-fossil-fuels-using new industrial commodity production systems are earlier in their technology readiness level progression than is the case with renewable energy generation technologies (solar, wind, batteries) (which are already very cheap and still getting cheaper). Let's consider the steel industry as an example – the iron and steel sector is currently responsible for about 8% of global final energy demand and 7% of energy sector CO_2 emissions (including process emissions) (IEA 2020).

WHICH IS A MORE EFFICIENT USE OF SUBSIDY FUNDS: HELP STEELMAKERS TRANSITION TO GREEN STEELMAKING EQUIPMENT, OR FUND CCS RETROFITS TO COAL-BURNING STEEL PLANTS? AN OPEN QUESTION

'Green steel' production systems that use hydrogen instead of coking coal are still in their infancy. CCS has been deployed in steelmaking only to a very limited extent at a handful of pilot projects. Two questions arise: Which is cheaper at present – replacing a coking-coal-burning steel plant with a green hydrogen-based steel plant, or adding CCS to the existing plant? And which will likely prove cheaper in the longer run? In Europe, two demonstration projects are underway that could help provide some first-estimate answers to these questions.

The Hybrit project now in development in Sweden aims to produce fossil-free steel using green hydrogen. In contrast, ArcelorMittal is implementing CCS in a part of its operations at its steel plant in Dunkirk, France, under the rubric "3D DMX demonstration project," with an investment of around €215 million (approximately $240 million); the plan is to capture 0.5 million tons of CO_2 annually. At the same time, ArcelorMittal will replace part of its coking-coal-using steelmaking capacity at Dunkirk with two electric arc furnaces and a direct-reduction iron plant, investing €1.8 billion. The latter investment is projected to reduce the emissions of France's entire industrial sector by 6%.

A follow-on question arises: Given that only a limited amount of public subsidy money is available to support emissions mitigation in a given sector, e.g., steelmaking, is it more efficient to spend money on CCS projects (which could cost billions in capex for a full-scale CCS system aimed at capturing the bulk of emissions from a large industrial facility making steel or cement, as distinct from a small demonstration project), taking into consideration that CCS is a relatively mature technology with known high costs per ton of CO_2 emissions? – or to spend the subsidy money, instead, on scaling up demonstration projects for cleantech replacement technologies (such as steelmaking with green hydrogen) that do not use fossil fuels at all, taking into consideration that these new technologies are not as mature?

It seems plausible that if subsidy funds are limited, it will be worthwhile to assess, on a case-by-case basis, whether the better use of limited funds may be in funding demonstration projects that accelerate the progression of new green technologies along their technology readiness levels toward lower unit costs, if there is a prospect that the green technology may eventually, once it has attained technological maturity, be cheaper than the fossil-fueled technology (cheaper in cost per unit commodity output).

This should remain true unless detailed cost modeling demonstrates that there is no plausible pathway to developing non-fossil-fuels-using cleantech sets in a given sector that could eventually beat fossil-plus-CCS technology sets on unit price. I.e., if detailed future cost modeling shows that fossil-plus-CCS technologies in a given sector will always beat alternative non-fossil-fueled technology sets in that sector on price, then subsidies should flow toward fossil-plus-CCS. However, this does not appear to be the case in any known sector except possibly cement-making – not in power generation, metals production, or agriculture. For most sectors, cost projections indicate that new non-fossil-fuels-using technology alternatives will eventually outperform fossil-plus-CCS technology on levelized production costs.

SECTION 9: NATURAL GAS SUPPLY CHAINS IN A FUTURE CLIMATE POLICY CONSTRAINED WORLD

Natural gas is an extraordinarily useful and versatile raw material with a multiplicity of uses, of which generating about a quarter of the world's electricity supply is one, and providing nearly a quarter of the world's industrial process heat is another. However, mining and burning of natural gas may face severe constraints in a future climate-constrained global policy environment, not only because burning natural gas releases carbon dioxide, but also because molecules of methane, the main component of natural gas, have a much more powerful global warming potential (GWP) than molecules of CO_2. Some leakage from the natural gas supply chain is inevitable – and according to some technical studies, just 2 to 3% fugitive emissions can put the life-cycle GWP of natural gas on par with coal-burning. This means that even bio-methane is not necessarily a climate-friendly energy solution, and fossil natural gas is often worse than coal in GWP terms, because natural gas leakage rates are routinely well above 2%.

Excess anthropogenic methane currently causes about 30% of global heating impact, according to IEA's Global Methane Tracker 2022. While global atmospheric CO_2 levels are up by 52% compared to the pre-industrial level (420 ppm CO_2, up from 277 ppm (parts per million) in the year 1750 CE), atmospheric methane has nearly tripled, from 722 ppb (parts per billion) in 1750 to 1931 ppb in early 2024.

Methane leakage from the natural gas supply chain must therefore be considered when evaluating the technical potential of natural gas to serve as a relatively low-cost transition fuel that, in the absence of fugitive emissions, might have reduced global warming impact as the world moves away from burning coal and oil for power and heat and toward renewable or nuclear sources.

However, these concerns do not necessarily mean that climate policy will foreclose natural gas utilization. Carbon capture and storage (CCS) of post-combustion emissions is one technical option for mitigating the climate warming impact of natural gas utilization, and while it is expensive, in some applications it may prove cost-effective.

Another way to use natural gas in a climate-friendly way is as an input into a carbon dioxide removal (CDR) technology via the 'lime cycle.' This can involve burning cheap, stranded natural gas to heat limestone (calcium carbonate), 'calcinating' it to make quicklime (calcium oxide) and CO_2, capturing and geologically storing the CO_2 released from the heating process using CCS technology, then hydrating the quicklime with a water to make calcium hydroxide (hydrated lime), and finally exposing the hydrated lime to atmospheric CO_2, which turns the lime back into limestone; and then repeating the entire process. Variations on the 'lime cycle' approach to carbon removal are in development by carbon removal startups Heirloom Carbon (USA) and Origen Carbon (UK). Using 'stranded' natural gas in remote locations for heating the limestone can have the advantage of low energy cost.

This single application – carbon removal via the lime cycle – has significant potential as a future major source of demand for natural gas because the potential future scale of the global carbon removal market is very large, as we saw in Section 2.

According to Origen Carbon, life cycle analysis (LCA) shows that their process results in net carbon removal from the atmosphere, even when natural gas is burned to provide the energy input (provided the CO_2 emissions from burning the natural gas are captured and stored). Note that other heat sources, including renewable energy, can also be used as inputs in the process – natural gas is only one possible source of the required heat input. The LCA for Origen's lime cycle process should be similar to that for ocean liming.

A third climate-friendly way to use natural gas is to produce "turquoise hydrogen," i.e., hydrogen produced via pyrolysis of methane, which is the subject of the following subsection.

Provided that fugitive methane emissions from the natural gas supply chain are strictly and successfully mitigated, all three pathways – combustion of natural gas plus CCS; use of stranded natural gas to provide heat for lime-cycle carbon removal; and turquoise hydrogen production – offer technically interesting ways to make low-climate-impact use of natural gas.

Note, however, that even relatively climate-friendly uses of natural gas will be faced with competition from non-fossil-fuels based alternative technologies in a future climate policy constrained world. As an example of competition between natural gas plus CCS versus non-fossil-fueled alternative technologies, consider industrial process heat. Among its many uses, natural gas combustion is very widely used to generate heat for industrial processes. Process heat applications of natural gas could be equipped with CCS to provide mitigate their climate impact. However, as previously noted, CCS systems are expensive to build and operate. Recently developed 'hot bricks' thermal energy storage systems, which store excess renewable energy produced when solar or wind power supply exceeds immediate demand, could eventually replace some high-temperature applications in which natural gas currently supplies industrial process heat.

Unexpectedly rapid declines in the cost of renewable energy equipment and other non-fossil-fuels-based technologies appear to be narrowing the economic window for transition applications of natural gas. In some regions, electricity from solar or wind energy backed by energy storage systems already now can cost-competitively replace natural gas or coal for power generation, including for peak demand periods ('peaker plants'), even where coal and gas power plants are not burdened by carbon capture and storage (CCS) obligations. Natural gas fired power plants burdened with CCS are therefore likely to have difficulty competing in price per MWh against power generated by combinations of solar PV, wind turbines, batteries, and other energy storage devices.

The remainder of this section examines methane pyrolysis as an emerging pathway for utilization of natural gas as the key input into a relatively low-cost pathway for making low-climate-impact hydrogen.

TURQUOISE HYDROGEN: AN EMERGING PATHWAY FOR NATURAL GAS UTILIZATION WITH LOWER CLIMATE IMPACT

As hydrogen demand rises, supply will rise to meet the demand. "Turquoise hydrogen" is hydrogen produced via pyrolysis of methane, with solid carbon black (elemental carbon in solid form) as a byproduct. Turquoise hydrogen avoids much of the global warming impact normally associated with natural gas combustion or with steam methane reforming, the conventional, high-CO_2-emissions way of producing hydrogen. This is interesting because of the many prospective uses for hydrogen in multiple industries, e.g., for generating industrial process heat or as an input for chemical synthesis. Pyrolysis of natural gas may be a cheaper way to produce low-climate-impact hydrogen than "green" hydrogen produced via electrolysis of water, according to a June 2024 report by Hydrogen Europe and a 2023 analysis by the India's CEEW (Council on Energy, Environment, and Water).

The process of turquoise hydrogen production emits much less CO_2 than steam methane reforming, the standard existing way of producing hydrogen from natural gas. Turquoise hydrogen thus deserves special mention as a potential game-changer for the natural gas industry as it faces increasing pressure to reduce Scope 1, 2, and 3 emissions.

While the amount of useful energy inherent in the hydrogen produced via methane pyrolysis is only half that of the methane from which it was produced, the turquoise hydrogen production process may become a cost-effective and energy-efficient way to produce low-emission hydrogen. It also produces a potentially marketable byproduct in large quantities: carbon black. Today, carbon black is used in making tyres and inks, among other uses. In future, given a large, cheap supply via the methane pyrolysis process, carbon black could find many other uses, e.g., as an additive to asphalt that improves its performance on hot days, or to concrete and other construction materials to enhance their strength, durability, and conductivity.

For natural gas wells far from a pipeline, it may be useful to operate modular Haber-Bosch ammonia (NH_3) production facilities to turn the 'turquoise' hydrogen generated into ammonia (a key ingredient of fertilizer) on-site at the natural gas well-head, thereby generating a relatively easily transportable marketable product (instead of trying to ship H_2 via pipeline or as a compressed gas, which is more expensive than shipping ammonia).

Turquoise hydrogen could thus prove to be an interesting opportunity for the natural gas industry. Considering the wider supply chain, Ingale et al. (2022) estimated that turquoise hydrogen production could attain 70% lower emissions than steam methane reforming, which releases large amounts of CO_2 per unit of H_2 produced. This would be significantly better than the estimated 50% reduction of emissions that can be attained by "blue hydrogen," i.e, production of hydrogen from steam methane reforming plus capture and storage of the consequent CO_2 emissions. However, since hydrogen and methane released to the atmosphere both have global warming impacts, life-cycle analysis suggests that stringent leakage avoidance will be necessary if climate impact mitigation benefits are to be achieved via blue or turquoise hydrogen.

The direct greenhouse gas impact of a natural gas supply chain devoted to turquoise hydrogen production does depend in part on fugitive methane emissions, which could be minimized with due attention to detail. Mixing biogas (methane from decomposing biomass) as an input to the turquoise hydrogen production process, along with fossil natural gas, could further reduce the net greenhouse warming impact, again depending on how carefully fugitive emissions are avoided.

PROS AND CONS OF TURQUOISE HYDROGEN

Pros: Produces valuable products: hydrogen and carbon black. Lower CO_2 emissions compared to conventional 'grey' hydrogen production via steam methane reforming. Prospectively a lower-cost way of producing low-emissions hydrogen than 'green' hydrogen made via electrolysis of water with renewable electricity as the key input.

Cons: Limited commercial deployment so far. Unclear whether the large quantities of carbon black produced will find marketable uses. Transporting solid carbon black from remote natural gas production or pyrolysis sites to potential markets for carbon black could be challenging. Some remaining fugitive methane emissions and hydrogen emissions will cause climate impacts from operation of natural gas wells.

A note on terminology: While the term 'CCUS' generally denotes capture of gaseous carbon dioxide and its subsequent utilization and/or storage, it can encompass any form of hydrocarbon processing that enables hydrocarbon resource utilization whilst preventing its carbon content from affecting the climate. This applies to turquoise hydrogen production. The solid carbon black byproduct of the turquoise hydrogen production process can be considered a form of CCUS. Carbon black can used as an input into various production chains, e.g., asphalt production. Alternatively, where no viable market demand can be accessed or developed (if the turquoise hydrogen production site is too far from any existing market for carbon black), the carbon black could, in principle, be stored on-site by heaping it into discard piles or burying it. In that case, this is a form of natural gas utilization with carbon capture and storage, CCS.

SECTION 10: BIO-ENERGY CARBON CAPTURE AND STORAGE, BECCS

INTRODUCTION TO BECCS

Bioenergy with Carbon Capture and Storage (BECCS) is a process that involves growing biomass, burning it to produce energy, and capturing and storing the resulting CO_2 emissions. BECCS has been proposed as a large-scale carbon dioxide removal (CDR) method in many net-zero scenarios in Integrated Assessment Models (IAMs).[4] However, recent evaluations suggest that its net CDR potential has been overstated and its ecological impact understated or in some cases ignored. Optimistic projections of BECCS' net carbon removal potential do not appear to be based on careful life-cycle analysis of its environmental impacts.

The following assessment draws on findings from several reports, including "Bioresources within a Net Zero Economy" prepared for the Energy Transitions Commission (2021), "Biomass in a Low-Carbon Economy" for the UK Climate Change Committee (2018), "BECCS deployment: The risks of policies forging ahead of the evidence" (2021) for Chatham House, a 2023 report entitled "Why scaling bioenergy and bioenergy with carbon capture and storage (BECCS) is impractical and would speed up global warming" by Dr. Joe Romm (U.Penn.), a 2022 report by the European Academies Science Advisory Council's Joint Research Centre entitled "Forest bioenergy update: BECCS and its role in integrated assessment models (IAMS)", and IPCC Assessment Report 6. An inference from these several sources' assessments of BECCS can be summarized at the outset:

Contrary to assumptions built into many IAMs that BECCS will deliver several $GtCO_2$ annually by mid-century, it may turn out that BECCS will not attain Gigaton scale, due to a high financial cost per ton of carbon removed and per MWh of electricity produced, large land requirements and environmental impacts per ton of carbon removed, dubious life-cycle net CO_2 impact per ton of biomass (depending on biomass source, transport distances, and other details), multiple competing higher-value uses for productive land and biomass, and low social license.

This picture could perhaps change in favor of BECCS if future large-scale bioenergy crop plantations are grown on marginal land that was not previously productive, such as semi-desert land watered by desalinated seawater and fertilized using high-efficiency systems as proposed by Caldera and Breyer 2023 in "Afforesting arid land with renewable electricity and desalination to mitigate climate change," or if BECCS relies on biomass from seaweed or kelp plantations grown in the oceans. However, here again, multiple competing uses for that biomass will likely exist. For example, one potential use of biomass for carbon sequestration is conversion of biomass to biochar to provide soil amendments or as input for durable products, e.g. asphalt or other building materials.

Waste biomass with few or no other uses, e.g., waste from municipal water treatment facilities, could be used to generate industrial process heat. For example, waste biomass can supplement coal in cement-making. One review (Kusuma et al. 2022) found that 20–30% of fossil fuels can be replaced with biofuels in cement-making facilities with minimal capital investments. The percentage of biomass can be enhanced with investments enabling pre-processing of biomass and process optimization. Clinker substitution with biomass ash can be in the range of 3–80%.

As of 2019, just five BECCS projects were in operation around the world, collectively capturing about 1.5 million tons of CO_2 per year, according to a report by the Global CCS Institute, "Bioenergy and Carbon Capture and Storage." As of 2022, a report by Energy Futures Initiative, "Surveying the BECCS Landscape," lists 16 BECCS projects in operation globally.

The image below shows a schematic of a bio-energy carbon capture and storage process, BECCS, similar to that of the controversial Drax power plant in Yorkshire, UK, which has plans to burn through 8 million tons of wood pellets per year. The basic BECCS approach is to burn biomass in a thermal power plant, capture the resultant CO_2 emissions using CCS equipment, and dispose of the CO_2 in permanent storage, e.g. by pumping it into saline aquifers deep underground.

Whether the process succeeds in achieving a net reduction in atmospheric carbon can be estimated by life-cycle analysis. It depends on the quantity of emissions caused by growing, harvesting, transporting, and processing the biomass used as input. It also depends also on the opportunity costs of using the land and biomass for BECCS. For example, if a BECCS power plant is fueled by wood pellets made from trees cut from a plantation or forest that was growing and adding biomass at a faster rate than a newly planted post-clearcut plantation, there is an opportunity cost in foregone carbon sequestration imposed by turning the forest into wood pellets. Additional carbon costs are imposed by disturbing soils and increasing soil organic matter decomposition. Beyond the net carbon impacts, removing trees or other biomass for burning in BECCS plants has impacts on biodiversity and amenity values.

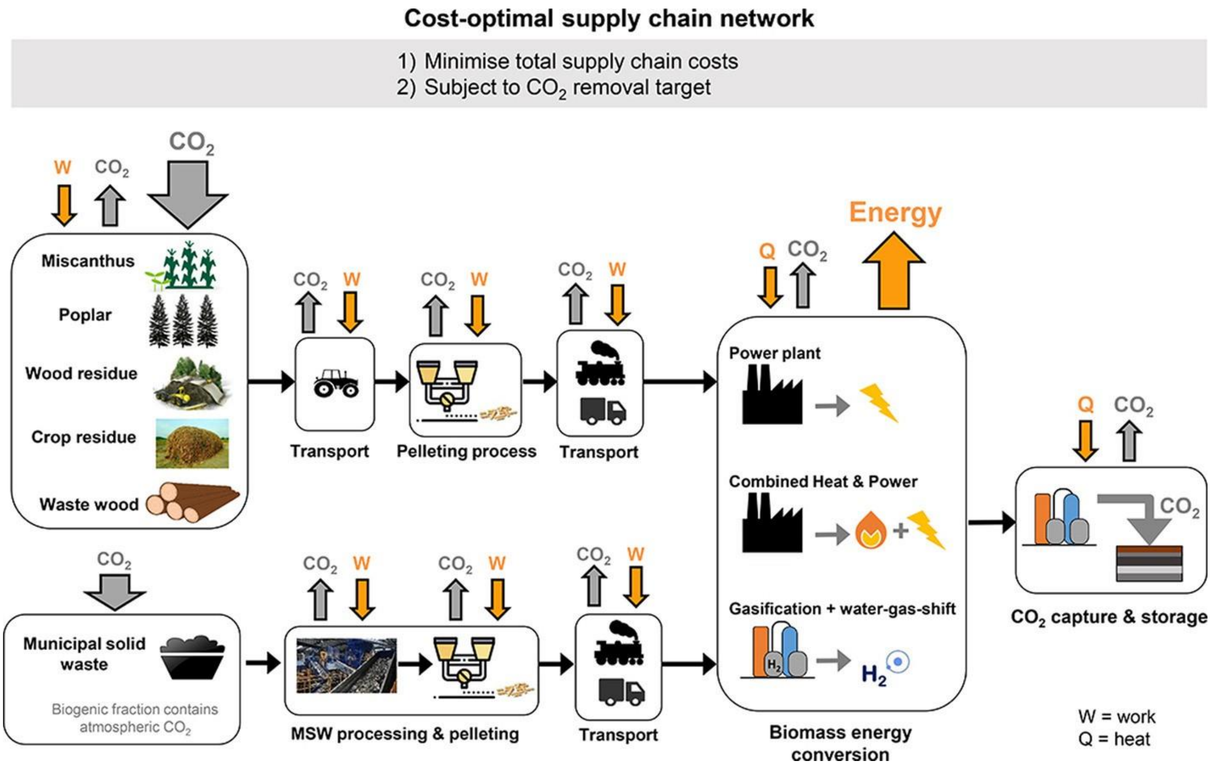


Image source: Bui et al. 2021, "Delivering carbon negative electricity, heat and hydrogen with BECCS – Comparing the options."

ASSESSMENT OF BECCS: BIOENERGY WITH CARBON CAPTURE AND STORAGE

A 2022 report by the European Academies Science Advisory Council's (EASAC) Joint Research Centre entitled "Forest bioenergy update: BECCS and its role in integrated assessment models (IAMS)" concludes that burning wood pellets tends to result in net CO_2 increases for several decades, due to the impacts of stopping further CO_2 absorption by cutting down trees that had been growing, and exposing forest soils to decomposition. The report criticizes IAMs' over-reliance on projections of large-scale BECCS deployment despite the paucity of real-world BECCS field trials to date and the lack of quantitative life-cycle assessments demonstrating the positive climate impact of BECCS.

The EASAC report concludes that: "**policy should avoid favoring BECCS** and proceed first on the cost-effective, nature-based solutions described by Griscom et al. (2017), while proceeding with research and demonstration across all potential means of CDR, including enhanced weathering and DACCS." Brack and King (2020) came to the same conclusion with their recommendation that the assumption that BECCS is the pre-eminent carbon removal solution should be abandoned, and BECCS should be analyzed – alongside all other NETs – based on full life-cycle carbon balances. The assumption that biomass feedstock is inherently carbon-neutral should be dropped.

There are several compelling lines of evidence in support of this conclusion, as follows.

Future demand for biomass will outstrip supply by a ratio of 11:1 to 16:1, according to an estimate from the UK Climate Change Committee in their 2018 report "Biomass in a Low-Carbon Economy."
In 2023, in a report entitled "Buyers' Guide to Sustainable Biomass Sourcing for Carbon Dioxide Removal: Mitigating the risks of biomass-based carbon dioxide removal contracting," the US consultancy Carbon Direct reinforced the point that a massive demand/supply imbalance will arise in coming decades.

IPCC AR6 reviewers note in Table TS.7 of WGIII's Technical Summary in the "Risks and Impacts" column that "inappropriate deployment of BECCS at very large scale leads to additional land and water use to grow biomass feedstock, and biodiversity and carbon stock loss from unsustainable biomass harvest." In the "Trade-offs and Spillover Effects" column, they note that BECCS entails "competition for land with biodiversity conservation and food production." They added: "The use of bioenergy can lead to either increased or reduced emissions, depending on the scale of deployment, conversion technology, fuel displaced, and how, and where, the biomass is produced." AR6 authors estimated that just 1.6 $GtCO_2eq/yr$ of carbon could be removed via BECCS in a way that is economic.

A comprehensive 2023 assessment of BECCS by Dr. Joe Romm (U. Pennsylvania) puts the land use impact into perspective: scaling up BECCS to 2 or 3 $GtCO_2$ per year would require a land area the size of India wholly dedicated to bio-energy crops. Allocating land to bio-energy plants rather than letting trees and soils store carbon on the same land could actually *increase* net global CO_2 emissions for several decades.
An analysis by Quiggin (2021) for Chatham House concludes with similar warnings against optimistic projections for the scalability of BECCS and warns of its enormous land use implications.

Limited available biomass will have to be allocated to highest priority uses. This point was underlined in a report published by the Energy Transitions Commission (ETC), a global consortium of energy business leaders, entitled "Bioresources within a Net-Zero Emissions Economy: Making a sustainable approach possible." According to the ETC report, CDR applications such as BECCS or wood vaulting (BiCRD) are unlikely to be counted among the highest-value uses for biomass in a future supply-constrained world. From p.93 of the ETC report:

> **"Dedicated land use for energy crops would require about 500,000 km^2** (i.e., an area about 700 km x 700 km or 50 Mha, **equivalent to the size of Spain) to sequester 1 $GtCO_2$ each year via BECCS** (bioenergy carbon capture and storage)/BiCRS (biomass carbon removal and storage).
> If the source of biomass for BECC/BiCRS was instead **forest residues,** which makes up the bulk of the supply in our prudent case, then a forest managed for stemwood production (i.e., focused on materials) of **five times this size** might be required to produce enough residues to sequester **1 $GtCO_2$ each year."**

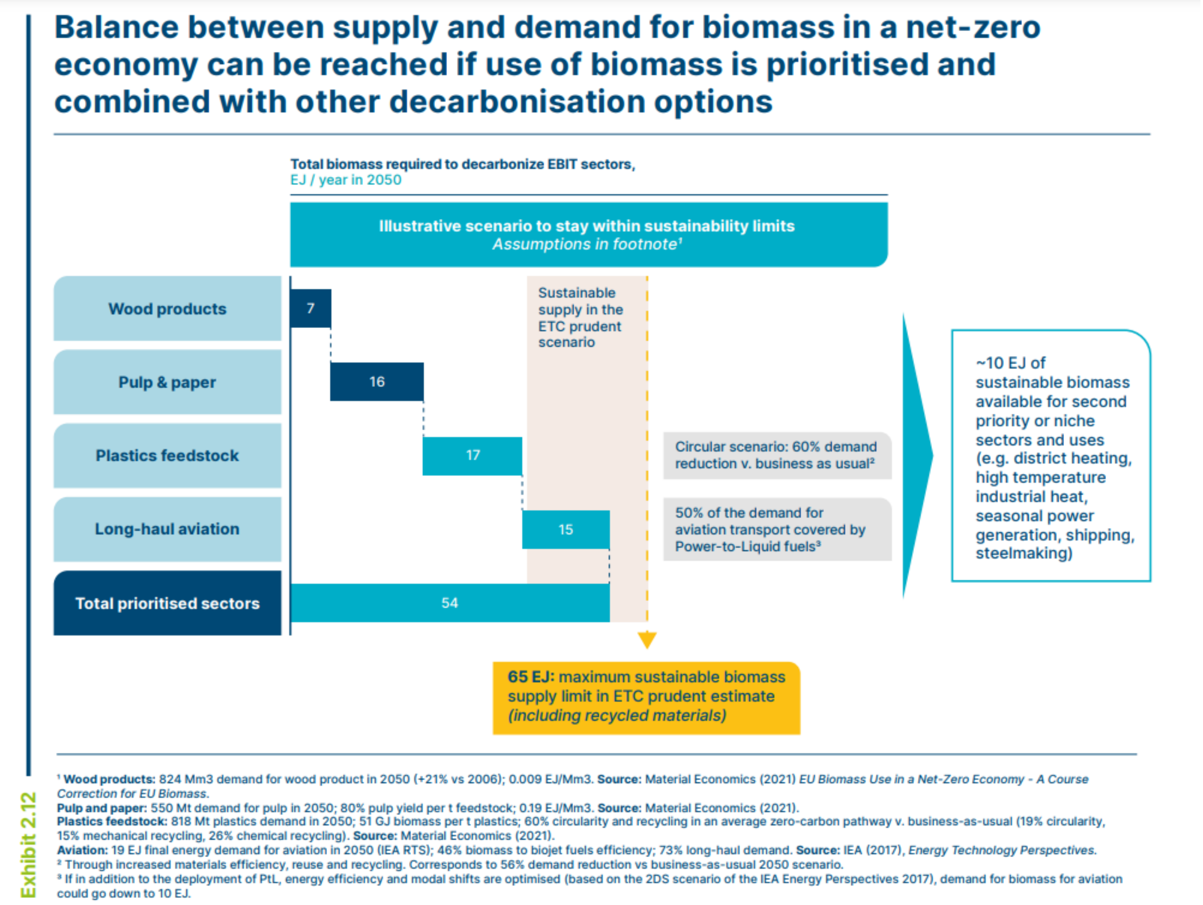
To repeat: An area the size of Spain *entirely dedicated to producing wood for BECCS* would deliver just one $GtCO_2$ per year. Amassing enough forest residue from logging operations (sawdust, branches, etc.) to deliver one $GtCO_2$ per year, whilst using the logs for other purposes (construction lumber, etc.), would require an area five times the size of Spain.

The Energy Transitions Commission notes that by 2050, the potential global demand for biomass for CDR and industrial uses could far outstrip supply (by an order of magnitude), given the wide range of categories of demand. This implies a need to prioritize biomass uses (to identify highest priority uses, for which better alternatives are unavailable). The report distinguishes two overall categories for using biomass: as a material or feedstock, or as an energy source.

The ETC report assesses the highest uses of biomass and concludes that **with the single exception of sustainable aviation fuel (SAF), biomass should not be used for energy production.** Instead, "materials and chemical feedstocks are the highest-value uses of bioresources," and "resource efficiency, in particular the use of land, in all cases argues in favor of electrification-based routes [including solar or wind energy production, rather than production of energy from biomass] if these are available."

The ETC report argues against BECCS and more broadly against bioenergy as an energy solution, noting that "most current applications of bioenergy – in particular in road transport and bulk power generation – will be uneconomic versus [renewable] electricity or [green or turquoise] hydrogen in the coming years." Exhibit 2.4 on p.64 of the report shows that **for energy supply in industrial, transport, and power & heating applications, "bio-based options are ~8-70x more land intensive than all alternative decarbonization options."**

The figure below shows the expected highest-priority uses of biomass according to ETC's assessment. In their view, by mid-century, 54 EJ of biomass will be allocated annually to wood products, pulp & paper, bioplastics feedstocks, and SAF for long-haul aviation, out of a total "prudent estimate" of 65 EJ of sustainable global biomass supply. That leaves just 11 EJ for all other uses, such as biofuels for non-aviation sectors, steelmaking, and high-temperature industrial heat.



Balance between supply and demand for biomass in a net-zero economy can be reached if use of biomass is prioritised and combined with other decarbonisation options

[1] **Wood products:** 824 Mm3 demand for wood product in 2050 (+21% vs 2006); 0.009 EJ/Mm3. **Source:** Material Economics (2021) *EU Biomass Use in a Net-Zero Economy - A Course Correction for EU Biomass.*
Pulp and paper: 550 Mt demand for pulp in 2050; 80% pulp yield per t feedstock; 0.19 EJ/Mm3. **Source:** Material Economics (2021).
Plastics feedstock: 818 Mt plastics demand in 2050; 51 GJ biomass per t plastics; 60% circularity and recycling in an average zero-carbon pathway v. business-as-usual (19% circularity, 15% mechanical recycling, 26% chemical recycling). **Source:** Material Economics (2021).
Aviation: 19 EJ final energy demand for aviation in 2050 (IEA RTS); 46% biomass to biojet fuels efficiency; 73% long-haul demand. **Source:** IEA (2017), *Energy Technology Perspectives.*

[2] Through increased materials efficiency, reuse and recycling. Corresponds to 56% demand reduction vs business-as-usual 2050 scenario.

[3] If in addition to the deployment of PtL, energy efficiency and modal shifts are optimised (based on the 2DS scenario of the IEA Energy Perspectives 2017), demand for biomass for aviation could go down to 10 EJ.

Figure source: p. 83 in "Bioresources within a Net-Zero Emissions Economy: Making a sustainable approach possible," Energy Transitions Commission, July 2021.

NOVEL BIOMASS SOURCES FOR NET CARBON SEQUESTRATION

There is a possibility that biomass in the form of micro-algae grown in seaside saltwater ponds in low-value locations (e.g. empty stretches of coastal Mauritania) or macroalgae (kelp) grown in floating offshore kelp farms could provide a source of biomass for BECCS with less fraught implications for land use. However, here again, there are alternative, potentially higher value bio-economy uses for microalgal and kelp biomass. Moreover, a review by Pessarrodona et al (2024) show that unless and until the kelp farming supply chain (which is currently dependent on diesel fuel) is comprehensively defossilized, there will be no net carbon sequestration benefit to kelp farming.

Another interesting option for generating large quantities of biomass has been proposed by Caldera and Breyer (2023) in "Afforesting arid land with renewable electricity and desalination to mitigate climate change." They estimated that if RE-powered desalination plants were used to irrigate forests on arid land over the period 2030–2100, cumulative CO_2 sequestration potential of 730 $GtCO_2$ could be achieved during the period, at a global average cost of €457 per tCO_2 in 2030 but decreasing to €100 per tCO_2 by 2100, driven by the decreasing cost of RE and increasing CO_2 sequestration rates of the forest plantations. Regions closer to the coast with abundant solar resources and cooler climate show the lowest costs, as low as €50 per tCO_2 by 2070. The authors of the study note that these CDR quantities for afforestation of arid lands are theoretical maxima, and offer many caveats in their paper. However, if 15% of the maximum potential were realized, i.e. about 110 $GtCO_2$ cumulatively by 2100, that would already be a substantial contribution.

In conclusion: BECCS will likely play a role in future CDR, but not a large role. Very large areas of land would be required to grow dedicated bio-energy crops for BECCS in quantities sufficient to obtain even 1 $GtCO_2$, and in most cases, that land could be more efficiently used for other purposes. For example, far smaller amounts of land devoted to solar photovoltaic (PV) panels, wind power, or agrivoltaics would generate more electricity at a lower financial and ecological cost.

Available surplus waste biomass could in some cases be cost-effectively used to provide bio-energy for heat or power, and in other cases, it could be better utilized by converting it into durable products, e.g. wood/bio-epoxy composites, or into biochar, which sequesters carbon in the soil and improves soil health, rather than transporting it to BECCS facilities for incineration.

Despite these caveats, it remains possible that some biomass grown on marginal lands and some forms of organic waste, e.g. municipal waste, could be cost-effectively processed via BECCS, subject to case-by-case evaluations.

SECTION 11: SOURCES OF INFORMATION ON CDR METHODS, CDR R&D ROADMAPS, KEY R&D INSTITUTIONS, CDR PROJECTS, AND STARTUPS

The research community and scientific literature on CDR methods is rapidly growing, as are CDR research communities and startup ecosystems, especially in North America and Europe. This section provides an overview of some of the key sources of information on CDR and identifies some groups and networks. It is not a comprehensive listing.

Reference Texts on CDR: Three key reference texts were used in the preparation of this report, covering a full range of currently known CDR methods. Each was written by teams of leading experts. One is the online publication "CDR Primer" (2021), edited by Jennifer Wilcox, Ben Kolosz, and Jeremy Freeman. Another is "Greenhouse Gas Removal Technologies" (2022), edited by Mai Bui and Niall Mac Dowell; it is part of the Energy and Environment series of reference works published by the UK Royal Society of Chemistry. A third is the online publication "The State of Carbon Dioxide Removal" First Edition, 2023, the content of which was summarized by its lead authors in a post on CarbonBrief.org. (A Second Edition of the State of CDR Report, as it is informally known, was released on June 4, 2024.) The State of CDR Report summarizes the current state of the basket of nascent CDR industries. The Negem Project (negative emissions project), an EU-funded research project for "assessing the realistic potential of carbon dioxide removal and its contribution to achieving climate neutrality," was another source.

Many other sources also informed this report, some of which are linked in the table in this report entitled "Categories of CDR methods and their estimated scalability" (see 'Sources' column at right in that table). The table provides estimates of the maximum theoretical and realistic potential scalability of each category of CDR method. Note that these estimates are highly uncertain, contested, and likely to be superseded by revised estimates in coming years, as CDR research continues.

Two illustrations from IPCC Assessment Report 6 (AR6) of 2022 provide basic information about CDR methods are a fact sheet and a taxonomy. Please click to view.

A well-curated online course on CDR is the Carbon Removal Academy section of the Climate Change Academy. Another learning resource is the CDR Academy, a set of curated publications and webinars. CO_2RE maintains a useful CDR explainer section on its website. A German CDR research consortium maintains a comprehensive, constantly updated global streaming CDR news tracker.

An interesting new tool is CDRai, a Large Language Model (AI LLM) trained exclusively on high-quality sources of information on CDR. The underlying LLM is the Claude 3.5 Sonnet LLM.

Global CDR Technology Development Roadmaps: Ocean Visions, a global network of leading ocean CDR research centers, is on a mission to assess marine CDR methods by 2030 and has published a corresponding marine CDR roadmap. RMI, a US-based NGO, published an Applied Innovation Roadmap for CDR in 2023. Mission Innovation, a global forum for governments that is focused mainly on clean energy innovation, includes a CDR Mission; in 2022, they published a report entitled "CDR Technology Roadmap: Innovation gaps and landscape analysis." In 2022, the US National Academies Press published a "Research Strategy for Ocean-Based Carbon Dioxide Removal and Sequestration."

A set of two 'Perspective' articles published in the journal Frontiers in Climate (2022) provide a thorough look at technical (non-biology-based) CDR methods. They are "Geochemical Negative Emissions Technologies: Part I. Review," and "Geochemical Negative Emissions Technologies: Part II. Roadmap."

The US National Academies of Sciences, Engineering and Medicine in 2021 published "A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration (2021)."

CDR Governance: SWP, a German think-tank, compared US, European, and Chinese CDR governance landscapes in a Nov. 2022 report. A World Resources Institute (WRI) paper from 2023 explores international governance of technological CDR. Prof. Wil Burns, a leading expert on CDR legal frameworks, explored governance of ocean-based CDR in a 2023 paper. The Institute for Responsible Carbon Removal is a unit of the American University in Washington DC focused on governance, law and policy relevant to CDR; many relevant publications and webinars can be found on its website.

CDR Credits, CDR Markets, and CDR Financing: A useful review of design options for institutional CDR financing methods by Sebastian Manhart of CarbonFuture, a carbon crediting MRV process company (MRV: monitoring, reporting, and verification of carbon credits), entitled "Strategic financing paths for scaling carbon dioxide removal" (2024) provides an overview of seven possible CDR crediting and financing approaches. These come in three categories: compliance markets; public procurement; and fiscal incentives.

Hickey et al. (2023), "A review of commercialization mechanisms for carbon dioxide removal," provides a thorough overview.

ICAP, the International Carbon Action Partnership, a forum for governments intent on developing cap-and-trade emissions trading systems, publishes useful documents on emissions trading and CDR market design (removals trading).

CDR public procurement can take several forms, including (i) direct procurement, (ii) feed-in tariffs, or (iii) contracts for difference. Government can set CDR prices either by implementing reverse auctions or by administrative price-setting based on technical analysis. See Hickey et al. (2023) or, in briefer form, Manhart for details.

Fiscal incentives are tax breaks given to companies for investing in a project (here, CDR). This is a principal tool used in the USA. Section 45Q of the US tax code has since 2008 offered performance-based tax credits for CCS, CCUS, and CDR projects, and enlarged these in 2018. The Inflation Reduction Act of 2022 further expanded the scope of 45Q credits for CCS, CCUS, and CDR projects (see Oxford Institute for Energy Studies analysis (2023).

CDR compliance markets can be set up by integrating CDR into Emissions Trading Systems (ETS), e.g. in Europe, the European Union's Emissions Trading System. According to the Carbon Gap Policy Tracker, the EU ETS does not yet encompass CDR, but it likely will do so in future: the European Commission is set to report, by 2026, on how negative emissions could be accounted for and covered by emissions trading. That said, the Innovation Fund, a key source of EU support for nascent carbon removal projects amongst several other clean technologies, is funded by auctioning of ETS allowances. At 75 euro/tCO_2, the ETS is set to provide some €38 billion from 2020 to 2030 to the Innovation Fund, some portion of which will likely be allocated to CDR projects.

Alternatively, CDR compliance markets could be set up via new, separate Removal Trading Systems (RTS). No RTS exists yet. An RTS would entail creating a dedicated compliance market where removal credits can be traded. An RTS imposes an obligation on certain sectors to achieve a specific level of CO_2 removal, thereby incentivizing the development and use of CDR technologies through market dynamics. CarbonFuture analysts suggest that a stand-alone RTS is preferable to inclusion of CDR into ETS so as to ensure ETS incentives for defossilization of industries are not weakened by mixing with CDR incentives. Failing that, if the European Union decides to incorporate CDR into its ETS, they suggest an intermediary institution in the form of a European Carbon Central Bank be established as a buffer between the emissions trading market and carbon removal market (as per Edenhofer et al. 2023, "On the governance of carbon dioxide removal – a public economics perspective").

The Ecologic Institute prepared a 2023 report for the German federal government looking ahead to the EU's 2040 climate targets, exploring how CDR can be governed and financially incentivized. The report examines the ETS, RTS, and Carbon Central Bank options, among other topics.

An Open Letter to the European Commission signed by 116 academics, businesses, civil society organizations, and research institutions urged the EU to separate emissions reductions, land-based sequestration, and permanent carbon removals in the EU's post-2030 climate framework. This separation, they wrote, should be at the heart of both the setting and the implementation of the 2040 target and associated plans. This separation could prevent companies from using up the limited amounts of land available in Europe for reforestation or wetlands restoration projects to claim offset credits for emissions that could readily be avoided instead of offset. Emissions mitigation and CDR are two different things. CDR should be used primarily for remedial cleanup of past (historical) excess CO_2 emissions and so reduce atmospheric carbon levels, not as a mechanism to offset continuing emissions from fossil fuels use, except in edge cases where those emissions cannot feasibly be avoided or abated at source, e.g. in the case of emissions from jet fuel combustion in aircraft. The tripartite approach recommended in the Open Letter also recognizes that novel CDR methods will be needed (beyond land-based nature restoration), and that these will require separate investment for their development. This is why the authors recommended three separate EU mandates and administrative structures governing and funding emissions reductions, land-based sequestration, and novel CDR methods.

Whatever the form decided on for future CDR compliance markets, it will be necessary to ensure that carbon removals are properly measured and certified. The European Union announced in February 2024 established a Carbon Removals Certification Framework, CRCF, for certification of permanent carbon removals, carbon farming, and carbon storage in products. It applies only to activities within the European Union. CRCF will help European farmers and businesses to monetize CDR activities.

A Carbon Central Bank in support of an RTS is not to be confused with economist Kenneth Rogoff's interesting proposal for the creation of a World Carbon Bank to fund the transition away from fossil fuels in developing countries. An early focus of the latter would be to pay coal-fired power station operators to replace their equipment with renewable energy power generation equipment, because coal accounts for 30% of global CO_2 emissions.

Global CDR Markets, CDR Corporate Networks, and Startup Businesses: A database of existing American and European CDR projects, many of them conducted by startup companies, is maintained by CarbonPlan, a US-based NGO. CDR.fyi, a volunteer-driven data NGO, tallies CDR investment deals and market activity. IDTechEx offers a 2023-2040 CDR markets forecast (paywall). The World Business Council on Sustainable Development offers a handbook for companies looking to buy carbon offsets.
Several CDR corporate business associations exist. The Carbon Business Council is a trade association of CDR and CDR-related companies (mostly startups). The Carbon Removal Alliance is another association of companies working on CDR methods. The Carbon Removal Partnership is a third; unlike the others, it is Global South focused. The Negative Emissions Platform is Europe-focused, with its HQ in Brussels.
Frontier Climate is an association of major companies (e.g. Stripe, Frontier's initiator, along with Alphabet, Meta, JP Morgan Chase, Shopify, and several others) that have pooled money under an "advance market commitment" framework – i.e. they buy tons of CO2 from CDR companies and pay in advance of delivery, often years in advance, as a way of providing non-equity-diluting financing for CDR startups.
Microsoft is another major corporate CDR funder. Microsoft deploys its CDR funding independently through its Microsoft Carbon Removal unit.

Chinese megacorporation TenCent is supporting CDR startups financially through its CarbonX program. None of the 13 winners of the first round of CarbonX prizes announced in May 2024 are based in China (8 are based in USA, 2 in Canada, 2 in UK, 1 in Switzerland), suggesting that China's CDR business development ecosystem remains undeveloped or absent.

The 13 winning companies were Climeworks (Zurich, Switzerland), CarbonCure Technologies (Halifax, Nova Scotia, Canada), Charm Industrial (San Francisco, California, USA), Running Tide (Portland, Maine, USA), Heirloom Carbon (San Francisco, California), Pachama (San Francisco, California), Project Vesta (San Francisco, California), Planetary Technologies (Dartmouth, Nova Scotia, Canada), Global Thermostat (New York, USA), Silicate Carbon (London, UK), Opus 12 (Berkeley, California), Carbon Clean Solutions (London, UK), and Prometheus Fuels (Santa Cruz, California).

There were about 300 entrants in the CarbonX competition. Note that the total prize money at stake was minor: TenCent put up RMB 200 million (or $28 million) for the first three years of CarbonX. The fact that such a small volume of prize money generated so much interest is another reminder that the CDR industry remains at a very early stage of development. The global CDR startup ecosystem will need more financial inflow to push CDR methods, technologies, and supply chains along their learning curves and scale them up from their very small scale today to multiple Gigatons per annum over the next two decades.

CDR Professional Networks: In addition to associations of companies in the CDR space (several of which are noted above), there are professional associations and peer support networks for people working in CDR. OpenAir Collective is a volunteer-driven global network focused on advancing carbon removal technologies and policies through grassroots action and open-source collaboration. AirMiners is a network of >1,600 people involved in CDR startups or looking for CDR careers; it includes online discussions and AirMiners BootUp, an accelerator program for CDR startup entrepreneurs.

US CDR Policy and CDR R&D: The Rhodium Group released a report in April 2024 on the US CDR policy landscape entitled "The Landscape of Carbon Dioxide Removal and US Policies to Scale Solutions." Resources for the Future, an NGO, has issued a report in 2024 on US CDR policy, "Policy incentives to scale CDR removal: Analysis and recommendations" (Feb. 2024) as well as a brief summary of that report (April 2024).

The US Office of Fossil Energy and Carbon Management and the National Energy Technology Laboratory, a unit within the US Department of Energy (DoE), maintain a work program on CDR, including the "Carbon Negative Shot" aimed at developing CDR methods scalable to at least one billion tons CO_2 per year and costing under $100 per ton within a decade. The DoE Office of Fossil Energy and Carbon Management also has sponsored a Request for Proposals entitled "Modular CDR for Community Integration," motivated by the idea that if a million people run small home-based modular CDR units and each removes one ton per year, that adds up to one $GtCO_2$ per year – and also helps the citizenry understand the carbon cycle. This line of technology development and concomitant financial incentivization could merit further exploration.

The US National Oceanic and Atmospheric Administration, NOAA, has outlined its current and potential role in advancing CDR. The White House outlined its marine CDR policy in October 2023. In 2021, the US National Academies (Sciences) published a research strategy for ocean CDR and sequestration.

European CDR Policy and CDR R&D: Germany funds and conducts two major research efforts on CDR, one for land-based CDR research called CDRTerra and the other on marine CDR called CDRMare. A useful CDR news tracker website with a global scope is maintained in affiliation with these efforts. A Carbon Removal Policy Tracker website ("navigating CDR policy development across Europe") is maintained by Carbon Gap, a European NGO.

UPTAKE, a European Union Horizon funded research project funded from Sept. 2023 to end Oct. 2027, "aims to develop resilient CDR strategies based on strengthened scientific evidence on the social, technological, economic, and environmental characteristics of CDR technologies and their interplay. The scientific evidence will be collated into a CDR knowledge inventory, openly accessible to the science, policy, business communities. Together with improved CDR modules in climate-energy models, a CDR roadmap explorer will be developed to help identify resilient and implementable CDR portfolios which enable net-zero strategies." UPTAKE (also described here), coordinated by Italian climate change research institute CMCC, is an important effort to assess and quantify the potential scope and cost-effectiveness of different CDR methods.

Relatedly, CO_2RE is the UK's national research hub on CDR. CO_2RE maintains a useful CDR explainer section on its website (albeit referring to GGR removal, i.e. Greenhouse Gas Removal, since climate-altering gases like methane and nitrous oxides are also covered, in addition to CO_2).

Chinese CDR Policy and CDR R&D: Section 7.2.4 (pp. 204-9) of a report published by Tsinghua University's Institute of Climate Change and Sustainable Development, "China's long-term low-carbon development strategies and pathways: Comprehensive report," briefly outlines the CDR options under consideration. China's CDR sector was largely beyond the scope of this report; more efforts to survey China's emerging CDR RD&D landscape would be useful.