Rhodium Group

The Landscape of Carbon Dioxide Removal and US Policies to Scale Solutions

Energy & Climate

April 10, 2024

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Executive Summary

As the speed, scale, and complexity of achieving US economy-wide decarbonization are better understood, carbon dioxide removal (CDR) is gaining more attention as an important piece of the puzzle. CDR is a broad set of processes and technologies that result in the net removal of CO_2 from the atmosphere. Because of policies implemented over the past few years, the US is now a global leader in policy support for CDR. However, more federal policy support is needed to expand the portfolio of CDR options and ensure a robust CDR market exists to support the goal of mid-century decarbonization. In this report, we survey the current and vast landscape of different CDR approaches in the US, informed by the latest peer-reviewed literature, dozens of expert interviews, and new analysis. We also assess the current state of policy support and additional policy options to help CDR scale to the level required for mid-century decarbonization in the US.

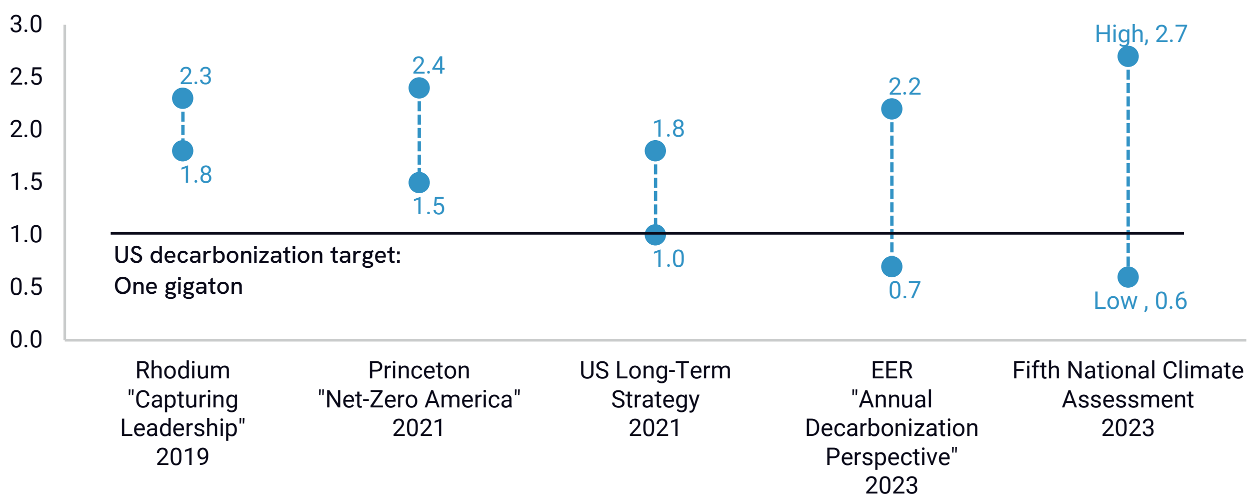
A robust CDR industry is necessary to complement US decarbonization

Based on global climate models, various decarbonization studies, and our own internal modeling estimates, in order for the US to decarbonize by mid-century, at least one gigaton of annual CDR capacity will need to be available by then (Figure ES1). That's up from low-single-digit megatons of CDR today and equal to the capacity to remove roughly 20% of the carbon dioxide (CO_2) emitted in the US in 2023. All of this CDR is above and beyond what natural carbon sinks are expected to contribute in the land use, land-use change, and forestry sector absent additional policy support. Exactly how much CDR is needed in the coming decades is uncertain and depends on the speed of other decarbonization actions, but access to CDR is undoubtedly an option the federal government needs to invest in to achieve mid-century decarbonization.

FIGURE ES 1

Estimates of CDR required by mid-century from US decarbonization studies

Gigatons of CO_2



Source: Rhodium Group; Princeton University Net-Zero America: Potential Pathways, Infrastructure, and Impacts; The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050; Evolved Energy Annual Decarbonization Perspective 2023: Carbon-Neutral Pathways for the United States; The Fifth National Climate Assessment

CDR can play two primary roles in decarbonizing the US economy. First, it can help the US achieve net-zero emissions by offsetting greenhouse gas (GHG) emissions from particularly hard-to-abate sectors, such as aviation and industry. Second, CDR can remove anthropogenic emissions that already exist in the atmosphere, often referred to as legacy emissions, to limit global temperature rise or, over time, potentially reduce global temperatures. Looking past mid-century and assuming the US and the world successfully decarbonize, CDR is the only strategy that can continue to reduce atmospheric concentrations of CO_2 in the long run. It's important to note that CDR is not a comprehensive solution for US decarbonization nor an excuse to continue emitting as usual. Instead, it is a strategy to complement deep emissions cuts across all sectors in an effort to limit global temperature rise as fast as possible.

Supporting a diverse array of CDR approaches

There is a wide variety of ideas and companies for removing carbon dioxide from the atmosphere, and more ideas are continuously being explored. In this report, we provide an overview of the current primary CDR approaches, divided into three categories: natural, hybrid, and engineered solutions. These approaches, summarized in Table 1, vary on intertwined factors including cost, scalability, tech readiness, permanence of carbon storage, and ease of monitoring.

In addition to increasing the magnitude of policy support, the US needs to support a diverse range of CDR approaches. There are risks involved in putting all decarbonization eggs in one technology basket. If the US invests in scaling up CDR, federal policy should be designed to incentivize a set of CDR solutions that maximizes avoided climate damages while minimizing costs to US taxpayers. All approaches have a role to play in a robust CDR portfolio, and policy should be designed to complement the various CDR attributes.

Policy support is needed to establish, expand, and scale the CDR market

In recent years, the US has jump-started investment in federal policies that support CDR. Some of the most important include revamped R&D programs, the regional direct air capture (DAC) hubs program, an expansion of the section 45Q tax credit, and USDA programs funding natural CDR. Combined, these actions make the US a global leader in CDR policy support. However, current policy will support less than 1% of what may be needed for economy-wide decarbonization. The magnitude of policy necessary to support a gigaton-scale CDR industry is on the order of 20 times larger than current policy support today.

Additional federal policy support is necessary to **establish** a large-scale, long-term revenue market for carbon dioxide removal in the US. Even with optimistic growth assumptions, voluntary markets alone are not enough. We find that policy support is still necessary to provide the majority of the roughly $100 billion in annual revenue needed to support a gigaton-scale CDR market. Policy support is also needed to **expand** the portfolio of CDR technology options available and **scale** CDR approaches that are ready to advance to the pilot, demonstration, or early deployment phases. In this report, we break policy support opportunities into three major areas: 1) demand-side policies, 2) research and development (R&D) policies, and 3) demonstration and deployment policies, and we expand on their details and considerations.

Establish large-scale, long-term revenue: demand-side policy

If the US government wants to be on track for a gigaton of CDR by mid-century, it will need to establish a reliable revenue market through demand-side policy, which can provide a long-term (at least 10 years), predictable revenue source to remove and store CO_2. We recommend demand-side policies collectively target providing annual revenue support to CDR of a minimum of $20 billion, $50 billion, and $100 billion in 2030, 2040, and 2050 respectively. Supporting multiple policy mechanisms summarized below will provide more political durability and increase the likelihood of achieving these minimum thresholds. These policy options include:

Production tax credits: These policies incentivize CDR on a $/ton of removal basis. This could be in the form of one overall CDR tax credit or multiple tax credits aimed at different approaches.

Procurement programs: These programs can be designed so the government sets a CDR goal that they are willing to fund, and the market bids in to accomplish that goal. Similarly, the federal government could develop something like the advanced market commitments seen in the private sector for CDR.

Regulatory programs: Regulatory programs like economy-wide or sectoral-level emissions standards can create markets that allow CDR as a compliance mechanism. A state-level example is the California Low-Carbon Fuel Standard (LCFS), which includes DAC as a compliance option. Policies like these can be created at the federal level.

Expand the technology options: research and development policy

Many CDR approaches and technologies already exist, but further R&D can help discover novel technological designs and expand the research around CO_2 permanence and monitoring, reporting, and verification (MRV). R&D programs should include substantial support for pilot projects and test centers to transition technologies out of the lab into real-world operating conditions. A comprehensive CDR R&D program can be developed, or existing individual programs can be expanded to fund a more diverse set of CDR approaches. If the US government wants to be on track for a gigaton of CDR by mid-century, we recommend a minimum of $6 billion in total R&D policy support over the next 10 years, including funding for pilot projects and test centers.

Scale the industries: demonstration and deployment policy

Demonstration and deployment policies can help CDR scale by supporting companies to transition out of the pilot phase, increase the facility size, overcome operational hurdles, and drive cost learning. These policies support approaches in the demonstration and early-deployment stage by providing or securing a large part of the capital investment required to build CDR facilities. Policy support for each stage ensures the approach will successfully achieve full-scale deployment, assuming long-term revenue is available. If the US government wants to be on track for a gigaton of CDR by mid-century, we recommend a minimum of $18 billion in total demonstration and deployment policy support over the next 10 years. Policy options include:

Demonstration programs: Once companies have piloted operations and are ready to scale their facilities, they still face enormous capital costs to build their initial large-scale operations, including the costs of feasibility studies and basic engineering. Demonstration programs like the current DAC Hubs can be replicated for other CDR approaches.

Loan guarantees: When companies are in the demonstration and early-deployment phases, they still face technological and operational risk that makes securing financing a challenge. The federal government can assist with these financing hurdles by providing loan guarantees.

In Chapter 1 of this report, we look at the role of CDR in economy-wide decarbonization and the scale needed to support mid-century decarbonization. In Chapter 2, we provide an overview of the diversity of CDR approaches available. In Chapter 3, we consider key themes and considerations in the broader conversation around scaling CDR approaches and policy design. Chapter 4 overviews current policy support for CDR and the remaining gap. And in the final chapter, we detail policy support options for establishing, expanding, and scaling the CDR industry.

TABLE 1

Summary of CDR approaches

Stage of deployment: Lab, Pilot, Demo, Commerical

Cost: $ Less than $150/ton; $$ $150 - $600/ton; $$$ Over $600/ton

Permanence: DECADES | 100-200 YEARS | 200-1,000 YEARS | MILLENNIA | MILLIONS OF YEARS

Natural

CDR APPROACH	STAGE OF DEPLOYMENT	COST	MONITORING, REPORTING, AND VERIFI...	PERMANENCE
Improved forest management	Commerical	$	Hard	Decades – 100-200 years
Afforestation/ reforestation	Commerical	$	Medium	Decades – 100-200 years
Coastal blue carbon	Commerical	$	Hard	Decades; *more research needed*
Soil carbon sequestration	Commerical	$	Hard	Decades – 100-200 years; *up to 1,000 years if soil cover is turned back into forest*
Peatland/wetland restoration	Commerical	$	Hard	*Wetlands*: Decades – 200-1,000 years; *Peatlands*: Decades – Millennia

Hybrid

CDR APPROACH	STAGE OF DEPLOYMENT	COST	MONITORING, REPORTING, AND VERIFI...	PERMANENCE
Ocean fertilization (Ocean BiCRS)	Lab	$ - $$	Hard	*shallow ocean*: Decades – 100-200 years; *deep ocean*: 200-1,000 years – Millennia
Macroalgae (Ocean BiCRS)	Pilot	$ - $$	Hard	*shallow ocean*: Decades – 100-200 years; *deep ocean*: 200-1,000 years – Millennia
Artificial upwelling and downwelling (Ocean BiCRS)	Lab	$	Hard	*shallow ocean*: Decades – 100-200 years; *deep ocean*: 200-1,000 years – Millennia
Biomass burial (Terrestrial BiCRS)	Demo	$	Medium	100-200 years – Millennia
Biochar (Terrestrial BiCRS)	Demo	$ - $$	Medium	200-1,000 years
Ocean alkalinity enhancement	Lab, Pilot	$ - $$	Hard	*100s of Millennia*
Bio-oil injection (Terrestrial BiCRS)	Pilot	$$	Easy	Millennia – Millions of years
BECCS* (Terrestrial BiCRS)	Pilot, Demo	$ - $$	Easy	Millennia – Millions of years
Surficial mineralization/ enhanced weathering	Pilot	$ - $$	Medium	Millennia – Millions of years
Ex situ mineralization (CO2 storage)	Lab, Demo	$ - $$	Easy	Millennia – Millions of years
In situ mineralization (CO2 storage)	Demo	$ - $$	Easy	Millennia – Millions of years

Engineered

CDR APPROACH	STAGE OF DEPLOYMENT	COST	MONITORING, REPORTING, AND VERIFI...	PERMANENCE
Direct ocean capture*	Pilot	$$	Medium	Millennia – Millions of years
Electrochemical* (DAC)	Lab	$$$	Easy	Millennia – Millions of years
Solid solvent/ mineralization* (DAC)	Pilot	$$$	Easy	Millennia – Millions of years
Solid sorbent* (DAC)	Demo	$$ - $$$	Easy	Millennia – Millions of years
Liquid solvent* (DAC)	Pilot, Demo	$$ - $$$	Easy	Millennia – Millions of years

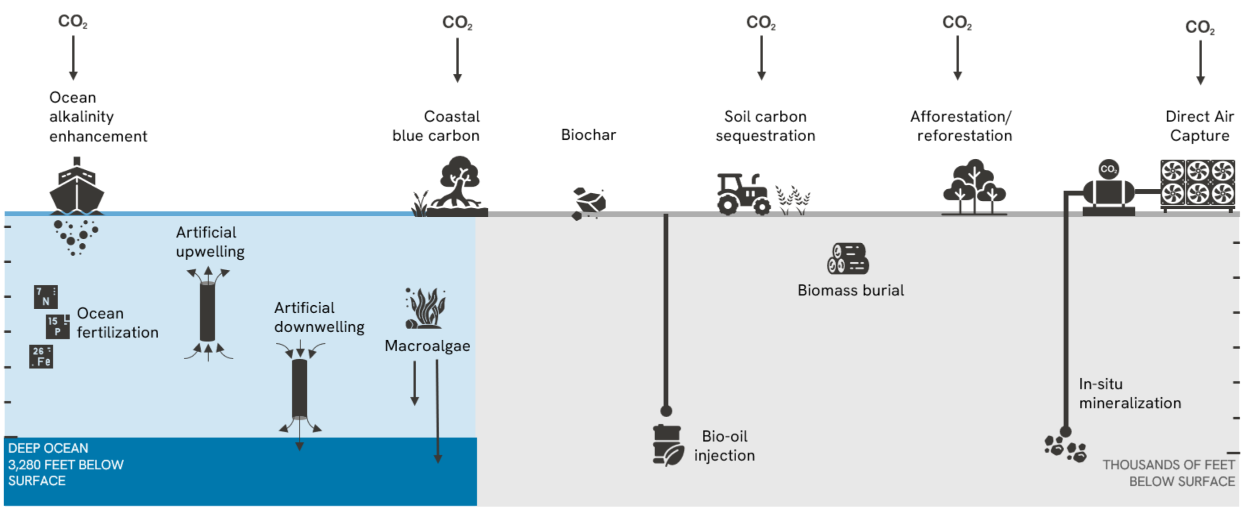
Source: Rhodium estimates based on a range of sources (see Table 1 section in References of full report). Note: Cost ranges reflect current cost estimates concurrent with the stage of development; they are not future cost projections. MRV for improved forest management varies depending on the practice used. For ocean BiCRS, shallow water refers to depths above 1,000 meters (3,280 feet) and deep ocean refers to depths below 1,000 meters. * These CDR approaches are means of capturing CO2 and involve being paired with a method of CO2 storage(e.g. saline storage or enhanced mineralization) to achieve the levels of permanence outlined

CHAPTER 1

The Importance of CDR for US Decarbonization

As the complexity of US economy-wide decarbonization becomes better understood, carbon dioxide removal (CDR) is gaining more attention as an important piece of the decarbonization puzzle. CDR is a category of climate change mitigation solutions that result in a net removal of CO_2 from the atmosphere. There are a variety of CDR approaches, ranging from longstanding ecosystem management techniques to novel technological solutions, that are both land and ocean-based (Figure 1). These methods include natural solutions such as afforestation and reforestation, processes that expedite natural carbon cycles such as enhanced weathering and oceanic artificial upwelling and downwelling, and engineered solutions like direct air capture. We provide a comprehensive overview of the different approaches in Chapter 2.

FIGURE 1
Illustration of select CDR approaches



Source: Rhodium Group

Since there can often be confusion between the two, it is worth mentioning that CDR is distinct from point-source carbon capture and storage. Point-source carbon capture works by adding equipment to industrial or power plants to capture CO_2 emissions before they are released, whereas CDR methods remove CO_2 that is already in the atmosphere. Simply put, point-source carbon capture is a form of carbon abatement, while CDR accomplishes net-negative emissions. If a point-source carbon capture facility and a CDR project both ultimately use geologic storage, they can share the same transport infrastructure and injection sites to sequester captured carbon. In this report, we are only focusing on CDR.

CDR can play two primary roles in decarbonizing the US economy. First, it can help the US achieve net-zero emissions by offsetting greenhouse gas (GHG) emissions from particularly hard-to-abate sectors, such as aviation and industry. Second, CDR can remove anthropogenic emissions that already exist in the atmosphere, often referred to as legacy emissions, to limit global temperature rise or, over time, potentially reduce global temperatures. Looking past mid-century and assuming the US and the world successfully decarbonize, CDR is the only strategy that can continue to reduce atmospheric concentrations of CO_2 in the long run. It's important to note that CDR is not a comprehensive solution for US decarbonization nor an excuse to continue emitting as usual. Instead, it is a strategy to complement deep emissions cuts across all sectors in an effort to limit global temperature rise as fast as possible.

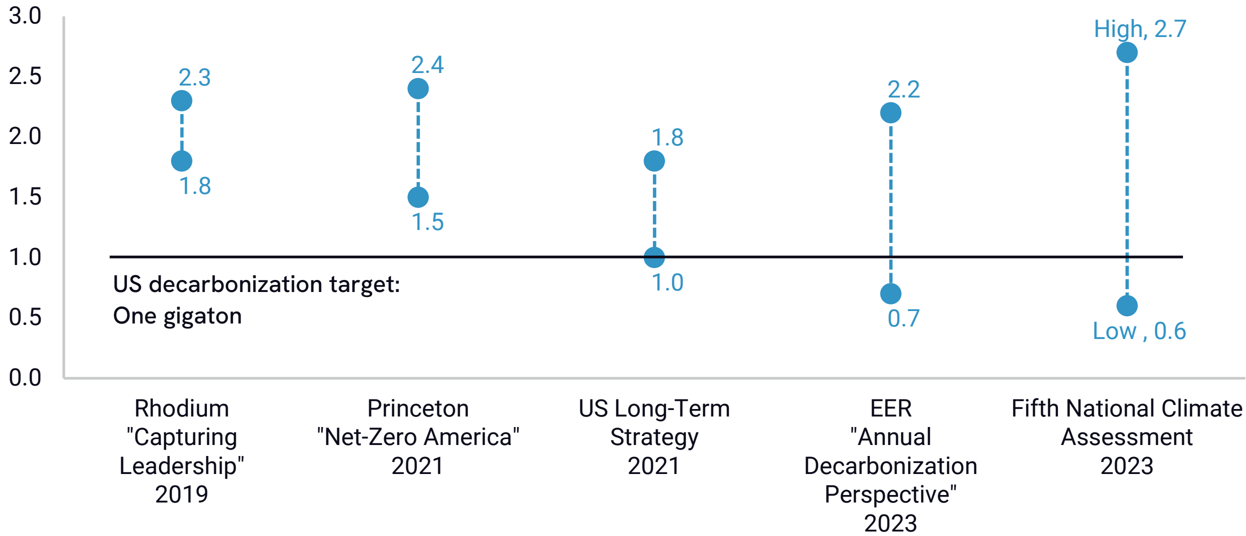
Based on global climate models, various decarbonization studies, and our own internal modeling estimates, for the US to decarbonize by mid-century, at least one gigaton of annual CDR capacity needs to be available by that time. That's equivalent to the capacity to remove 20% of the CO_2 emitted in the US in 2023. Exactly how much CDR is needed in the coming decades is uncertain and depends on the speed of other decarbonization actions, such as electrifying transportation and buildings and getting the electric power sector as close to zero emissions as possible. But CDR is undoubtedly an option the government needs to invest in to achieve mid-century decarbonization and to continue to remove CO_2 from the atmosphere after that to stabilize global temperatures at safe levels.

In a report we published in 2019, Capturing Leadership: Policies for the US to Advance Direct Air Capture Technology, we found that 1.8 to 2.3 gigatons of CDR will be needed for the US to achieve a 105% net reduction in greenhouse gas emissions from 2005 levels by 2050. Since then, several studies, including Princeton's Net-Zero America, the White House's Long-Term Strategy, Evolved Energy Research's Annual Decarbonization Perspective, and the Fifth National Climate Assessment report to the US Congress, have all detailed the need for CDR under various emissions reductions and temperature target scenarios (Figure 2). The results of these studies inform our finding that the US needs at least one gigaton of annual CDR capacity available in order to decarbonize by mid-century. That said, emissions reduction impacts and changing atmospheric temperatures operate in the global context. Later in this chapter, we look at the global need for CDR in order to limit temperature increases to make sure the findings of our modeling and others are in line with historic emissions and future global climate change mitigation needs.

FIGURE 2

Estimates of CDR required by mid-century from US decarbonization studies

Gigatons of CO_2



Source: Rhodium Group; Princeton University Net-Zero America: Potential Pathways, Infrastructure, and Impacts; The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050; Evolved Energy Annual Decarbonization Perspective 2023: Carbon-Neutral Pathways for the United States; The Fifth National Climate Assessment

US decarbonization pathways are uncertain

Over the past few years, the US has made historic decarbonization policy action under the Infrastructure Investment and Jobs Act (IIJA) and the Inflation Reduction Act (IRA). Our most recent Taking Stock report found that under current policy, the US is on track for a 29-42% reduction in greenhouse gas emissions in 2030. Assuming the US wants to fully decarbonize by mid-century, the US will need to take additional action to cut the remaining 58-71% of emissions.

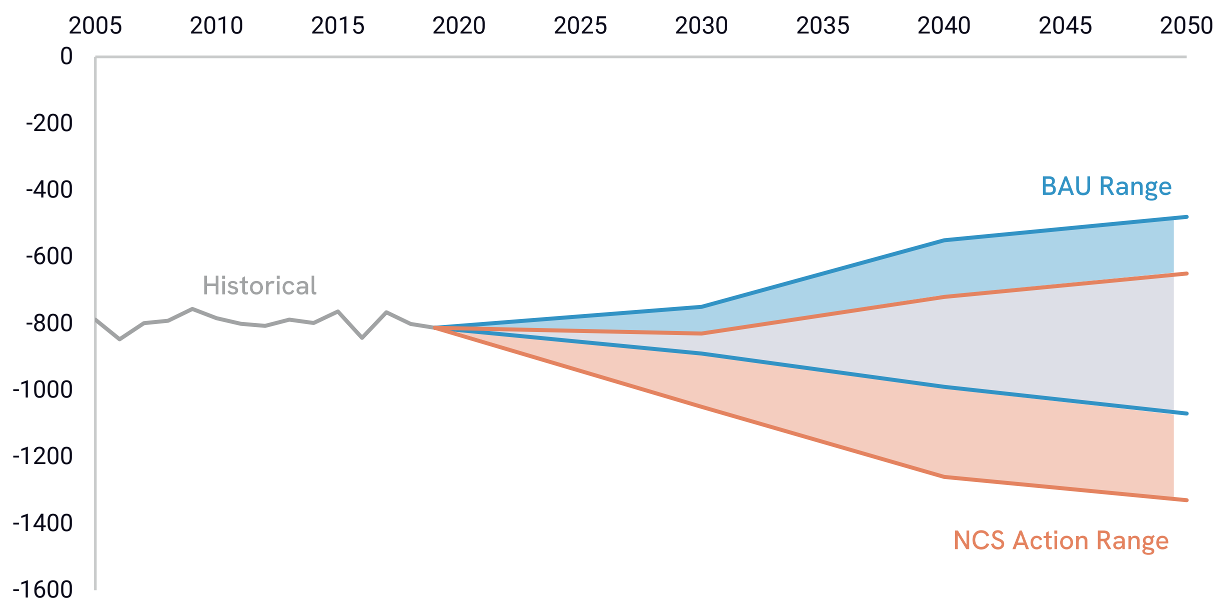
Through our own internal analysis and the highly-respected modeling from other groups mentioned in the previous section, we have a good understanding of the technical solutions and pathways to fully decarbonize the US economy. However, understanding technical pathways is still far off from knowing with certainty how these decarbonization levers will deploy over the next 25-30 years. There is still much uncertainty around land-use impacts, consumer adoption rates of clean technologies, infrastructure deployment constraints, and other factors, as well as the form and ambition of widely expanded policy support required to reach mid-century decarbonization. The uncertainty around decarbonization levers is what shapes the uncertainty around just how much CDR the US will need access to. We find undoubtedly that CDR is an effective insurance mechanism the US has to fill in these uncertainty gaps.

One area of uncertainty in particular worth diving into in this report is how much CO_2 will be absorbed through land use, land-use change, and forestry in the US. Today, it's estimated that around 0.7 gigatons of CO_2 is absorbed annually via natural sequestration mechanisms by soils, forests, and other ecosystems across the US. All the modeling studies detailed in the previous section include baseline natural removal of CO_2 under different assumptions. Assuming historic land-use conversion trends, we aren't optimistic that this level of natural sequestration will continue without expanded policy support because US forest stocks are maturing, leading to lower total net carbon removal. That said, further policy action can increase the likelihood that natural sequestration of CO_2 is maintained via some of the CDR approaches we detail in this report. Even so, the role of land-use-related carbon removal is very uncertain going into mid-century, as highlighted in the US Long-Term Strategy (Figure 3). This underscores our emphasis on the need for a robust CDR industry with many solutions, natural and technical, all at scale and available if needed to reduce net US emissions.

FIGURE 3

US land use (LULUCF) sink projections from 2021 US Long-Term Strategy

Million metric tons of CO_2e



Source: 2021 US Long-Term Strategy. Note: There is a range of possible CO_2 outcomes for both the reference case (BAU Range) and the Long-Term Strategy action case (NCS Action). Historic values are from the US GHG Inventory, and projected values are derived from a range of land sector models. Estimates include forest ecosystem carbon pools, harvested wood products carbon storage, and land use conversion fluxes across land types.

US action on CDR in the global context

In the 2015 Paris Agreement, countries around the globe pledged to work in cooperation to "hold the increase in global average temperatures to well below 2˚ Celsius above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5˚C above pre-industrial levels." There is still a lot of uncertainty around the amount of CDR that will be required globally to achieve either of the temperature goals stated in the Paris Agreement. It depends on a) the speed and extent to which emissions are reduced around the world, b) how the global climate responds to those emission declines, and c) the level of confidence the international community is seeking that either the 1.5˚C to 2˚C temperature targets are not exceeded (or the speed at which global average temperatures are brought down to these levels following an overshoot).

For this report, we reviewed global modeling conducted for the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) by research groups around the world for the following three climate futures:

1. **1.5˚C without overshoot**: A >50% chance of limiting global temperature increases to 1.5˚C with no or limited overshoot.

2. **1.5˚C with overshoot**: A >50% chance of reducing global temperature increases to less than 1.5˚C following a high overshoot.

3. **2˚C**: A >67% chance of limiting global temperature increases to less than 2˚C.

Across these three climate futures, focusing on the distribution of outcomes between the 25th and 75th percentiles, the global CDR required by 2050 ranges from 1.2 to 6.1 gigatons per year, and in 2100, it's 5.7 to 16 gigatons (Figure 4). In climate future 1, there is an average level of CDR deployment across the 95 modeling scenarios included of 4.6 gigatons in 2050, growing to 9.5 gigatons in 2100, with some scenarios yielding as high as 14.6 and 19.4 gigatons in 2050 and 2100 respectively.

In climate future 2, there is an average level of CDR deployment across the 123 modeling scenarios included of 4.3 gigatons in 2050, growing to 13.2 gigatons in 2100, with some scenarios yielding as high as 16.1 and 25.6 gigatons in 2050 and 2100 respectively.

In climate future 3, there is an average level of CDR deployment across the 298 modeling scenarios included of 2.9 gigatons in 2050, growing to 9.6 gigatons in 2100, with some scenarios yielding as high as 10.5 and 22 gigatons in 2050 and 2100 respectively.

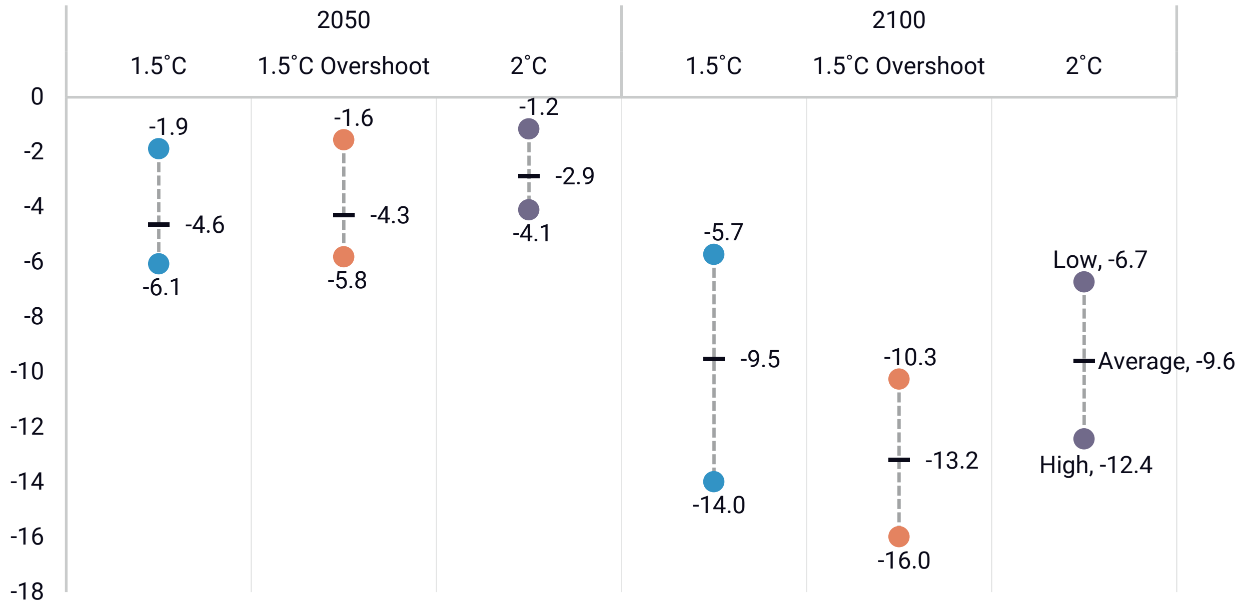
The US has an opportunity to be a global leader in the CDR space and remove a meaningful portion of the CO_2 emissions it has contributed to the atmosphere. According to our global emissions estimates, the US was responsible for just under 14% of global gross annual CO_2 emissions in 2021. An alternative perspective is that historically the US has contributed 25% of cumulative global gross CO_2 emissions since the beginning of the industrial revolution.

Using these annual and historical percentages as examples of CDR responsibility, the US could aim to remove 0.4 to 1.2 gigatons of CO_2 in 2050, assuming an average global CDR need of 2.9 to 4.6 gigatons in 2050 as identified by the IPCC. To put this into perspective, the lower end of this average range is slightly more than the total annual CO_2 emissions from California in 2022. The upper end is around the same amount of annual CO_2 emissions as Texas and California—the two highest emitting states—combined. Nevertheless, some scenarios yield as high as 4 gigatons of US CDR in 2050.

FIGURE 4

Global levels of CDR deployment across three climate futures

Gigatons of CO_2 removal, average deployment is the solid center point, 25th & 75th percentiles used as the range



Source: AR6, Rhodium Analysis. Note: This chart shows the level of CDR deployed across multiple model scenarios. The average is the solid center point, and the 25th and 75th percentiles are used as the bounds. 1.5˚C indicates a >50% chance of limiting global temperature increases to 1.5˚C with no or limited overshoot (95 scenarios included).

Being a global leader in CDR not only means the US has an opportunity to lead in climate change mitigation, but it also has the additional benefit of putting US industries at the forefront of the nascent global CDR industry. In the next chapter, we walk through the wide variety of different approaches for CDR, and in Chapter 3 we turn to how the state-of-play has changed for CDR since the release of reports like AR6 and the other modeling studies cited here.

CHAPTER 2

An Overview of CDR Approaches

This chapter provides an overview of the diverse array of CDR solutions and gives a sample of companies associated with various approaches. Clever ideas for removing carbon from the atmosphere are continuously being explored. Thus, this is not an exhaustive list of all CDR methods or companies. Rather, we cover the primary CDR techniques being considered in current literature and those often discussed in conversations with the public and private sectors. New compelling approaches will almost certainly arise in the future.

We divide the approaches into three categories: natural, hybrid, and engineered solutions. As discussed in the previous chapter, CDR approaches are diverse. We divide the approaches into three categories: natural, hybrid, and engineered solutions. We dive into the details of the nuance of each approach in this chapter.

Natural solutions

Natural CDR solutions are processes that naturally capture CO_2 without requiring significant human or technological intervention. Many of these processes have been occurring for hundreds of millions of years; the difference here is we are now expanding or maintaining the locations where these natural processes are taking place.

ECOSYSTEM MANAGEMENT

Ecosystem management is a category of CDR that represents natural, land-based solutions to remove CO_2. One approach is improved forest management, which involves changes in forestry practices to increase overall biomass concentration and CO_2 retention. Some examples of this include extending timber harvesting schedules, thinning vegetation on and around the trees, and implementing fire management practices.

Reforestation is another method to increase CO_2 capture by planting trees in areas that have been deforested in the last 50 years. Similarly, afforestation refers to planting trees in areas where forests have not existed recently.

Another form of ecosystem management is peatland and wetland restoration. This method involves increasing the number of peatlands and wetlands, which capture CO_2 through the trapping of organic matter in a low-oxygen environment. This organic matter is eventually buried as more sediment accumulates, allowing for long-term storage of the CO_2.

Lastly, coastal blue carbon is a CDR method that improves or expands coastal vegetation such as salt marshes, mangroves, and seagrass to capture CO_2. This CO_2 is initially captured by vegetation and surrounding marine life and eventually is stored in coastal soils and sediment.

SOIL CARBON SEQUESTRATION

Soil carbon sequestration is a CDR technique that involves changing land use practices to increase the amount of carbon contained in soils. Examples of this include no-till farming, changes to crop planting rotations, and applying compost to fields.

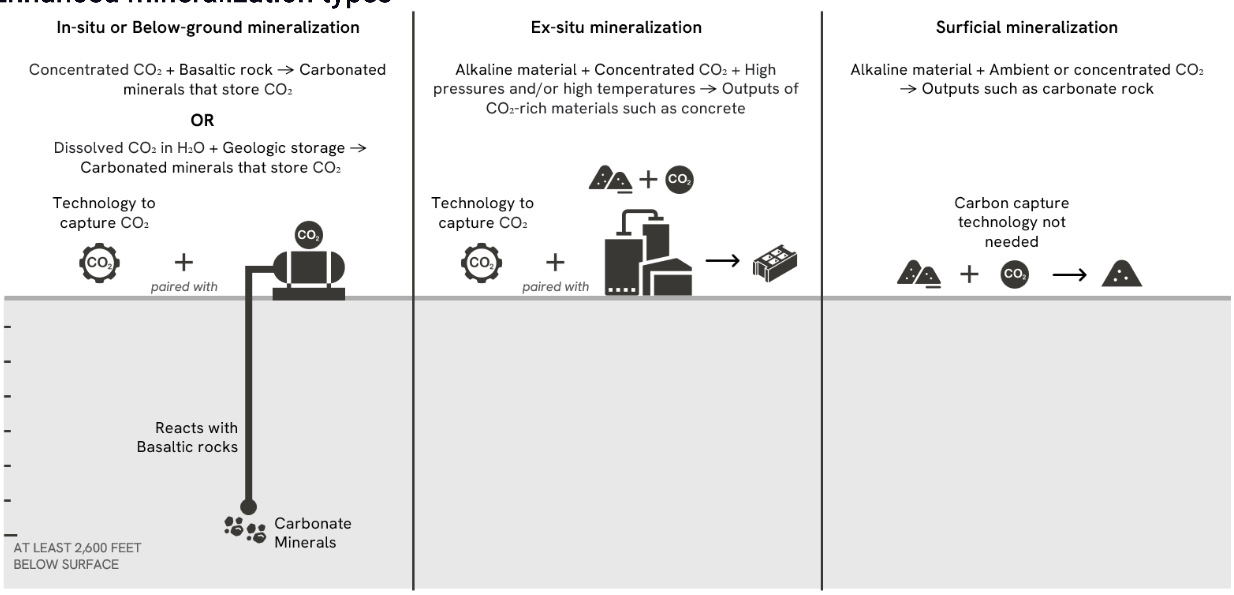
Hybrid solutions

Hybrid CDR solutions are processes that enhance the speed of natural CO_2 capture and/or transfer the captured CO_2 to more permanent storage. Many of these processes naturally occur today but at a slower pace than is desired for meaningful decarbonization.

ENHANCED MINERALIZATION

Enhanced mineralization refers to a category of CDR that involves the acceleration of CO_2 becoming a solid mineral. There are currently three mineralization techniques for CO_2 that apply to CDR (Figure 5).

FIGURE 5
Enhanced mineralization types



Source: Adapted by Rhodium Group from World Resources Institute

In-situ, or below-ground, mineralization: This method is used to increase the speed at which CO_2 forms into mineralized material compared to natural processes and conventional storage methods, such as saline storage. This is usually accomplished through injection into basalt rock or injecting pre-dissolved CO_2 into a geologic reservoir. The most notable company doing in-situ mineralization is Carbfix. They dissolve captured CO_2 in water and inject it into basalt formations to speed up the natural mineralization process.

Ex-situ, or above-ground, mineralization: This method involves reacting CO_2 with alkaline material in a lab or industrial setting at high pressures and/or high temperatures. In many cases, the goal of this method is to capture CO_2 while making a usable product or building material such as concrete. Both in-situ and ex-situ mineralization do not include the capture of CO_2. Instead, they must be paired with a technology that provides a source of concentrated CO_2, such as DAC, to accomplish carbon removal. Examples of companies focused on ex-situ mineralization include CarbonCure and CarbiCrete. CarbonCure injects CO_2 into concrete during the mixing process. This creates calcium carbonate in the mixture, which allows for less concrete to be needed while not impacting the integrity of the mixture. CarbiCrete produces concrete but replaces cement in the mixture with steel slag. Once the concrete product is created, it is cured with pressurized CO_2 to allow the product to reach full strength.

Surficial mineralization: This type of mineralization, which includes enhanced rock weathering, is a technique that uses mafic rock or alkaline waste to capture CO_2 in ambient conditions, usually through grinding or crushing the material to increase surface area and CO_2 capture potential. This method does not need to be paired with another technology to capture CO_2 in ambient air. There are a handful of surficial mineralization companies that use varying processes. Arca processes ultramafic mine tailings and maximizes their surface area to capture CO_2 in magnesium carbonate minerals. Lithos, UNDO, Carbon Drawdown Initiative, and Eion utilize crushed or powderized rock (such as basalt) on agricultural land to capture CO_2 in the form of bicarbonate ions. Vesta uses crushed olivine, a common mineral that composes ultramafic rocks, to react with rain and seawater to capture CO_2 in the form of bicarbonate ions. This process could also be considered as a type of ocean alkalinity enhancement.

TERRESTRIAL BIOMASS WITH CARBON REMOVAL AND STORAGE

Terrestrial biomass with carbon removal and storage (BiCRS) refers to land-based CDR methods that capture CO_2 through the use of biomass. BiCRS can serve as a carbon removal pathway because the biomass that it uses as a feedstock absorbs CO_2 via photosynthesis while growing, and that carbon is subsequently isolated and stored in some form—for instance, in CO_2 injection wells or locked away in a material. Several forms of terrestrial BiCRS exist in the CDR space. One form of terrestrial BiCRS is bioenergy with carbon capture and storage (BECCS), which we unpack further in the next section.

Biochar: Another method of terrestrial BiCRS is biochar, which is produced from the low-grade heating of biomass (often plant waste) in a low-oxygen environment. This biochar is then buried at shallow depths to retain CO_2 within the soil. Companies that currently produce biochar include:

- Pacific Biochar: Modifies power plants that run on biomass to be used for biochar production. The biochar is produced from forest biomass, which is then distributed in agricultural fields or compost yards.
- Wakefield Biochar: Uses scrap wood from paper mills to create biochar through pyrolysis. The produced biochar is primarily used for agricultural purposes.

- Rainbow Bee Eater: Uses biomass from agriculture crops or timber waste to create biochar through pyrolysis. The main products of this are biochar and lesser amounts of wood vinegar and hydrogen.
- Ecoera: Uses certain pellet-based biomass blends that result primarily in syngas and biochar as products from pyrolysis. The syngas is burned for heating purposes.
- Wonderchar: Uses woody biomass to create biochar through pyrolysis. The products of this are primarily biochar and heat.
- Myno: Will use agricultural and timber waste to produce biochar through pyrolysis. The first facility will produce biochar and grid-connected electricity.

Bio-oil injection: This is a similar terrestrial BiCRS method that is produced from higher heating rates (~500°C). The bio-oil produced is stored deep in the subsurface through the use of injection wells. Currently, Charm Industrial is the primary producer of bio-oil. They use waste agricultural biomass to produce bio-oil in a pyrolyzer. The oil produced from this is stored in the subsurface.

Biomass burial: This is another CDR method that stores CO_2 from waste wood and vegetation biomass. This involves creating a trench, filling it with wood material, and covering it with clay, silt, or sand to keep the wood from decomposing and releasing CO_2. Several companies exist in the biomass burial space, including:

- Carbon Sequestration, and Carbon Lockdown Project: Takes woody biomass and buries them in trenches that are designed to keep water and oxygen out, ensuring anaerobic conditions that maximize the permanence of this method
- Enhanced Biomass Sequestration: Takes woody biomass and buries it in a below-ground chamber designed to create a no-oxygen environment. The chamber is then flooded with hypersaline water, which slows the decomposition of the biomass.
- Kodama Systems: Takes woody biomass from areas at high risk of wildfires and stores it in an underground chamber in a desert environment. This location slows the decomposition of the biomass due to its low presence of oxygen, water, and microbes.
- Graphyte: Takes woody and agricultural biomass and stores it underground. They first dry and condense this biomass before wrapping it in an impermeable casing to keep the biomass and trapped CO_2 secure while stored.

BIOENERGY PRODUCTION WITH CARBON CAPTURE AND STORAGE (BECCS)

Bioenergy production technologies with carbon capture and storage (BECCS) are a subtype of the broader BiCRS approach covered in the previous section. BECCS technologies are characterized by three distinct attributes:

1. They produce an energy product or feedstock typically derived from fossil fuels.
2. Biomass is the main feedstock in the production process.
3. They capture and store a gaseous CO_2 stream from the production or combustion process that produces the energy product or feedstock.

We categorize BECCS technologies into three major categories:

1. Those that produce electricity from solid or gaseous feedstocks.

2. Those that produce hydrocarbon fuels or feedstocks like ethanol, biofuels, or sustainable aviation fuels.

3. Those that produce hydrogen.

Examples of BECCS processes include biomass combustion for electricity generation, ethanol fermentation to produce liquid fuels, Fischer-Tropsch production of sustainable aviation fuels, and biomass gasification for hydrogen production—among many other existing and novel pathways.

As with other BiCRS approaches, BECCS can reach carbon negativity because the carbon contained in its feedstock is captured and stored. Whether a BECCS process also qualifies as a CDR approach is dependent on the life-cycle emissions of the entire process, including the emissions intensity of the biomass feedstock from its production and transportation as well as any land use change that it induces, the emissions intensity of the energy used during the BECCS process, and the amount of CO_2 captured and stored. For the entirety of this report, we are only referring to BECCS processes that result in net-negative emissions, but BECCS processes can exist that capture emissions but do not result in net-negative emissions.

In practice, this carbon negativity requirement means that the biomass feedstock has a low-carbon intensity, the energy source is low-emitting (clean or renewable), and most or all of the process and combustion emissions are captured and stored. For a biomass feedstock to have a low-carbon intensity, it will most likely be sourced from biomass waste or residues. It's unlikely that a BECCS process that uses dedicated energy crops as a feedstock would qualify as CDR.

Most BECCS processes derive the thermal and electrical energy they need from the combustion of the biomass feedstock used in the process. In the case of BECCS for electricity generation, the pathway itself is a stand-alone combustion process. This can make the energy source low-emitting because the only carbon being released into the atmosphere is the carbon sequestered in the feedstock via photosynthesis. If that biomass is produced with a low lifecycle emissions footprint, its use to produce energy is inherently relatively clean. If the process does not rely on biomass for the energy needed for the process, the energy or electricity used to fuel the process needs to come from an alternative low-emissions source to maintain the net negativity of the entire process. Lastly, we find that for a BECCS process to maintain net negativity and qualify as a CDR option, at least 80% of the emissions from the process need to be captured and stored.

BECCS is also distinct from other CDR approaches because it produces a saleable product with meaningful revenue in addition to removing CO_2 from the atmosphere. Other CDR approaches may have additional benefits beyond their net carbon negativity, like habitat preservation or improved soil productivity, but developers of these other pathways generally do not see a revenue stream from these co-benefits.[1] On the other hand, BECCS producers receive revenue from the sales of the energy products and feedstocks they generate while also reducing CO_2. BECCS can also play an important role in individual energy sector decarbonization and therefore can have distinct policymaking considerations from a CDR perspective, which we cover in Chapter 5.

There are several companies using BECCS, including:

- Drax and Arbor: Burns biomass such as wood pellets or organic matter to produce electricity. The released CO_2 is sequestered using carbon capture and storage technology. Under current feedstock use, this process is not carbon-negative.
- Archer Daniels Midland: Produces ethanol from corn and sequesters the released CO_2 using carbon capture and storage technology. Under current feedstock use, this process is not carbon negative.
- Mote: Takes woody biomass and pure oxygen and reacts them in a furnace at high temperatures. The resulting gas mix is separated into H_2 to be utilized and CO_2 to be sequestered using carbon capture and storage technology.

OCEAN ALKALINITY ENHANCEMENT

Ocean alkalinity enhancement (OAE), also referred to as ocean alkalinization, is a process that allows CO_2 in the oceans to be transformed into carbonate and bicarbonate ions through the introduction of alkaline material. This reduces the CO_2 concentration of ocean waters, allowing them to re-absorb more CO_2 from ambient air. There are two primary types of OAE:

1. Mineral-based OAE, which includes adding minerals such as olivine or rocks like limestone or basalt to ocean water or coastlines, and

2. Electrochemical-based OAE, which involves facilities capturing acidic seawater from the oceans and returning the more alkaline portion of the seawater back to the ocean.

Mineral-based OAE companies include Skyology and Planetary. Skyology loads a floating reactor with alkaline mining waste to react with seawater. This reaction captures CO_2 and produces bicarbonate, which is stable in oceans for long periods of time. Planetary reacts mine tailings and water in an electrolyzer to produce hydrogen and pure magnesium hydroxide. The magnesium hydroxide can be added to ocean water to remove CO_2 and produce bicarbonate, which is stable in oceans for long periods of time. An example of an electrochemical-based OAE company is Ebb. This company uses an electrochemical process to separate seawater into acidic and alkaline solutions. The alkaline solution is released back into the ocean, while the acidic solution is either sold for industrial uses or disposed of.

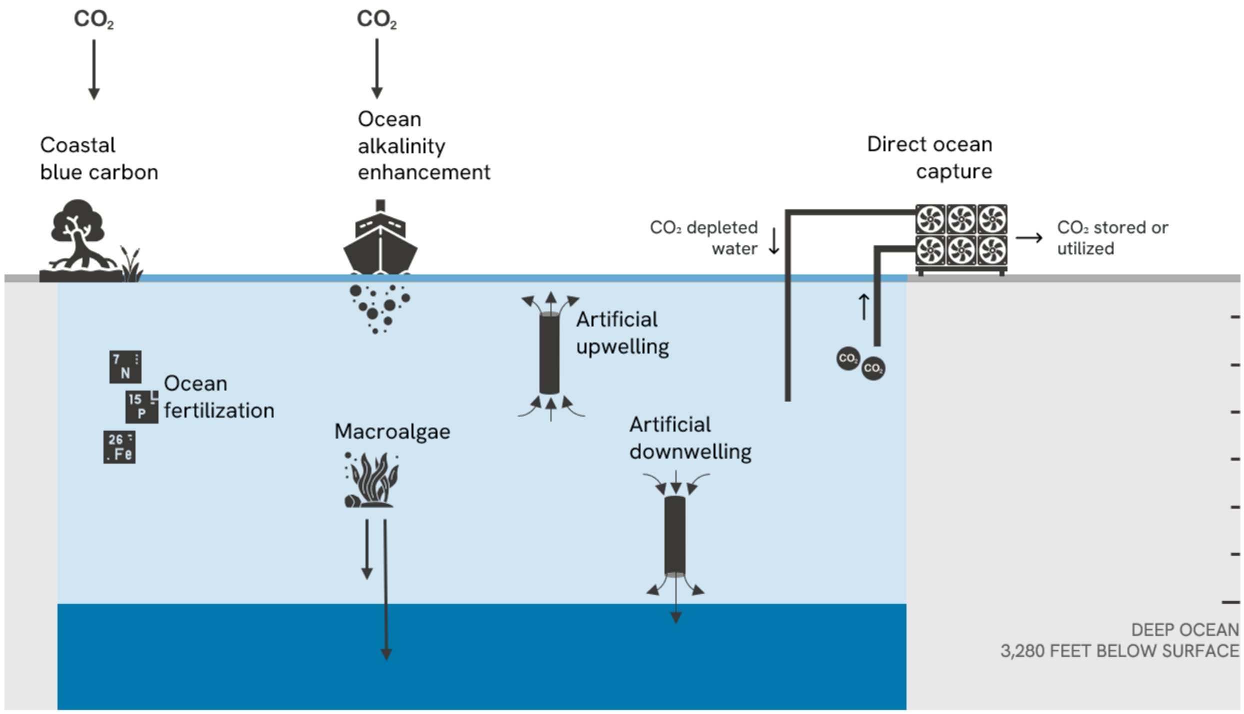
[1] Direct air capture (DAC), discussed in more detail below, is an exception in that the captured CO_2 can be sold for utilization purposes, though the utilization of that CO_2 may have important implications for the permanence and net negativity of the approach.

OCEAN BIOMASS CARBON REMOVAL AND STORAGE

Ocean BiCRS is a category of CDR that involves methods to increase ocean biomass and its ability to be stored through burial on the seafloor (Figure 6).

FIGURE 6

Ocean-based CDR methods, including ocean BiCRS



Source: Rhodium Group

Ocean fertilization: This involves adding nutrients to ocean waters to increase phytoplankton growth. The primary nutrients added are nitrogen, phosphorus, or iron. Each element is associated with varying degrees of environmental concern due to the type of algae produced or potential eutrophication. The phytoplankton will continue to grow and capture CO_2 before dying and being buried on the ocean floor along with the CO_2 they have captured. One company focused on ocean fertilization is the Ocean Nourishment Company. Their process creates a mixture of nutrients, including nitrogen, phosphorous, iron, and silica. This mixture is slowly released into the oceans, stimulating phytoplankton growth.

Artificial upwelling and downwelling: Artificial upwelling involves redirecting colder and more nutrient-rich waters towards the surface of the ocean, where microalgae primarily grow. Artificial downwelling can redirect surface water rich in microalgae (and therefore CO_2) towards the bottom of the ocean, allowing the microalgae to sink to the ocean floor and be sequestered more easily. Both provide a pathway to stimulate microalgae growth and increase CO_2 sequestration. A couple of companies focused on artificial upwelling are Ocean-based Climate Solutions Inc. and the Climate Foundation. Both companies would use a long tube to pull nutrient-rich water from deeper in the ocean and bring it near the surface, providing nutrients for phytoplankton to grow and multiply.

Macroalgae: This involves the farming of seaweed to allow for the capture of CO_2. The seaweed can either be released to the bottom of the ocean or harvested for use in bioplastics or for biochar and bio-oil production. There are several companies in the macroalgae CDR space, including:

- Phykos: Builds platforms in the ocean to grow seaweed, which is then harvested and sunk into the deep ocean to maximize storage potential.
- Running Tide: Compacts terrestrial and marine biomass, coats it with alkaline material, and releases it into the ocean. The biomass will float, allowing alkaline material to dissolve into the ocean before sinking into the deep ocean.
- Seafields: Grows and harvests seaweed in a nearshore farm. Some seaweed is sold for use in bio-based products, while the rest is baled and sunk in the deep ocean.
- Brilliant Planet: Initially grows algae in a lab before transferring it to large outdoor ponds to grow. Eventually, the seaweed is harvested, dried, and buried in a lined desert landfill. This method could also be considered as biomass burial.
- Ocean Wise: Plants, manages, and maintains kelp forests to capture CO_2. At this time, it is unclear if the kelp will be utilized or stored once grown.

Engineered solutions

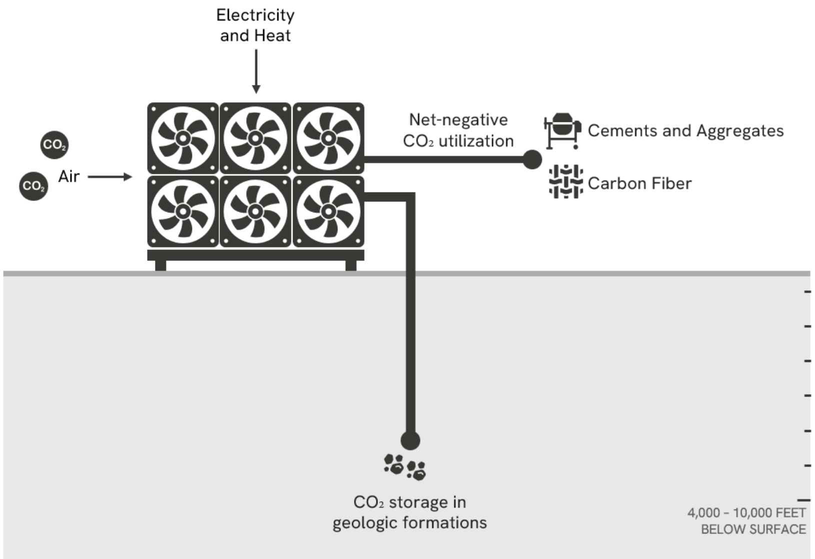
Engineered CDR solutions are processes that use human-made technologies to capture CO_2 from ambient air or oceans. These processes can lead to significantly faster CO_2 removal than would otherwise occur using natural methods of removal.

DIRECT AIR CAPTURE

Direct air capture (DAC) is an engineered CDR approach that involves the capture of CO_2 from ambient air (Figure 7). DAC was the topic of our flagship Capturing Leadership report in 2019 and has been a focus of much Rhodium analysis since then. While novel forms of DAC are continuously being explored, we will elaborate on four of the leading methods.

FIGURE 7

Example of direct air capture technology



Source: Adapted by Rhodium Group from World Resources Institute. Note: This diagram is a boiled-down, illustrative example of a DAC process. Each DAC approach will have a unique process. The depth range listed is the typical range where geologic storage of CO_2 takes place.

Solid sorbent: This type of DAC uses solid filters to chemically and/or physically bind with CO_2 from the atmosphere. Once saturated, these filters are heated to around 100°C, allowing concentrated CO_2 to be released for storage or utilization. There are several solid sorbent DAC companies, including:

- Global Thermostat: Uses a ceramic honeycomb contactor with a sorbent material to trap CO_2. This CO_2 is released using steam and concentrated for utilization or geologic storage.
- Climeworks: Air is filtered into a contactor, where the sorbent material traps CO_2. The sorbent is heated, releasing the CO_2 so that it can be mixed with water and sent to geologic storage.
- CarbonCapture Inc.: Air is filtered into a contactor containing sorbent that traps CO_2. The sorbent is heated, releasing the CO_2 for utilization or geologic storage.

Liquid solvent: This type of DAC captures CO_2 using an aqueous solution to dissolve CO_2. Liquid solvent DAC currently requires much higher temperatures, around 900 °C, to release the captured CO_2 for storage or utilization. One company utilizing liquid solvent DAC is Carbon Engineering. The CO_2 is captured using potassium hydroxide, creating a carbonate salt. This salt is heated in a calciner to release pure CO_2 for utilization or geologic storage. Another company building out liquid solvent DAC is Holocene. They use an amino acid solution to capture CO_2 and add guanidine to this to form a carbonate salt. This salt can be heated at lower temperatures (around 100°C) to release CO_2 for utilization or geologic storage.

Electrochemical: Another less developed method is electrochemical DAC. Several similar variations of this type of DAC exist, but generally involve using a solvent or sorbent to capture CO_2 and an electric current to release the CO_2 for storage or utilization. Verdox and Mission Zero are two DAC companies that both use electrochemical processes to capture CO_2. Verdox uses stacked electrodes to remove CO_2 from air using a specific voltage. The CO_2 attaches to the electrodes and is released for utilization or storage when the voltage is reversed. Mission Zero uses a similar capture approach to liquid solvent DAC but uses an electrochemical separation process to remove the CO_2 for utilization or geologic storage.

Solid solvent/mineralization: Finally, we refer to a more recently developed method of DAC as a solid solvent (or mineralization DAC). This method involves using solvents like sodium hydroxide or calcium oxide to capture and dissolve CO_2 from ambient air. The CO_2 is then removed from this material by heating or other methods so that it can be stored or utilized. The leftover solvents from these processes are re-exposed to ambient air to capture CO_2 and restart the process. Here is a list of solid solvent DAC companies and the solvents they use:

- Heirloom: Uses calcium oxide on stacked trays to capture CO_2. The newly formed calcium carbonate is heated in a kiln to release the CO_2 for utilization or geologic storage.
- Sustaera: Uses an alkali-based sorbent to capture CO_2
- Capture 6: Uses sodium hydroxide to capture CO_2 before mixing it with seawater to create carbonate minerals, which are then stored in the subsurface.
- Calcite: Uses a calcium hydroxide solution to absorb CO_2 and create calcium carbonate. This calcium carbonate is heated in a kiln to regenerate calcium hydroxide and capture pure CO_2 for utilization or geologic storage.

DIRECT OCEAN CAPTURE

Direct ocean capture (DOC) is a CDR method that removes CO_2 from ocean waters by changing the pH, pressure, and/or temperature of the water (Figure 6). This CO_2 is stored or utilized, and the CO_2-depleted water is returned to the ocean to recapture CO_2 from the atmosphere. This process could be viewed as similar to DAC, but instead of capturing CO_2 from ambient air, the CO_2 is captured from ocean water. There are several companies utilizing DOC, including:

- Captura: Uses electrodialysis to create an acidic and alkali stream of ocean water. When the acidic stream is added to ocean water, it triggers a reaction that allows CO_2 to be extracted for utilization or storage. The alkali stream of water is mixed with the remaining acidic water to neutralize it so it can be returned to the ocean.
- SeaO2: Uses a similar approach as Captura, but instead uses an electrolyzer to separate the water into acidic and basic streams.
- Equatic: Also uses a similar approach as Captura, except they also produce hydrogen from the electrolysis of ocean water. They also bubble atmospheric air through the alkaline water and use alkaline rock to further neutralize the acidic stream of water before returning it to the ocean.

As stated at the beginning of this chapter, this is not an exhaustive list of CDR approaches or companies. As the CDR space continues to advance, novel approaches may arise, and new companies will certainly emerge. In the next chapter, we will evaluate the current state of CDR and key attributes of the methods outlined above.

CHAPTER 3

Understanding the state of CDR

The release of the IPCC Special Report on Global Warming of 1.5°C in 2018 marked a considerable shift in US public-policy dialogues towards a focus on net-zero emissions. That report also elevated the role of net-negative emissions in future temperature target scenarios. Around the same time as the release of the IPCC 1.5°C report, the National Academies released their report on Negative Emissions Technologies, and Rhodium Group followed up with Capturing Leadership the following year. The increase in understanding of net-negative technologies and net-zero emissions scenarios around this time shifted the tides for the CDR industry. That momentum has continued, and now the industry is much larger and more diverse than it was just five years ago. Indeed, the space is dynamic and moving fast. We've done our best to capture all important developments as of the time of publication, but inevitably new and exciting developments will occur going forward that won't be captured here.

Scaling a diverse set of CDR options is essential

If the US invests in scaling up CDR, federal policy should be designed to incentivize a set of CDR solutions that maximizes avoided climate damages while minimizing costs to US taxpayers. Therefore, approaches of all types have a role to play in a robust CDR portfolio. As momentum has increased for CDR, the number of CDR approaches and technologies that are now in development has also greatly increased. In most cases, we use the term "approach" to describe individual CDR processes, but we consider "approach," "process," and "solution" to be synonymous in the CDR space. Not all CDR approaches are "technologies," but we still find utility in using "technologies" as a description in the relevant cases because it's a more intuitive categorization in the energy and climate policy space. Table 1 provides an overview of the current leading CDR approaches, building off the deep dive in Chapter 2. We then survey the key attributes—stage of development, cost range, monitoring, reporting, and verification (MRV) difficulty, and permanence across these approaches. These factors are important when considering how to construct and invest in a diverse CDR portfolio. We then go deeper into each factor and consider how different CDR approaches fit within this broader framework.

TABLE 1
Summary of CDR approaches

Natural

CDR APPROACH	STAGE OF DEPLOYMENT (Lab / Pilot / Demo / Commerical)	COST ($ Less than $150/ton; $$ $150 - $600/ton; $$$ Over $600/ton)	MONITORING, REPORTING, AND VERIFI...	PERMANENCE: DECADES	100-200 YEARS	200-1,000 YEARS	MILLENNIA	MILLIONS OF YEARS
Improved forest management	Commerical	$	Hard	■	■			
Afforestation/ reforestation	Commerical	$	Medium	■	■			
Coastal blue carbon	Commerical	$	Hard	■	more research needed			
Soil carbon sequestration	Commerical	$	Hard	■	■	up to 1,000 years if soil cover is turned back into forest		
Peatland/wetland restoration	Commerical	$	Hard	■	■	Wetlands; ■	Peatlands	

Hybrid

CDR APPROACH	STAGE OF DEPLOYMENT (Lab / Pilot / Demo / Commerical)	COST ($ Less than $150/ton; $$ $150 - $600/ton; $$$ Over $600/ton)	MONITORING, REPORTING, AND VERIFI...	PERMANENCE: DECADES	100-200 YEARS	200-1,000 YEARS	MILLENNIA	MILLIONS OF YEARS
Ocean fertilization (Ocean BiCRS)	Lab	$ - $$	Hard	shallow ocean	■	deep ocean	■	
Macroalgae (Ocean BiCRS)	Pilot	$ - $$	Hard	shallow ocean	■	deep ocean	■	
Artificial upwelling and downwelling (Ocean BiCRS)	Lab	$	Hard	shallow ocean	■	deep ocean	■	
Biomass burial (Terrestrial BiCRS)	Demo	$	Medium		■	■	■	
Biochar (Terrestrial BiCRS)	Demo	$ - $$	Medium			■		
Ocean alkalinity enhancement	Lab, Pilot	$ - $$	Hard				100s of Millennia	
Bio-oil injection (Terrestrial BiCRS)	Pilot	$$	Easy				■	■
BECCS* (Terrestrial BiCRS)	Pilot, Demo	$ - $$	Easy				■	■
Surficial mineralization/ enhanced weathering	Pilot	$ - $$	Medium				■	■
Ex situ mineralization (CO2 storage)	Lab, Demo	$ - $$	Easy				■	■
In situ mineralization (CO2 storage)	Demo	$ - $$	Easy				■	■

Engineered

CDR APPROACH	STAGE OF DEPLOYMENT (Lab / Pilot / Demo / Commerical)	COST ($ Less than $150/ton; $$ $150 - $600/ton; $$$ Over $600/ton)	MONITORING, REPORTING, AND VERIFI...	PERMANENCE: DECADES	100-200 YEARS	200-1,000 YEARS	MILLENNIA	MILLIONS OF YEARS
Direct ocean capture*	Pilot	$$	Medium				■	■
Electrochemical* (DAC)	Lab	$$$	Easy				■	■
Solid solvent/ mineralization* (DAC)	Pilot	$$$	Easy				■	■
Solid sorbent* (DAC)	Demo	$$ - $$$	Easy				■	■
Liquid solvent* (DAC)	Pilot, Demo	$$ - $$$	Easy				■	■

Source: Rhodium estimates based on a range of sources (see Table 1 section in References of full report). Note: Cost ranges reflect current cost estimates concurrent with the stage of development; they are not future cost projections. MRV for improved forest management varies depending on the practice used. For ocean BiCRS, shallow water refers to depths above 1,000 meters (3,280 feet) and deep ocean refers to depths below 1,000 meters. * These CDR approaches are means of capturing CO2 and involve being paired with a method of CO2 storage(e.g. saline storage or enhanced mineralization) to achieve the levels of permanence outlined

Stage of development

CDR solutions range from novel ideas being explored in a lab to established processes happening at the commercial level. Even within one category of CDR (e.g., direct air capture), the sub-technologies can be at different stages of development. Sometimes this idea is referred to as technology readiness level, and technologies are ranked on a scale of 1 to 9. For simplicity and since not all CDR solutions are technologies, we break the stages of development into four phases: lab, pilot, demonstration, and commercial (Table 1).

LAB

The lab phase indicates that a theory has been proven; however, it is still being studied in a lab setting. The process or technology is being conducted in a controlled environment on a lab bench or as a computer simulation. The overall goal of the lab phase is to retire the scientific risk of a technology or approach. Approaches that are still in the lab phase include electrochemical DAC, ocean fertilization, artificial upwelling and downwelling, some OAE approaches, and most ex-situ mineralization methods.

PILOT

The pilot phase is when the process is taken out of the lab setting and is being tested in a real-world operating environment. The process or technology is still being conducted at a smaller scale than its intended size.

Pilots are often used as a place to innovate and optimize an approach. The overall goal of the pilot phase is to reduce the engineering risk associated with a technology or approach. Therefore, the primary goal is not yet to remove carbon. Rather, it is a place to work out kinks, maximize efficiency, and continue to innovate. The lessons learned during the pilot phase will help improve demonstration and commercial facilities. CDR solutions that are in the pilot phase include certain types of BECCS, mineralization-based DAC, some types of liquid solvent DAC, bio-oil, certain OAE approaches, macroalgae, surficial mineralization, and direct ocean capture.

DEMONSTRATION

The demonstration phase can be thought of as a prototype. This stage includes the first-of-a-kind plant. In the demonstration phase, the CDR project is operating with the objective of capturing CO_2 and at a size that is either at or approaching the commercial goal. The overall goal of the demonstration phase is to reduce the operational risk associated with a technology or approach.

Demonstration projects often incur the highest levelized costs since they are operating at their largest scale to date but have not yet benefited from economies of scale. As a riskier investment, they also may face greater challenges being financed. CDR solutions in the demonstration phase include in situ mineralization, most terrestrial BiCRS solutions, solid sorbent DAC, and the ex situ mineralization company CarbonCure Technologies.

Additionally, Carbon Engineering has broken ground on two liquid solvent DAC demonstration facilities.

COMMERCIAL

The final stage, the commercial phase, is when a technology is ready to scale. At this stage, the process is operating at its intended size, and the scientific, engineering, manufacturing, and operational risk is retired. The first batch of commercial projects will likely need policy support similar to that of demonstration projects. Once there are enough commercial projects, it becomes a mature process as the costs come down the learning curve. As of now, natural CDR solutions are the only CDR approaches that have reached the commercial level. As we discuss more in the policy section of this report, we don't anticipate that CDR approaches will ever be "commercial" in the traditional sense, meaning that a technology relies solely on private markets for its revenue, because policy is necessary to create the markets CDR will operate in.

Cost per ton of CO_2

CDR approaches span a wide range of costs—from less than $100 per ton of CO_2 removed to more than $1,000 per ton of CO_2. These costs are influenced by many factors, including the stage of development, capital costs, construction and engineering when applicable, financing, labor, and any operating or energy input costs. Our cost estimates are based on publicly available data (such as Frontier's application database), proprietary data, and Rhodium estimates.

To add even more complexity, certain CDR methods could have additional streams of revenue beyond a carbon market. For example, in addition to the carbon it captures, BECCS can produce and sell electricity as another source of income.[2]

In Table 1, we use three cost ranges indicated by the number of dollar signs. Within a given CDR approach, costs often reflect a range due to factors including varying stages of deployment, differing energy prices and requirements, the type of feedstock used, project location (e.g., onshore vs. offshore), and transportation considerations. The costs in Table 1 demonstrate current costs; therefore, they are subject to change if costs decline with continued investments in research and development and/or benefit from economies of scale.

Monitoring, reporting, and verification

To confirm that a CDR project is, in fact, achieving net-negative emissions, monitoring, reporting, and verification (MRV) is imperative.

Developing a uniform MRV framework can be challenging since the process for capturing and storing CO_2 varies greatly across CDR approaches. For instance, it is relatively easy to monitor how much carbon is captured within the walls of a DAC facility and verify that amount at the point of underground injection. Compare this to surficial mineralization, where rocks are dispersed over an open field, and sediment is often washed offsite by

[2] Table 1 does not net out revenue streams in the cost estimates.

open-air elements like rainfall. Precisely monitoring and verifying how much CO_2 has been removed from the atmosphere for this type of project is far more complicated.

New start-ups are beginning to pop up to be the first movers in the CDR MRV space, but further policy support will be needed to establish MRV oversight and continue to advance research and decision-making in this space. In Table 1, we summarize how difficult MRV is for each CDR approach today. We classify approaches based on our judgment using the following criteria:

a. If there is an established and widely-verified state or federal policy accounting framework for quantifying the amount of CO_2 removed, and

b. If the method of CO_2 storage has high scientific certainty and/or the amount of remission can be quantified with high scientific certainty

CDR approaches classified as "easy" are those for which a) and b) are both true. For those classified as "medium," either a) or b) is true. And for those classified as "hard," neither a) nor b) are currently true.

Certain CDR approaches outlined in Table 1 encompass a range of strategies and practices (i.e., improved forest management, coastal blue carbon, and ocean alkalinity enhancement). Therefore, the sub-categories may have differences in levels of MRV difficulty. For improved forest management, Table 1 reflects a hard MRV classification associated with certain practices, including thinning and fire management. However, we would classify practices such as lengthened or deferred harvesting schedules as medium. Moreover, the science of electrochemical-based OAE is better understood than that of mineral-based OAE; despite this variation, they both fall under hard using our classification system.

Continued innovation in the MRV space will be vital to advance the ease and rigor with which all CDR approaches can trace their CO_2.

Permanence or CO_2 storage durability

Permanence, sometimes referred to as durability, describes how long a CDR approach keeps CO_2 out of the atmosphere. Some methods may only store carbon for a handful of years, whereas others operate on geologic time scales (millions of years). Below, we provide an explanation for the permanence ranges found in Table 1 for each category of CDR. There is no consensus on what exact threshold of time is considered a permanent solution, though many people refer to CDR approaches that store CO_2 for at least 1,000 years as "permanent." We will discuss how policymakers can think about permanence from a climate impacts and public policy-making perspective in Chapter 5.

NATURAL SOLUTIONS

Natural CDR solutions are processes that naturally capture CO_2 without requiring significant human or technological intervention. Many of these processes have been occurring for hundreds of millions of years; the difference here is we are now expanding or maintaining the locations where these natural processes are taking place. Natural solutions for CDR include improved forest management, afforestation and reforestation, peatland and wetland storage, coastal blue carbon, and farming applications.

Improved forest management is an umbrella of strategies, and thus, the range of permanence depends on the practice used. For example, there is a high degree of uncertainty regarding the permanence of some tactics, such as thinning and fire management, which lends to a permanence estimate of decades. However, the impacts of practices such as lengthened or deferred harvesting schedules can reach 100-120 years.

In the case of afforestation and reforestation, if forests are harmed (due to human activity or natural events such as wildfires), CO_2 can be released back into the atmosphere. The forests will only remove CO_2 for as long as they lived prior to a disturbance, leading to a low-end permanence estimate of decades. However, if undisturbed, trees can live beyond 100 years, depending on the tree species. Currently, 17% of US national forests are old-growth, meaning they are at least 120 years old.

We find that the potential permanence of peatland and wetland storage spans the widest timeframe of the natural solutions. If there are significant changes in the climate (such as sea level rise or more arid conditions), these ecosystem management efforts may only store carbon for decades. However, under the right conditions, wetlands have the potential to store carbon for hundreds, potentially thousands, of years. If undisturbed, peatlands are known to have even longer permanence—with the potential to store carbon for millennia.

For coastal blue carbon, some experts believe the permanence is under 100 years, while others argue it is hundreds to thousands of years. Furthermore, coastal blue carbon is also an umbrella of multiple practices with potentially different permanence profiles. More research is needed on the permanence of these CDR practices.

In farming applications, soil carbon sequestration typically removes CO_2 for decades to 100 years. There is the potential for the carbon to be stored in the soil for a thousand years if the land is turned back into a forest, since having forest coverage keeps the carbon in the soil for longer.

HYBRID SOLUTIONS

Hybrid CDR solutions are processes that enhance the speed of natural CO_2 capture and/or transfer the captured CO_2 to more permanent storage. Many of these processes naturally occur today but at a slower pace than is desired for meaningful decarbonization. Hybrid solutions include BECCS, bio-oil injection, biochar, and various approaches to enhanced mineralization.

Enhanced mineralization methods of CDR can store CO_2 for thousands to millions of years. Ex situ mineralization and surficial mineralization have similar permanence profiles given that they both use carbonate rocks, which are known to be able to store CO_2 for thousands and up to millions of years. In the case of in situ mineralization, mineralized CO_2 that is underground has been proven to be stored for millions of years in most cases. While terrestrial BiCRS solutions all use biomass as a feedstock, they vary in terms of how they ultimately store the captured CO_2. Therefore, permanence also varies across these CDR methods. BECCS and bio-oil both use geologic injection to store the CO_2. Thus, the expected length of permanence is on the order of geologic timescales—from millennia to millions of years. Biochar is expected to store CO_2 for hundreds to 1,000 years. An important factor in the ultimate length of permanence is the hydrogen carbon (H/C org) ratio of the biochar. Last, biomass burial is expected to have a permanence of at least 100 years. In the right conditions, woody biomass has been preserved for up to 7,000 years.

The permanence of ocean alkalinity enhancement can span thousands to hundreds of thousands of years. The residence time of dissolved inorganic carbon in oceans is on the order of hundreds of thousands of years. But the formation of carbonate minerals in the ocean and interactions with ocean organisms can reduce the permanence to thousands of years.

The permanence of ocean BiCRS approaches is largely dependent upon the ocean depth the biomass reaches. If the biomass remains at shallow depths, the permanence is expected to be between decades to hundreds of years. This is because the remineralization and decomposition of the organic matter in shallow waters can lead to the carbon being reintroduced to the atmosphere. If the biomass reaches deep ocean waters—more than 1,000 meters (3,280 feet)—these CDR approaches can store CO_2 for hundreds to thousands of years.

ENGINEERED SOLUTIONS

Engineered CDR solutions are processes that use human-made technologies to capture CO_2 from ambient air or oceans. These processes can lead to significantly faster CO_2 removal than would otherwise occur using natural methods of removal and include direct ocean capture and various direct air capture approaches.

For direct air capture and direct ocean capture, the pure stream of CO_2 captured is paired with geologic storage. This can be in the form of conventional saline storage or more novel CO_2 storage, such as in-situ mineralization methods. The CO_2 is safely stored thousands of feet underground with low risk of re-emissions. Thus, the expected length of permanence is on the order of geologic timescales—from millennia to millions of years.

The themes discussed here are summarized below (Table 1). The findings in this table are a culmination of an extensive literature review, expert interviews, conversations with industry players, and Rhodium analysis. In the following chapter, we walk through the CDR approaches summarized here individually.

Scaling considerations

Though there have been promising recent developments in CDR deployment, nearly all of the removal approaches we consider in this report are starting from very low levels of commercial-scale installations and will face challenges in growing to gigaton scale. Each approach has a unique set of challenges in building at scale, but there are some unifying threads that connect these challenges. In this section, we categorize scaling considerations into three major groups: resource constraints, environmental impacts, and non-cost barriers. We also discuss environmental justice concerns, which often cut across multiple categories of consideration. For these CDR approaches to meaningfully contribute to decarbonization, policymakers will need to carefully consider how to contend with these constraints.

RESOURCE CONSTRAINTS

Most CDR approaches are heavily reliant on one or more resources for the process to result in removal. Commonly, this resource is land. For instance, BiCRS (biomass carbon removal and storage) approaches require a biomass feedstock as an input to the process, and this biomass could be produced on land that would otherwise be used for another purpose, including agriculture and timber cultivation. There are a couple of important impacts that arise from these competing land uses. First, it is crucial to conduct a careful lifecycle assessment of the entire BiCRS approach to ensure that the biomass feedstock demand attendant in the process is not causing land use change that results in net increases in GHG emissions. Many BiCRS approaches seek to avoid this outcome by using waste biomass. Still, a thorough examination of the impacts of that consumption is necessary as the industry scales up. Second, a change in land use from another productive use to biomass production may have implications for commodity prices in the sectors of that original productive use—showing up in the form of higher food or timber prices, for example. Similar concerns apply to other land-intensive CDR approaches, including ecosystem management and DAC (which can rely on large amounts of renewable electricity generating capacity, occupying large amounts of land, for power).

Other resource constraints will also come into play as these approaches scale. Many CDR approaches are energy intensive, requiring large amounts of clean energy for heat and/or power in the process. Depending on the type of DAC technology, a one million metric ton facility could require between 180-500 MW of electric generating capacity—the size of a large wind farm or solar array. Growing demand for clean electricity across the economy will put CDR in direct competition with other uses for these zero-emitting electrons, straining the ability of the power grid to serve this increasing load. Biomass production for BiCRS often requires a large amount of water, and several forms of DAC have high water utilization, with typical water demand being up to seven tons per ton of CO_2 range. Particularly as climate change may make water a scarcer resource in part of the country, ensuring that CDR is a responsible water user is critical.

There are some specialized needs specific to certain CDR approaches as well. Direct air capture, direct ocean capture, and BECCS (bioenergy with carbon capture and storage) approaches require the injection of CO_2 into suitable geologic storage in order to ensure its permanent sequestration. Though the US has a vast amount of geologic storage potential, it doesn't exist uniformly across the country, so proximity is likely to be an important driver of the siting of these facilities. Surficial mineralization also needs accessible basalt or alkaline material and suitable land to work with.

ENVIRONMENTAL IMPACTS

Large-scale deployment of CDR must also avoid a range of adverse environmental impacts. One leading concern is the impact that certain CDR approaches can have on local air quality. The combustion of biomass, a component of some BiCRS approaches, can result in emissions of particulate matter (PM), ammonia, and hydrogen sulfide into the atmosphere. The construction and operation of many types of CDR can increase truck traffic and the use of diesel generators in and around the operational site, which also contributes to elevated PM levels and increases in other air pollutants like nitrous oxide. Ammonia can also be released from amine-based DAC and carbon capture approaches as the sorbents degrade. High levels of exposure to air pollutants have negative public health impacts, including increased risk of heart and lung disease, heart attacks, and asthma, particularly in communities closest to the facility.

Water quality is another issue that can be impacted by certain CDR approaches. Nutrients and fertilizers used for terrestrial BiCRS feedstocks and ocean fertilization can make their way into drinking water and the oceans, causing contamination and potential harm to marine life. There are also water quality concerns around the injection and storage of CO_2 if leakage from the geologic reservoir were to occur.

There is also the potential for habitat and species disruptions caused by increased deployment of CDR. Ocean BiCRS solutions and OAE at scale may cause marine ecosystem impacts, which could have food chain implications. Additionally, there are concerns that without tight guardrails, terrestrial BiCRS could incentivize deforestation, which has important habitat considerations in addition to the carbon accounting concerns discussed above. This is an important and growing area of research with high relevance to the CDR community, so special attention to this topic is warranted in the coming years.

NON-COST BARRIERS

Some barriers that CDR approaches will face in scaling up are a function of the policy context. Nearly all CDR approaches will need to go through a host of permitting and siting processes, some of which can take years to complete. Depending on the facility, construction may entail air and water quality permits, siting approval, and, in the case of any approach that sequesters CO_2 in the subsurface, a Class VI injection permit from the EPA or a state (if granted primacy). Some of the CDR approaches we discuss are still quite novel and may face additional new permitting steps as well.

Another set of barriers comes from the novelty of many of these projects. Given where these technologies are situated in terms of technology readiness, some of these approaches may have a hard time securing access to capital at all, or that available capital might come at a very high-cost premium, inflating the overall price tag of a project. It's also not yet clear whether each specific approach will progress to full commercialization and, if it does, how long that will take.

Workforce development is another key barrier to large-scale CDR. Many of these approaches lack a large workforce with the experience to construct and operate CDR facilities. It will be important to emphasize training in occupations that will be needed for future CDR buildout.

Lastly, public perception and potential resistance to CDR facilities could be a concern. The general public is not familiar with most of the hybrid and engineered CDR approaches, which could lead to increased concern and resistance in communities where these approaches are set to be implemented.

ENVIRONMENTAL JUSTICE CONSIDERATIONS

As CDR deployment scales, it is critical to ensure that decision-makers and other stakeholders in the policy process focus on outcomes for communities of color and other populations that are historically overburdened by the impacts of pollution and energy production. This is a thread that runs through many of the scaling considerations discussed above, but that expands beyond those topics as well.

For instance, one consideration is the potential public health impacts of CDR approaches. While many CDR approaches are unlikely to create significant health impacts, careful attention is necessary for those that do. When air or water quality is affected, it most directly impacts those people living closest to the facility—and in the past, these have often been communities that haven't been represented in decision-making processes. There are a host of other impacts on fenceline communities, including pipeline siting, location of heavy machinery, noise and light pollution, and other adverse impacts primarily from the construction of CDR facilities.

There are also concerns over economic disparities that can occur in communities, like communities not benefitting from the use of land for CDR projects. Projects tend to be sited on large plots of private land, often owned by wealthier members of the community. These owners stand to benefit from lease payments for land and subsurface pore space, without benefit accruing to others in the community. It is similarly important to consider where jobs will be sourced for the construction and operation of a facility, with an eye toward emphasizing the need for local employment so that community members could directly benefit from the project. Additionally, local communities could be impacted by increased energy prices as a result of large electrical demand for a facility if sufficient supply is not built beforehand.

Private sector vs. public sector goals and standards

Though we don't suggest that the US rely on voluntary markets to scale CDR to gigaton levels, private sector incentives and the procurement of CDR are still important and relevant for the current and future CDR industry. However, how the private sector procures CDR, including the standards set to do so, can be different than the program design, standards, and protocols set by the federal government. The reason for this is that the private sector and the public sector aren't necessarily optimizing for the same end goal (though, in some cases, they may be).

Generally, in the private sector, voluntary markets connect suppliers of CDR to buyers who want to offset some or all of the emissions that they are responsible for over a given period of time. The public sector, on the other hand, has the goal of maximizing avoided climate damages while minimizing costs to US taxpayers. There are certainly cases where private sector and public sector goals are aligned, but if the goals are different, the programs, protocols, and standards don't necessarily need to be the same. That said, the toolsets used to assess CDR attributes such as MRV, life-cycle assessments (LCAs), permanence values etc. can be shared by the private and public sectors, and the protocols and standards can be shared to inform decision-making across sectors. Overall, we caution against a rigid adherence to the same set of principles when the goals are different because flexibility will be required to achieve gigaton levels of CDR.

PRIVATE SECTOR ACTIONS PRIMING THE CDR MARKET

As part of this momentum, demand and support for CDR in private markets is growing. An increasing number of companies have announced goals to reduce emissions and become carbon neutral. Some of these companies made CDR purchases to help meet these goals.

Here is an overview of several companies that have made CDR purchases along with their goals and expectations for future CDR demand:

- Microsoft has been arguably one of the most ambitious companies in terms of reducing emissions, setting a goal of being carbon-negative by 2030 and capturing all of the company's historical emissions by 2050. While increasing efficiency and reducing emissions is a necessary part of their strategy, they will also require large amounts of CDR. Microsoft is projecting that they will capture five million tons of CO_2 per year by 2030 through their CDR purchases. They purchased 1.3 million tons of removal in 2021 and 1.44 million tons in 2022 from multiple companies with different CDR technologies. In 2022, they also announced they have over five million tons of contracted carbon removal to occur over the coming years.
- Frontier Climate is a market connecting buyers and sellers of CDR created to help facilitate demand for carbon removal. It was created by companies such as Stripe, Alphabet, Shopify, Meta, and McKinsey. To date, there has been over $156 million in pre-purchases and 339,000 tons of CDR contracted. The goal is to receive over $1 billion in commitments to purchase CDR by 2030.
- Amazon is another company that has been a leader in voluntary CDR purchases, with the goal of helping them achieve carbon neutrality by 2040. The company has created a $2 billion climate pledge fund designed to help build sustainable technology and invest in startups in the CDR space. They have purchased 250,000 tons of removal from Oxy via DAC and announced an equity stake in CarbonCapture Inc.
- Though not an explicit purchase of CDR, the XPrize for Carbon Removal is another example of private sector momentum to support CDR. XPrize for Carbon Removal launched in 2021 funded by the Musk Foundation, and the grand prize winner will be announced in 2025. The Prize commits $100 million to help support early-stage CDR ideas, companies, and demonstrations. The goal of the prize is to reward companies that can demonstrate CDR at pilot-scale with a solution that is scalable to a gigaton per year.

Though the voluntary markets are important and influential, especially for the current CDR industry, in total, they support a relatively small amount of CDR compared to the gigaton or more needed by mid-century. It's also very uncertain how much the voluntary markets will expand over the coming decades. Growth in CDR support from the voluntary markets is dependent on the extent to which companies keep net-zero commitments and how many more companies commit to them, how successful companies are in decarbonizing with other levers, and how permissive standard setters are in allowing CDR. Because of this level of uncertainty, if the US wants to be on track to have access to at least a gigaton of annual CDR by mid-century, they should prepare to supply the necessary revenue support under federal policy. If the voluntary markets do expand, this will complement US efforts and make it more likely that the US can fully decarbonize by mid-century.

In the next chapter, we review all of the policy support currently in place to support CDR deployment in the US and estimate how much deployment may occur.

CHAPTER 4

Current Policy Support for CDR

In order to scale annual CDR capacity to a gigaton or more by mid-century, the US will need to enact much more policy support to incentivize large-scale CDR deployment.

A robust CDR policy portfolio includes:

- demand-side support to establish a long-term revenue stream,
- research and development support innovation for approaches still in the lab, cost innovations and MRV and permanence research,
- demonstration and deployment policy to move out of the lab and incrementally scale them towards their intended size, as well as provide the capital support necessary for early deployment, and
- infrastructure policy to support a carbon management network.

Fortunately, the US government has begun to make progress in implementing supportive CDR policies. In the last few years, numerous policies to bolster CDR research, deployment, and infrastructure have been enacted. In this chapter, we will cover recent key policy developments in the US.

Current demand-side policy

All CDR solutions included in this report need demand-side policy support to reach full-scale commercialization. Therefore, this type of legislation is of the utmost importance and is why we highlight policy developments in this category first. Current demand-side policy on the books includes:

45Q ENHANCEMENTS UNDER THE INFLATION REDUCTION ACT

The 45Q tax credit is a policy that helps support the deployment of certain methods of carbon removal (primarily BECCS and DAC) by providing a financial incentive per metric ton of CO_2 stored. Under the Inflation Reduction Act (IRA), tax credits for 45Q were increased for carbon capture projects and CO_2 removal using DAC. The tax credit for carbon capture paired with geologic saline storage that BECCS would qualify for was increased from $50/ton to $85/ton. Additionally, the tax credit was expanded to include a new tier of the credit for DAC to $180/ton when paired with geologic saline storage. This is more than three times what the tax credit previously provided per ton of CO_2 removed via DAC. 45Q also includes lower tax credits for CO_2 utilization projects.

The minimum facility size was also significantly reduced as part of the 45Q updates under the IRA. This is relevant for BECCS because power plant facilities now only need to capture 18,750 tons per year and not less than 75% of baseline emissions. All other point source facilities need to capture 12,500 tons per year, which is 1/8th as much as formerly required.

Previously, DAC facilities needed to capture over 100,000 tons of CO_2 per year to be eligible for 45Q. DAC facilities now need to capture 1,000 tons per year to qualify for 45Q.

This change is particularly beneficial to pilot and demonstration DAC facilities that were previously too small to qualify but can now benefit from the 45Q tax incentive.

Additionally, projects that qualify for 45Q can now receive direct payments for the first five years of carbon capture from a project.

STATE PROCUREMENT TARGETS

To complement federal action, climate-concerned states have started to put forward climate policies that support a market for CDR. For instance, certain states have taken the first steps toward establishing CDR procurement targets. Under such programs, the state is committing to purchasing certain levels of carbon removal over a determined amount of time. To date, most action has been in the form of setting non-binding goals. For example, under California's Scoping Plan, the state aims to remove 7 million metric tons of CO_2 in 2030. By 2045, this goal increases to 75 million metric tons of CO_2. Some states have seen legislation introduced to establish mandatory procurement programs, like New York's Carbon Dioxide Removal Leadership Act, which aims to procure 10,000 tons of CO_2 starting in 2024. This amount doubles each year over the five-year legislation.

LOW-CARBON FUEL STANDARDS

Low-carbon fuel standards (LCFS) are another policy lever that states are using to support the deployment of CDR. Low-carbon fuel standards are regulations designed to decrease greenhouse gas emissions associated with the transportation sector. To date, California, Oregon, and Washington have enacted legislation regulating the lifecycle carbon intensity of fuels. As of now, at least seven states have pending legislation for low-carbon fuel standards, and five others are in active discussions to present legislation.

State LCFSs can support the deployment of some CDR solutions in two ways. First, if a CDR solution produces a pure stream of CO_2, it can be used as a feedstock in a qualifying low-carbon liquid fuel. While this does not result in a net-negative process or CDR, it does advance the deployment and scale-up of solutions such as DAC, DOC, and BECCS, which should lead to future cost reductions that can make CDR cheaper and more available. The second way some CDR solutions are supported by an LCFS is through eligibility for the generation of compliance credits for CDR. For example, qualifying DAC with geologic storage can produce compliance credits that can be sold to regulated entities under the California LCFS. Compliance credits in the California market have recently traded in the $60-$85/ton range.

CLEAN ELECTRICITY PRODUCTION AND INVESTMENT TAX CREDITS FOR BECCS

Like an LCFS, clean electricity production tax credits (PTC) and investment tax credits (ITC) can also indirectly support the deployment of certain CDR solutions, namely BECCS. These policies currently provide a tax credit on the basis of electricity generated or investments made for certain types of biomass-fired electricity, which can help reduce the cost of installing BECCS relative to a fossil-fired alternative like a natural gas plant. Currently, open and closed-loop biomass and some types of biogas can qualify to receive a credit.

The IRA enacted a new framework, transitioning from this technology-specific approach to an emissions-rate qualification. Beginning in 2025, any electricity generator using biomass that can demonstrate a lifecycle emissions rate of no more than zero grams of CO_2-equivalent per kilowatt-hour can qualify to receive up to around 2.6 cents per kilowatt hour of electricity generated for 10 years or a 30% tax credit based on the investment in the facility. Notably, generators can only claim one of the PTC, ITC, or 45Q tax credits, so developers would need to determine which credit is most economically beneficial on a facility level.

In addition to the direct incentives BECCS technologies can receive under the current clean electricity ITC and PTC, these policies are also beneficial in bringing down the costs of CDR methods like DAC and DOC, which use electricity to power their CO_2 removal processes. The clean electricity ITC also allows credits for direct use geothermal, which could have applications for technologies that need low-grade heat, including certain DAC and other non-electricity producing BECCs technologies.

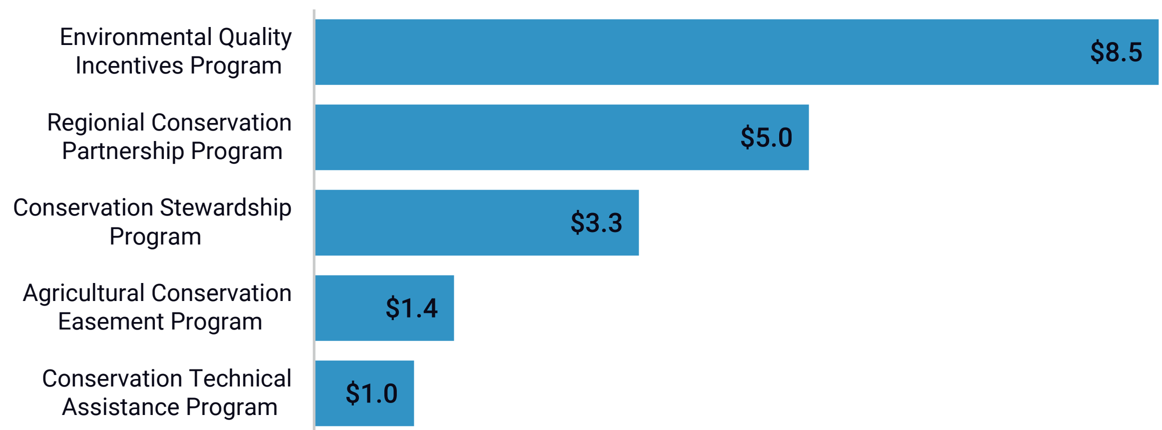
USDA PROGRAMS FUNDED BY THE IRA

Through the US Department of Agriculture (USDA), the IRA has funded several conservation programs that promote natural CDR methods. In total, about $19.5 billion has been allocated to the following USDA programs (Figure 8).

FIGURE 8

USDA cumulative funding levels for programs that benefit CDR projects

US billions of dollars, Fiscal years 2023-2027



Source: USDA

As a part of IRA funding, the USDA recently announced an additional investment of $500 million over five years to fund their Agricultural Conservation Easement Program (ACEP) and Environmental Quality Incentives Program (EQIP). Funds from the ACEP will help to conserve natural grasslands to prevent soil carbon loss, agricultural lands that are at threat of being converted to other uses, and crop cultivation in soils with high organic content. Additionally, funds will be used to conserve wetlands with high organic content and existing forests and help restore and manage hardwood forests.

CDR PURCHASE PILOT PRIZE

In September 2023, the Department of Energy's Office of Fossil Energy and Carbon Management (DOE-FECM) launched a new prize program to accelerate CDR innovation and deployment. The CDR Purchase Pilot Prize allows companies to compete for the opportunity to sell CDR credits directly to DOE. The program is an effort to develop the market for verified CDR credits and construct new purchasing models. In March of 2024, Google pledged to match DOE's $35 million devoted to CDR credit purchases, amplifying the impact of the program.

Current research & development policy for CDR

Given that no hybrid or engineered CDR approach has reached full-scale deployment yet, funding to support research, development, demonstration, and deployment (RDD&D) is critical to achieve innovation and advance these solutions. In 2021, the Department of Energy's Office of Fossil Energy (DOE-FE) was renamed the Office of Fossil Energy and Carbon Management (DOE-FECM). This name change reflects a reset of DOE's vision to support carbon management endeavors, including CDR projects. As such, DOE-FECM has become an important driving force behind RDD&D focused on CDR in the US. Current RDD&D policy includes:

CARBON REMOVAL RD&D PROGRAM AND DAC PRIZE

In December 2020, Congress passed the Energy Act of 2020, which created the first federal RD&D program specifically focused on carbon removal. Housed within the Department of Energy's Office of Fossil Energy and Carbon Management, the CO_2 Removal program focuses on technologies and strategies for large-scale removal of CO_2 from the atmosphere. By consolidating carbon removal research in one place, DOE can take a holistic and portfolio-wide approach to the RD&D needs of a range of emerging technologies.

In 2021, DOE launched its Carbon Negative Shot initiative with the goal of driving the cost of CDR down to less than $100/ton by 2032, supported by robust MRV, and securing geologic storage and enabling gigaton-scale removal. This cross-department effort leverages programs under the Energy Act of 2020, the IIJA, and other legislation. In line with efforts to meet the Carbon Negative Shot goal, the CO_2 Removal Program administers a direct air capture prize to advance DAC technology development. The prize provides up to $15 million for pre-commercial projects and up to $100 million for commercial projects to innovative approaches at various points of development. An additional $100 million is available through a separate FECM program to fund pilot-scale testing of advanced technologies and detailed MRV protocols. The National Renewable Energy Laboratory is also leading a multi-lab effort to improve MRV across CDR applications.

REGIONAL DIRECT AIR CAPTURE HUBS PROGRAM

One of the most notable provisions of the Infrastructure Investment and Jobs Act (IIJA) includes $3.5 billion in funding to develop four DAC hubs that will capture at least 1 million metric tons of CO_2 per year at each hub. As of now, two of those hubs have been announced. The South Texas DAC Hub and Project Cyprus have been approved for $1.2 billion of funding in total. Two more DAC hubs are expected to be announced in the near future. In addition to the four large-scale hubs, the DAC Hubs program also includes support for projects at earlier stages of development. This includes funding for feasibility assessments and front-end engineering and design (FEED) studies.

Supporting infrastructure and feedstocks

Multiple CDR approaches that capture CO_2 must be paired with carbon storage, including DAC, BECCS, and direct ocean capture. Therefore, policies that support and expedite the build-out of CO_2 transport and storage infrastructure will help these approaches succeed. Moreover, CDR approaches depend on a range of inputs and feedstocks. Policies that help bring down these upstream costs will bring down the overall cost of CDR options. Recent policy progress in this area includes:

CLASS VI WELL PERMITTING AND STATE PRIMACY

Under the Safe Drinking Water Act (SDWA), the US Environmental Protection Agency (EPA) has the authority to regulate the injection of liquids underground. The geologic storage of CO_2 is regulated under EPA's SDWA Class VI permitting program. The EPA sets standards and requirements for safe, long-term CO_2 storage, and any developer who wants to establish a CO_2 injection well and geologic storage site must meet these requirements before receiving a permit for the well. Under the SDWA, states may apply for and be granted primary permitting and enforcement authority for class VI wells so long as they demonstrate that their programs are at least as rigorous as those of the EPA. This is referred to as permitting primacy. At the time of this report, North Dakota, Wyoming, and Louisiana have received primacy for Class VI wells. This gives these states the freedom to manage and approve Class VI wells following EPA guidelines and expands overall permitting capacity beyond what EPA can do on its own. The IIJA includes over $48 million in funding for additional states to apply for and implement Class VI primacy programs.

There are at least three states in the application and pre-application process for obtaining primacy. Several other states have also shown intent to apply for primacy. Allowing additional states to receive primacy would speed up the approval times for class VI wells and help expand CDR for methods that incorporate geologic storage. Additionally, many states have identified CDR and geologic storage as an economic opportunity.

CO_2 LOCATE DATABASE

A major public concern for Class VI wells is the potential for CO_2 leakage, especially as the result of unsecured or unknown wells within the site. Funding from the IIJA has been used to create the CO_2 Locate database, which is designed to keep track of active and abandoned wells to inform decision-makers for Class VI wells and to minimize risk. This tool will be continuously updated to help provide data to future Class VI projects.

CARBON STORAGE ASSURANCE FACILITY ENTERPRISE

The IIJA also funded programs to accelerate carbon storage in the US. One of these is the Carbon Storage Assurance Facility Enterprise (CarbonSAFE). CarbonSAFE is designed to explore economic and technical carbon storage feasibility at potential geologic storage locations that could secure greater than 50 million metric tons of CO_2 within a 30-year injection period. In total, $444 million in funding was given to assess potential at 16 storage locations.

CARBON STORAGE VALIDATION AND TESTING

Additionally, the IIJA has given funding through the Office of Clean Energy Demonstrations to create a Carbon Storage Validation and Testing program. This program gives funding to eligible participants for permitting, site characterization, and construction of carbon storage sites. Round one of funding provided $242 million for nine storage projects.

CARBON DIOXIDE TRANSPORTATION INFRASTRUCTURE FINANCE AND INNOVATION ACT

The IIJA also included funding for the Carbon Dioxide Transportation Infrastructure Finance and Innovation Act (CIFIA) to support a network of CO_2 transport. To overcome hurdles such as high capital costs and market uncertainties, CIFIA will finance projects that develop shared CO_2 transport infrastructure. Such legislation will be imperative in establishing interconnected carbon management infrastructure.

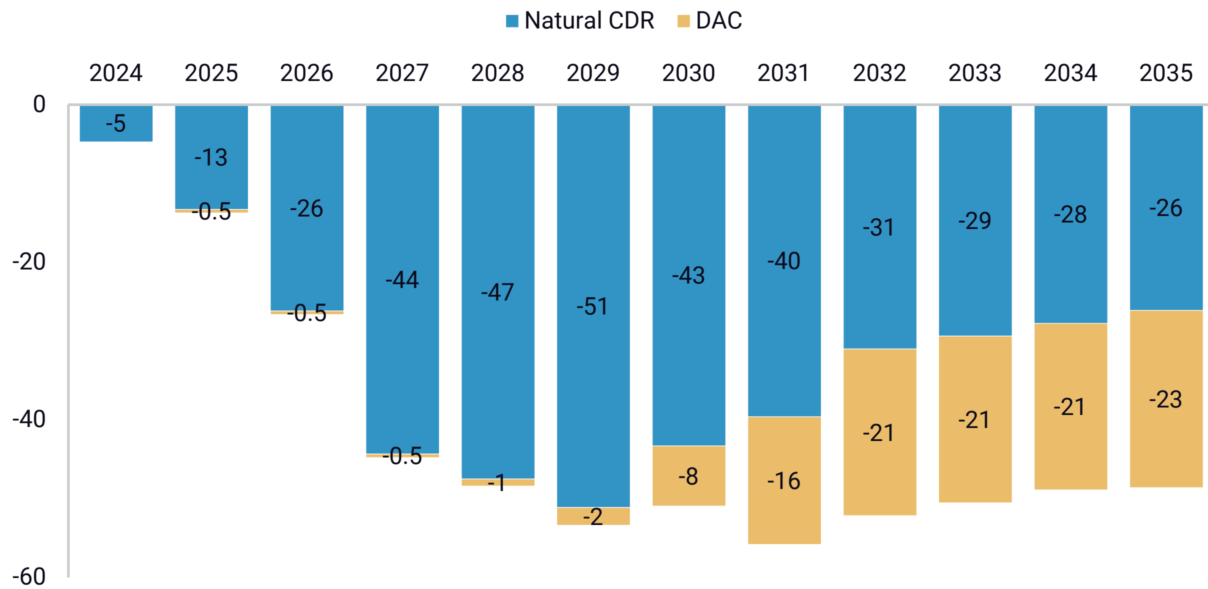
CDR deployment under current US policy

Under the current policies detailed in the previous section, we find that CDR, inclusive of new policy-driven deployment and what natural systems are expected to deliver without policy interventions, accounts for 701 to 1,023 million metric tons (MMT) of net-negative CO_2-e in 2035 in the US. Roughly 90% of this removal, between 628 and 877 MMT, is attributable to the natural sequestration from existing forests and soils in the US land sink we referred to in Chapter 1. In 2021, CDR accounted for 754 million tons, nearly 100% of which came from natural land sinks. Our 2035 range reflects low and high sequestration scenarios, which are aligned with US Biennial Report 5 projections. As we also discussed in Chapter 1, the amount of CO_2 that will be sequestered under baseline assumptions is highly uncertain. We isolate this uncertainty by quantifying how much CDR is deployed above and beyond our projections due to policy interventions, including those covered above.

FIGURE 9

CDR in the US, excluding baseline natural CDR

Net million metric tons (MMT) of CO_2e removal



Source: Rhodium Group's Taking Stock 2023, under our mid-emissions scenario.

We find that policy-driven natural CDR solutions are associated with 5 MMT of annual CO_2 removal today and peak in 2029 at 51 MMT due to IRA investments for carbon sinks associated with natural and working lands (Figure 9). From there, natural CDR slowly decreases to 26 MMT by 2035 as IRA investment recedes. The two hybrid and engineered CDR solutions we model are BECCS and DAC respectively. We find no substantial BECCS deployment that qualifies as net-negative after including the feedstock carbon intensity impacts under current policy. We project 23 MMT of CO_2 removal from DAC in 2035. Therefore, in both 2030 and 2035, our modeling shows roughly 50 MMT of total CDR, excluding assumed baseline land sinks under current policy, underscoring that more policy action is needed if the US goal is to scale CDR capacity to a gigaton or more. Indeed, much of the current policy support expires by the early part of the 2030s. We discuss what potential additional policy support could look like in the next chapter.

Certain benefits of current policy—including investments in infrastructure and costs coming down the learning curve—will outlive existing policy support. However, projects that only pencil given policy support may stop operating if this funding is not extended. Therefore, drawing a straight line from CDR under current policy support to future projections is an oversimplification. Renewed, sustained, and expanded policy support will be required to maintain our US CDR projections beyond 2035. From there, extensive new policies will be required to increase CDR deployment by at least eightfold between 2035 and 2050.

CHAPTER 5

Getting to a Gigaton: Policy Options and Considerations to Scale CDR

While most other decarbonization technologies and solutions operate within existing private markets, that is not the case for CDR services. Clean electricity generators can sell their product, electrons, into existing markets. Electric vehicle manufacturers sell a zero-emissions version of the same mobility service offered by internal combustion engines. CDR, however, is much more similar to waste management than anything else. Unless private entities are required to manage waste through policy interventions, the government tends to provide the service paid for by taxpayers. Currently, there is no market for removing and storing CO_2 from the atmosphere outside of relatively small voluntary markets. In fact, when we talk about CDR approaches reaching "commercialization," we are referring to the approaches reaching a state where the scientific, engineering, manufacturing, and operational risk is retired and the approach is ready to scale, not the point where the technology is receiving commercial revenue. Though the voluntary markets are influential and important, especially in today's CDR industry, the growth in these markets is highly uncertain. Even when assuming optimistic growth in the voluntary markets, policy will still need to create the majority of the revenue support for a gigaton-scale CDR industry. It is this revenue security that will drive the private capital into the industry necessary to build CDR facilities and infrastructure. Even though CDR will not be able to rely on private markets for much of the revenue needed at the gigaton scale, private capital is still very necessary for CDR financing.

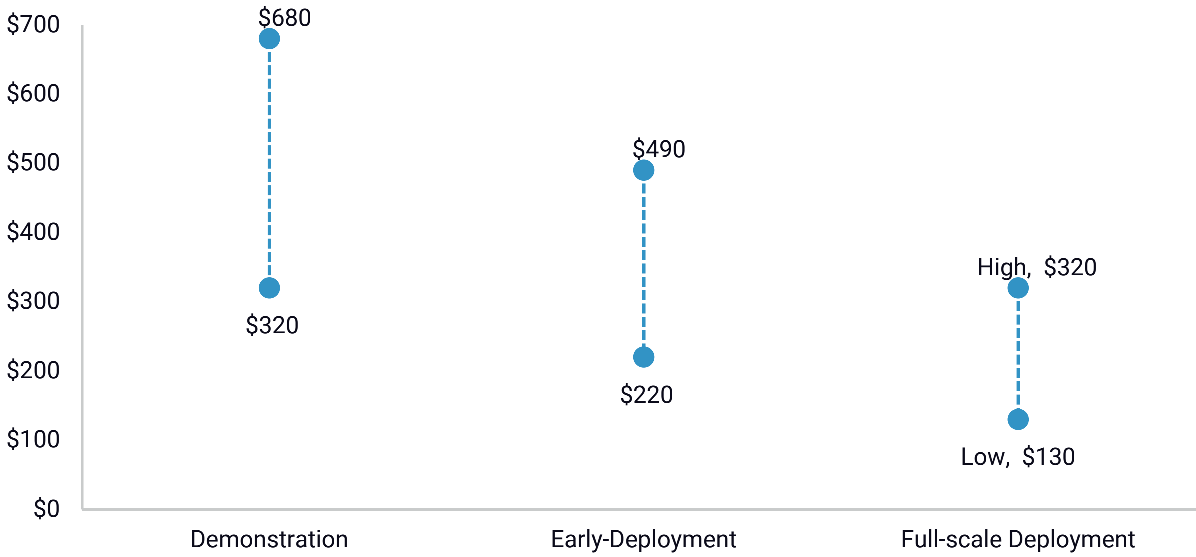
We estimate that in today's dollars, roughly $100 billion in annual revenue will be required by a gigaton-scale CDR industry. To put this level of revenue support in context, it's roughly similar to the annual funding for the US Department of Agriculture. When we estimate the revenue needs of a gigaton-scale industry at mid-century, we assume CDR costs $150/ton removed on average. That's much lower than most CDR approaches costs today. We assume those cost reductions are driven by demand-side revenue in combination with research, development, demonstration, and deployment policies. These are separate areas of policy support needed for CDR outside of demand-side policies to expand the portfolio of CDR approaches available and to scale up CDR approaches so they are on track for full-scale deployment by mid-century and beyond. In particular, research and development policies help to expand the range of technologies available, solidify the necessary science for MRV and permanence protocols, and discover opportunities for component cost learning. After the R&D phase, demonstration and deployment policies scale technologies out of the lab and assist with capital funding through early-stage deployment when costs are still high.

To illustrate how policy support can drive down costs and help solutions achieve full-scale deployment, we use the example of direct air capture. Rhodium has invested substantially in understanding and projecting direct air capture technology costs. We first published those costs in Capturing Leadership and have since updated those costs to account for inflation, technology evolution, and real-world equipment cost updates. Our latest estimate is that DAC costs will be between $320 to $680 per ton for initial large-scale demonstration plants, some of which are being supported by the DOE Hubs program discussed in the previous chapter. As more facilities are built with this policy support, costs can decrease to $220 to $490 with increased deployment. Provided demand-side policy support for DAC continues, DAC can continue to benefit from reduced costs through learning as the technology moves to full-scale deployment (Figure 10).

FIGURE 10

Projected DAC cost declines, assuming full-scale federal policy support

Levelized $2022/metric ton



Source: Rhodium Group. Note: These costs do not include any revenue, such as the 45Q tax credit.

It's worth noting here that though DAC receives substantial policy support, more policy support will be needed to get to the cost reductions shown under full-scale deployment. The 45Q tax credit, which provides $180 per ton of CO_2 removed via DAC and stored, expires after 12 years, and projects must begin construction by 2032. Therefore, DAC facilities only receive the tax credit for a limited amount of their useful lifetime. Extending the 45Q tax credit payout timeframe as well as the commence construction deadline or some other form of demand-side policy support will still be needed to get to full-scale DAC deployment.

In this chapter, we lay out policy options for the US to successfully scale the CDR industry to a gigaton level by mid-century. We discuss pros and cons and trade-offs between options as well.

Gigaton-scale demand-side policy options

Policies to create long-term revenue for CDR come in different shapes and sizes. What is most important for a demand-side policy is that it provides a long-term (at least 10 years), predictable revenue source to remove and store CO_2. If the US wants to be on track for a gigaton of CDR by mid-century, we recommend demand-side policies collectively target providing annual revenue support to CDR of a minimum of $20 billion, $50 billion, and $100 billion in 2030, 2040, and 2050, respectively. Supporting multiple policy mechanisms summarized here will provide more political durability and increase the likelihood of achieving these minimum thresholds. We leave the assessment of the political viability of each option to the reader.

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CDR TAX CREDITS

Much of the recent policy support, including the increased 45Q tax credit, is geared towards DAC. However, as Chapter 2 explained, a CDR strategy will be most effective if it can support a diverse portfolio of solutions. Tax credits have the benefit of not needing to go through annual appropriations, providing more policy certainty than annual federal budget spending. Additionally, tax credits are typically active for a set amount of years, which adds revenue certainty.

As it stands, DAC and BECCS are the only CDR solutions that the 45Q tax credit funds. The federal government could establish a separate, more inclusive tax credit where the sole focus is CDR and therefore encompasses a wider range of CDR technologies. Alternatively, the government could make 45Q more inclusive to advance other CDR approaches. Either of these options has the potential to stimulate deployment across CDR methods. Keeping such a policy technology neutral keeps the door open to CDR solutions that are still in the development phase. The potential of qualifying for such a tax credit could spur innovation for early-stage CDR solutions as well. Tax credits can be pursued as a fiscal measure as part of a budget reconciliation process. This means a simple majority in both chambers of Congress could lead to enactment.

Credit level considerations for CDR tax credits

As Chapter 3 explained, the cost per ton associated with removing a ton of carbon varies greatly depending on the method of CDR removal. Furthermore, certain CDR methods, such as BECCS, may have additional sources of income beyond a carbon market. CDR options also vary in their level of permanence, and we explore how to factor this into policy design later in this chapter. The wide range of costs and supplementary revenue streams creates a challenge when developing a technology-neutral CDR tax credit. If all CDR methods qualify for the same level of tax credit, there is the potential for the market to naturally favor cheaper approaches over others that may be more expensive but could have larger climate benefits.

Therefore, a well-designed tax credit should consider tiers of policy credit to accommodate CDR pathways with differing cost profiles, such as additional revenue streams. This is a common approach taken in tax credits to provide a more even playing field. For instance, 45Q already includes a different credit amount for point-source carbon capture projects versus DAC projects, given that DAC is more expensive but an important part of decarbonization.

The limits of tax credits

Tax credits are attractive as a policy pathway to support CDR because they are not subject to annual budget appropriations by Congress. Congress puts a tax credit into the tax code and sets eligibility parameters, and CDR developers can generally count on such support. While an act of Congress could change or repeal a tax credit, history suggests that once a tax credit is in place, it's relatively hard to remove it. Another advantage of tax credits is that there is no statutory cap on the total level of annual payments, unlike appropriations where there is a specified limit.

There are limits to tax credits in supporting gigaton-scale CDR deployment. First, congressional budget rules and wariness of long-term spending can lead to limitations on the duration of tax credit payments. The current 12-year payment period for 45Q is a case in point. For CDR to scale, providers need to be paid for their service for the useful life of the CDR project, which may often be longer than 12 years. Second, there is only so much tax appetite that can support tax credits. The only way tax credits can be monetized is by offsetting corporate income tax liability. Recent changes put in place as part of the Inflation Reduction Act allow tax credits to be transferred from a developer to any corporate off-taker, making it relatively straightforward to monetize credits. In some cases, developers can receive a direct payment instead of a tax credit, removing all barriers to monetization. Unless direct payment provisions are expanded in the future, total corporate income tax liability represents a fundamental limit on how much CDR tax credits can support. Between fiscal years 2015 and 2023, total federal corporate income tax revenue ranged from $250 to $440 billion dollars per year. It's worth remembering that the tax credits are used to incentivize the deployment of a wide array of clean technologies as well as clean technology manufacturing, affordable housing, retirement savings, and to serve a variety of other policy goals. CDR will compete alongside these other activities. The total pool of tax liability is a function of economic trends, tax rates, and other tax credits. As a point of comparison, the average projected cost of all current energy-related federal corporate tax credits (including the IRA) from FY2023 through FY2027 is $55 billion per year.

FEDERAL PROCUREMENT PROGRAMS

A federal procurement program could benefit an array of CDR solutions. Under such a program, the government pays for CDR services in increasing amounts over time. This type of policy design is often used for services that are deemed a public good, such as waste management and national defense. In this scenario, removing CO_2 from the atmosphere is pollution or waste management benefiting the public in the US and globally through contributions to a stable climate system.

A procurement program can be structured to pay by the ton for CDR or pay for practices that provide CDR. The latter may be useful for supporting CDR approaches where measurement of CDR is relatively uncertain such as some natural solutions. An illustration of this are the recent USDA programs recently funded by IRA that support natural CDR solutions by providing per acre payments for forest and soil management practices. Payment per ton is the same approach as with tax credits and activities in voluntary markets.

An agency must be authorized and funded by Congress to administer a CDR procurement program. Current DOE is the center of expertise on CDR in the federal government and could be a candidate to run the program. On the other hand, some have argued for a new stand-alone agency with the mission, funding, and authority to procure CDR. There are multiple ways an agency could procure CDR. To help provide certainty and stability to the CDR industry, a program should enter into long-term fixed-price contracts for regular delivery of specific quantities of CDR and increase the total amount of CDR procured over time with the mandate to reach a gigaton or more of CDR by midcentury. To manage costs and foster innovation, procurement should be done in a competitive manner while also leaving space for promising emerging approaches to participate. As discussed later in this chapter, permanence should also be factored into procurement if the program is large-scale (greater than roughly $10 billion per year or 50 million tons per year).

Funding procurement

The biggest challenge with a procurement program is providing sufficient, reliable funding. A procurement program funded solely through annual budget appropriations, as most government programs are, leads to a high risk of uncertain and potentially volatile funding over time. Such uncertainty will not foster a stable and growing CDR industry and will not lead to at least a gigaton of CDR by mid-century. Congress could appropriate a large lump sum into a fund to get a procurement program started. EFI suggests an amount of $33 billion to be spent over a 10-year period to get things started with Congress reauthorizing the program, presumably with larger lump sums at the end of the first decade. Assuming current and new policies help the CDR industry grow and mature, at some point, there may be a broader, established set of interests that can advocate for higher levels of funding over time. As of now, it's difficult to envision a scenario where there is sufficient political will to enact legislation for a procurement program with at least $100 billion per year in funding that getting to a gigaton by midcentury may require. That said, putting in place a less ambitious program sooner may be an important stepping stone towards what's ultimately needed. Congress may need to get creative on how to construct a dedicated funding framework that can reliably supply the necessary level of resources over the long term. Depending on how a program is structured, it may be seen as a fiscal measure compatible with the budget reconciliation process, requiring a simple majority in both chambers for passage. It is not clear whether such a legislative pathway would allow for the inclusion of key requirements for maintaining high-quality standards and other non-fiscal attributes of a procurement program, and so some aspects of a policy may require 60 votes in the Senate under current procedures.

REGULATORY POLICIES

Regulatory policies such as economy-wide or sectoral-level emissions standards can create compliance markets that can permit CDR credits as a means of compliance. An example of this at the state level is the California Low-Carbon Fuel Standard (LCFS). Under California's LCFS, transportation fuel retailers must reduce the average lifecycle carbon intensity of the fuels they sell over time. They can comply by changing feedstocks and product processes, switching purchased electricity to clean sources, and other actions. One compliance option is to purchase credits from qualifying DAC with geologic storage projects that meet California's eligibility standards for MRV.

Policies like these can be created at the federal level to create a revenue source for CDR solutions. Federal emissions requirements can include a national clean fuels standard similar to the LCFS. Or a clean product standard could require reductions in the lifecycle carbon intensity of energy-intensive products like steel and cement. Essentially, any carbon-based requirement on emitters or fuels could include CDR credits as a compliance option. For any policy to contribute to achieving deep decarbonization, the standards need to be set at a level stringent enough to drive reductions in covered emissions and CDR, eventually getting to net zero. Similarly, a regulatory requirement could be put on large emitters or energy producers to purchase CDR credits in line with an increasing share of their annual emissions without any additional emissions or emissions intensity reduction requirement. Proposed legislation in California, SB308, is one example of this policy idea. Such a policy would create ongoing expanding demand for CDR while also incentivizing reductions on covered emissions when they are cheaper than the going price for CDR credits.

Compliance markets don't necessarily provide the same level of revenue security for CDR projects that tax credits or procurement programs can provide since credit values are typically established in trading markets. This is an important consideration because revenue security and predictability are what allow companies to obtain the capital investment required to build their plants. That said, there are policy design mechanisms within compliance markets, like credit price floors, that can enhance the security of the revenue streams. Other policies, such as tax credits, can play a role in establishing a minimum level of stable revenue that compliance credit revenue can be layered on top of.

Federal emissions standard proposals covering various sectors are regularly proposed in Congress but rarely progress through committees or further through the legislative process. Under current legislative rules, it's highly likely that any emissions standards would require at least 60 votes to pass the US Senate.

Demand-side policy considerations: The discounted value of permanence

When designing CDR policies, a common source of debate is whether CDR solutions must keep CO_2 out of the atmosphere for a minimum amount of time to qualify for the policy. Quantifying the societal value of CDR options with different levels of permanence is complicated, but it is not without precedent. The federal government currently uses a similar process to conduct benefit-cost analyses on policies that reduce greenhouse gas emissions through the Social Cost of GHG emissions (SC-GHG).

When devising a CDR demand-side policy that is large-scale (greater than roughly $10 billion/yr or 50 MMT/yr), policymakers should employ a process similar to the development of estimates of the SC-GHG for permanence valuation. This process will require the same kind of public comment and participation that EPA uses when developing emission reduction regulations. It also requires a state-of-the-art understanding of how permanent CDR will be based on the types of solutions considered in the process. This makes current and new investments in MRV all the more useful and important. Determining the relative societal value of CDR with different levels of permanence ultimately depends on the choice of discount rate (a normative choice we discuss), as well as assumptions about future changes in global emissions and temperature and the impact of those changes on human welfare. How policymakers should value permanence in determining levels of fiscal or other policy support for different CDR technologies depends on the following:

1) **Baseline atmospheric concentrations**: The atmospheric lifetime of an additional ton of CO_2 is higher at higher background levels of CO_2 concentrations. That means a ton of CO_2 removed has a greater cumulative effect on reducing atmospheric concentrations over time if projected future concentrations are high than if projected concentrations are low. Counteracting this, the impact of a reduction in atmospheric concentrations on global temperatures is smaller if projected background concentrations are high than if they are low. In short, the impact of a ton of CO_2 removed from the atmosphere on global temperatures over time depends on projected global CO_2 emissions and concentrations before that removal occurs.

2) **The shape of the climate damage function**: The impact of changes in global temperature on human welfare is a subject of ongoing research and considerable uncertainty (see the Climate Impact Lab's work for a good example of the state of the science). If this impact (referred to in the economics literature as a "damage function") is upward sloping as some research suggests (meaning a 0.1 degree C reduction has more value from a 3 degree C base than a 2 degree C base), then CDR has greater value at points in the future with higher starting temperatures than lower starting temperatures.

3) **Future socioeconomics**: Research from the Climate Impact Lab and others indicates that a 0.1 degree change in global average surface temperatures has a much greater impact on poorer communities, both because they tend to be located in places with higher temperatures currently and because they have fewer economic resources with which to protect themselves from extreme weather. The value of CDR in the future relative to CDR today will therefore be determined in part by future income growth and the extent to which poorer communities in the future have a greater ability to adapt than poorer communities today.

4) **Discount rate:** The most important consideration policymakers will need to grapple with in determining how much to value permanence is the choice of discount rate, i.e., how much to value avoided climate damage in the medium term (the next few decades) vs. the long term (more than 100 years). Policymakers use discount rates in evaluating temporal tradeoffs on a wide range of issues, though the extremely long time horizons at play in climate policymaking raise a somewhat unique set of discount rate considerations.

To highlight the sensitivity of permanence valuation, we conducted a stylized exercise using the Finite-amplitude Impulse Response (FaIR) model. FaIR is a reduced-complexity climate carbon-cycle model representing the global average climate system, taking into account the timescales of carbon and heat exchange, as well as different greenhouse gas (GHG) and aerosol species. It is a lightweight, fast, transparent, and simple model that accurately reflects the climate response to emissions. FaIR calculates atmospheric GHG concentrations from GHG emissions, the effect of changing concentrations on radiative forcing (how much the planet's energy imbalance changes), and ultimately, the change in global average temperature resulting from the changing energy imbalance. This model was used extensively in the IPCC's 6th Assessment Report.

To simplify this analysis, we modeled the impact of three different stylized CDR options on cumulative global mean surface temperatures (GMST) between now and 2500:

1) **20-year removal:** In this scenario, 100 million metric tons of CO_2 are removed from the atmosphere for 20 years but then reversed.

2) **200-year removal:** In this scenario, 100 million metric tons of CO_2 are removed from the atmosphere for 200 years, but then reversed.

3) **Permanent removal:** In this scenario, 100 million metric tons of CO_2 are removed from the atmosphere permanently.

We chose these removal options because policies designed to require these levels of permanence would capture distinct sets of CDR solutions. While permanence for some CDR approaches is fairly uncertain, for this example we can make some generalizations. Starting with the least stringent, a policy that has a 20-year removal threshold would likely support all current CDR approaches (including natural, hybrid, and engineered solutions).[3] A 200-year removal threshold likely disqualifies current natural CDR solutions and most ocean BiCRS approaches; however, biochar would still qualify. Lastly, a policy that requires over 1,000 years of permanence has the potential to support a handful of hybrid solutions and all engineered solutions outlined in this report (revisit Table 1 for the permanence levels of various CDR approaches). Based on current CDR options available, this might include DAC, DOC and BECCS paired with geologic storage, bio-oil injection, and certain enhanced mineralization processes.

Analyzing the impact on cumulative temperature change is a stylized proxy for the cumulative impact on human welfare. It assumes a fixed relationship between temperature change and welfare over time, which, while certainly not correct, is sufficient to highlight the sensitivity of results to different discount rates. For background emissions and concentrations, we used the SSP245, which is the closest of the standard global emissions scenarios used by the IPCC to the mean global emissions projections from our recent Rhodium Climate Outlook.

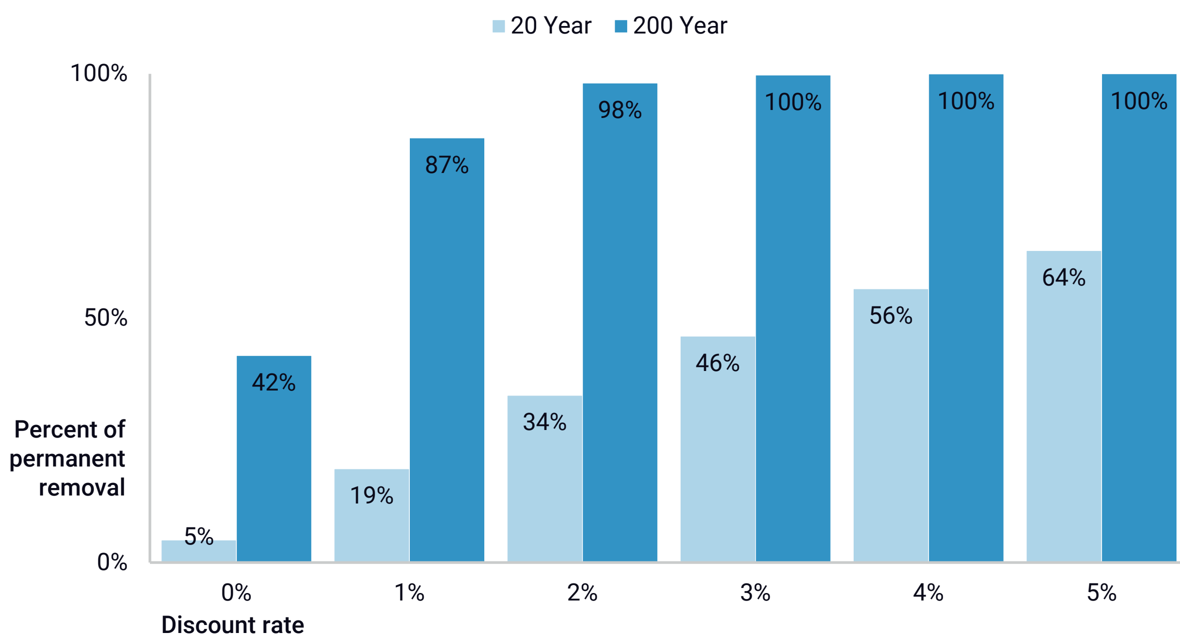
In assessing costs and benefits over shorter time horizons (i.e., less than 30 years), US policymakers generally use “descriptive” discount rates—a single discount rate applied to all future years. New guidance issued by the US Office of Management and Budget for regulatory benefit-cost analysis (known as Circular A4) recommends a 2% discount rate for shorter-term (less than 30 years) impact analysis based on evidence from financial markets regarding how much Americans prioritize current vs. future consumption. In this simplified analysis, 20-year removal has 34% of the value of permanent removal between now and 2500, while 200-year removal has 98% of the value (Figure 11).

[3] It’s important to note that permanence is just one of the criteria a policy can require. Thus, CDR solutions may be ineligible for a policy based on other factors such as MRV requirements or associated risks.

FIGURE 11

Simplified example - the relative value of less-than-permanent removal under various discount rate assumptions

Percent of cumulative temperature reductions through 2500 relative to permanent removal at different discount rates



Source: Rhodium Group

For long-term analysis like this that spans multiple generations, however, additional considerations apply. Circular A4 notes that "some believe that it is ethically impermissible to discount the utility of future generations. That is, government should treat all generations equally." Using a 0% descriptive discount rate, the relative value of 20-year removal falls to 5% of permanent removal, and the value of 200-year removal falls to 42%.

But, as Circular A4 notes, "even under an approach that does not discount the utility of future generations, it is often appropriate to discount long-term consumption benefits and costs—although at a lower rate than the near-term effects more likely to fall on a single generation—if there is an expectation that future generations will be wealthier and thus will value a marginal dollar of benefits or costs by less than those alive today, or if there is a non-zero probability of sufficiently catastrophic risks." This approach to discounting is often referred to as "prescriptive," rather than "descriptive," and while outside of the scope of this stylized analysis, is employed by the US Environmental Protection Agency (EPA) recently in valuing new methane emission reduction regulations (see below).

PRECEDENTS FOR A CDR PERMANENCE VALUATION POLICY PROCESS

As discussed in the previous chapter, robustly quantifying the societal value of CDR options with different permanence is complicated; however, it is not without precedent. The US government currently employs a similar process for valuing regulations that reduce greenhouse gas emissions through other means. The EPA has been incorporating estimates of the Social Cost of GHG emissions (SC-GHG) into regulatory benefit-cost analysis since 2008. EPA recently updated their SC-GHG estimates to reflect the most recent science, implementing recommendations from the National Academies of Science, Engineering and Medicine.

The same models used to estimate SC-GHGs (including the DSCIM model developed by the Climate Impact Lab) can be used to quantify the relative societal value of CDR options with different levels of permanence. These models capture many of the more complex elements described above that are not included in the simplified analysis presented here, including estimates of the impact of temperature on human welfare, projections of how that impact changes over time as economies change and develop, and a prescriptive discounting approach that grapples with questions of intergenerational equity, risk, and uncertainty.

Demand-side policy considerations: MRV oversight

As outlined in Chapter 2, monitoring, reporting, and verifying the amount of CO_2 a CDR project removes can be a challenge. This area of policy design considerations will be important to the CDR industry as a whole. On top of continued R&D into MRV strategies, a rigorous MRV framework is needed. Each CDR approach will need its own lifecycle analysis (LCA) boundaries and MRV guidelines. To remove the financial incentive to cheat an MRV system, it is ill-advised to let companies be solely responsible for their MRV process. Thus, this could require designating or establishing an agency for unbiased oversight.

Relying entirely on model based MRV may not the best process since it requires an array of assumptions to be made. Thus, a rigorous MRV protocol will likely require the use of satellites, drones, sensors, and people in the field tracking certain projects. This will demand capital investment that is currently not available.

Demand-side policy considerations: BECCS policy design

As discussed in Chapter 4, BECCS technologies are distinct among CDR approaches in that they produce and sell energy or feedstock while also contributing to net negativity. This energy or feedstock product can itself have important emissions attributes in addition to the overall net-negative footprint of the entire BECCS process. As such, it's important for policymakers to take special care when integrating support for BECCS into broader CDR policies.

Consider the example of BECCS for electricity generation. If a power generator sources biomass from an appropriately low-lifecycle carbon intensity source and combusts that biomass to generate steam that turns a turbine, that entire process can have a very low lifecycle emissions impact, as the only carbon coming out of the plant's flue is carbon that was previously absorbed from the atmosphere via photosynthesis. But this is not yet a CDR pathway—only once the CO_2 in that flue gas is captured and stored does the process reach lifecycle net negativity.

Combustion of low-lifecycle carbon intensity biomass may (or may not) be an efficient way to directly reduce emissions in the power sector—and policymakers could design power sector policies like a clean electricity standard or a tax credit to drive competitive and efficient decarbonization. The focus of CDR policy is driving the deployment of carbon-negative pathways, which, in the case of BECCS for electricity production, would be the application of a CO_2 capture approach onto an already low-emissions electricity generation process.

To the extent that the need for sectoral abatement drives the use of low-lifecycle-emitting biomass for specific purposes, any cost increase should be borne by that sector and not via CDR policy. In their recent Roads to Removal report, Lawrence Livermore National Laboratory (LLNL) provides a useful quantitative example of this concept. They find that a BiCRS portfolio optimized for carbon removal can remove 1 billion tons of CO_2 in 2050 at a total cost of $87 billion (net of any revenue from bioproducts like energy or feedstocks) or an average of $87/ton. When they conduct the same analysis but allocate sufficient biomass to produce 17.5 billion gallons of sustainable aviation fuel (SAF), or roughly half of the anticipated jet fuel demand that year, the total cost of the portfolio rises by nearly 50% to $129 billion, or $129/ton. If a CDR policy were established to pay $129/ton instead of $87/ton in an effort to cover the full cost of the BECCS-to-SAF-inclusive portfolio, such a policy would risk overpaying for a substantial amount of CDR approaches with a much lower marginal abatement cost—especially absent a real-world requirement to produce that level of SAF. A CDR policy that supported deployment at $87/ton could be complemented by specific sectoral policies like a SAF tax credit or low-carbon fuel standard to pay the additional cost for SAF production, thus avoiding the risk of overpayment for the broader CDR portfolio.

Stated more broadly, a CDR policy should focus on covering the cost of carbon removal and should be complemented by specific sectoral policies that focus on deep economy-wide decarbonization.

Research and development policy options

Many CDR approaches and technologies already exist, but further R&D can help advance CDR solutions through multiple avenues, including but not limited to spurring innovation, mitigating risks, allowing for breakthroughs, and bringing down costs. R&D programs that are inclusive of permanence studies and monitoring, reporting, and verification (MRV) will be especially impactful to advancing research in the CDR space. In order for the US to be on track for a gigaton of annual CDR capacity by mid-century, we recommend a total of $6 billion in funding for R&D programs over the next 10 years.

> “In order for the US to be on track for a gigaton of annual CDR capacity by mid-century, we recommend a minimum of $6 billion in total R&D policy support over the next 10 years.

R&D PROGRAMS FOR CDR

Investments in research and development (R&D) will help spur innovation, bring down costs, mitigate risks, and improve the performance of early-stage CDR methods. Since each CDR approach is unique, funding will be required across the range of CDR approaches. R&D programs are particularly beneficial to CDR projects that are still in the lab stage of development. This includes electrochemical DAC, ex situ mineralization, OAE, and ocean BiCRS. As we mentioned in the previous chapter on current policy, several R&D programs exist that support natural CDR solutions, and a new CDR R&D program was created under the Energy Act of 2020. Expanding and supporting existing individual programs is the best route for CDR R&D policy support.

An example of this type of support is the Carbon Removal, Efficient Agencies, Technology Expertise (CREATE) Act, which was introduced in the US Senate for the third time in June of 2023. This bipartisan legislation aims to develop an interagency group on Large-Scale Carbon Management to support R&D for natural, hybrid, and engineered CDR approaches.

Additionally, to bolster CDR methods that use geologic storage, including DAC, DOC, and BECCS, the federal government can continue to invest in R&D for geologic sequestration science and technology under the current programs to expand the characterization and understanding of geologic storage options in the US.

PILOT PROGRAMS

Pilot programs are designed to spur competition and fuel innovation. These programs can fund feasibility studies, basic engineering, and pilot-scale demonstrations for CDR approaches. The goal of these programs is to fund the initial stage of development when a technology moves out of the lab into real-world operating conditions. Current policy supports a DAC prize program as well as support for feasibility studies and front-end engineering and design (FEED). These policies are great examples of programs that can be expanded or re-created for other CDR approaches.

MONITORING, REPORTING, AND VERIFICATION R&D

To ensure CDR projects are achieving net negative emissions, continued research and development into the trickier MRV solutions is imperative. While start-ups and organizations are starting to pop up to fill this need, government support will serve as a catalyst for this research. This will require continued investments in the research and development of methods to ensure high levels of scientific certainty on CO_2 removal and reemission expectations. It’s important for the government to invest in MRV now so that there are strong protocols once more CDR technologies scale.

Demonstration and deployment policy

Once a technology is ready to leave the lab and transition into real-world conditions, it faces a new set of challenges to reach full-scale deployment. At the point of demonstration, costs can be at their highest, and it is harder to secure financing since there is a greater risk associated with an unproven process at scale. We estimate that $18 billion in policy support over ten years will be needed to get CDR on track for a gigaton by midcentury. Demonstration and deployment policies provide support for companies to transition out of the lab, increase the size of their facilities, overcome operational hurdles and drive cost learning. This policy area supports approaches in the demonstration, and early-commercialization stage of development by providing or securing a large part of the capital investment required to build CDR facilities. Policy support for each stage ensures the approach will successfully achieve full-scale deployment assuming long-term revenue support is available.

> “In order for the US to be on track for a gigaton of annual CDR capacity by mid-century, we recommend a minimum of $18 billion in total demonstration and deployment policy support over the next 10 years.

DEMONSTRATION PROGRAMS

Once companies have demonstrated real-world operations and are ready to scale their facility sizes, they still face enormous capital costs to build their initial large-scale operations. Demonstration programs like those established under the IIJA for DAC and clean hydrogen are a perfect example of policies that provide meaningful funding to support emerging decarbonization solutions. In addition to four hubs with a capacity of capturing one million metric tons of CO_2 per year, the DAC Hubs program also includes funding for projects at earlier stages of development. This includes funding for feasibility assessments and front-end engineering and design (FEED) studies. Similar programs can be replicated for other CDR approaches to support their transition to operating at scale. Demonstration programs don’t necessarily need to fit into the “hubs” format that currently exists; the goal of both prize and demonstration programs is to supply capital to all phases of project deployment from the lab to full-scale deployment. These also don’t need to be distinct programs; one comprehensive program could fund the full spectrum of feasibility studies, FEED studies, pilots, and demonstrations for CDR technologies or groups of CDR technologies.

LOAN GUARANTEES

Making the transition out of the lab to the pilot or demonstration phase requires a large amount of capital investment. The catch is that until CDR solutions have reached maturity, these projects will have a hard time securing financing since they still have engineering, manufacturing, and operational technology risks.

To address this hurdle, the federal government can provide loan guarantees at a favorable rate compared to the open market and assume a large part of the financial risk. This helps the project secure the rest of the private capital necessary to build the CDR facility. This funding can come from DOE’s Loan Programs Office (LPO) or the Office of Clean Energy Demonstrations (OCED).

Other policy support

In this section, we highlight policies that are important to setting the stage for gigaton-scale carbon dioxide removal. While they are tangential to specific CDR solutions, they will be imperative for the industry to succeed.

CO_2 TRANSPORT AND STORAGE SCALE-UP

A network of transportation and storage infrastructure for CO_2 will be fundamental to a mature CDR industry. Many forms of CDR capture pure streams of CO_2, which must be stored to achieve net-negativity, including direct air capture, direct ocean capture, BECCS. Projects are not always located on top of storage, requiring the transportation of CO_2.

As discussed in Chapter 4, the IIJA included multiple provisions to support CO_2 transport and storage infrastructure in the form of funding for Class VI Primacy applications, transport infrastructure financing under CIFIA, and the CO_2 Locate database to track active and abandoned wells. The federal government can continue to build upon these important policies to further support the development of an interconnected CO_2 transport and storage network. A deep dive into the federal policy needs of a CO_2 transportation and storage system is outside the scope of this report, but the magnitude of capital support required will be much larger than exists today. This will be a huge infrastructure build-out that will most likely need to be federally managed, in addition to the capital investment support that will be required.

OPPORTUNITIES FOR STATES

With an upcoming presidential election this year, states provide a pathway to make continued progress even if there is less support for climate action at the federal level. More states can adopt low-carbon fuel standards similar to those in California and the Pacific Northwest. Moreover, they can create or join existing state emissions markets, such as the Regional Greenhouse Gas Initiative (RGGI) in the Northeast. Additionally, if more states apply and gain approval for Class VI primacy, this will reduce the amount of applications the federal government has to approve and expedite CDR projects that use geologic storage.

Many of the federal policy options outlined above can be adopted and tailored to the state level. Examples include CDR tax credits, procurement programs, or fuel mandates. Any action taken by states will complement federal efforts and further support the deployment of CDR in the US.

WORKFORCE DEVELOPMENT PROGRAMS

Scaling CDR methods will require a trained workforce. In a recent analysis focused on direct air capture, Rhodium Group found that commercial DAC plants will require a variety of skilled laborers to build and operate facilities. This includes occupations such as carpenters, electricians, plumbers, and metal workers. We will be conducting a similar analysis across multiple CDR approaches later this year. One can presume that other engineered CDR technologies, for instance direct ocean capture, will require an availability of similar labor. Thus, occupational training programs will be imperative.

PUBLIC EDUCATION

Public support polling conducted at the end of 2020 found that 39% of US adults report having heard very little of CDR solutions, and 34% have not been exposed to CDR at all. Despite this lack of familiarity, nearly half of respondents supported the expansion of CDR regardless of political party. Only a small percentage of people, less than 8%, opposed the expansion of CDR across political parties.

Furthermore, the most intuitive and familiar forms of CDR (including forest management) had the most public support. On the other hand, novel engineered and hybrid approaches (such as DAC and enhanced mineralization) garnered less public support for expansion. This suggests that nascent CDR technologies may need additional publicity for the general public to understand their role and support their development.

Moreover, in conversations while preparing this report, we noticed a tendency towards lumping certain CDR categories together when considering scaling. One area we found this particularly true for is ocean-based solutions. However, as was outlined in the previous chapters, the processes for ocean CDR are distinct. Additionally, the risks of some are better researched and less concerning than those of others. Since the CDR landscape is vast, further education about the nuances between different CDR approaches will be important for policymakers and the public.

Getting to a gigaton: Policy summary

The policy support options and considerations highlighted in this report are vast and deep with nuance. The US has an opportunity to expand its leadership in developing a broad CDR industry. If the US decides to invest in scaling up the CDR industry to gigaton levels, there are several key takeaways for policy support:

1) CDR cannot rely on private markets for long-term revenue in the way that most decarbonization technologies can. Removing carbon dioxide should be viewed as a public service.

2) The magnitude of policy necessary to support a gigaton-scale CDR industry is on the order of 20 times larger than current policy support today.

3) Most additional policy support needs to be in the form of demand-side revenue support and capital support for projects to scale through the pilot, demonstration, and early-deployment phases.

4) Policy design protocols including monitoring, reporting & verification and permanence valuation are most important for large-scale demand-side policies. These protocols should be informed by the research & development, pilot, and demonstration phases.

5) Federal policy should be designed to complement the various attributes of CDR approaches and increase the diversity of CDR approaches available.

6) Federal policy should be designed to incentivize a set of CDR solutions that maximizes avoided climate damages while minimizing costs to US taxpayers.

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About this Report

In 2019, Rhodium published a report, Capturing Leadership: Policies for the US to Advance Direct Air Capture Technology, focused on one form of carbon dioxide removal (CDR), direct air capture. In this report, we zoom out to consider the full range of CDR options. We also identify policy actions to advance the deployment of these methods and key considerations to be made when creating such policies. The Linden Trust for Conservation, ClimateWorks Foundation, and Spitzer Trust provided financial support for this analysis. The research was performed independently, and the results presented in this report reflect the views of the authors and not necessarily those of the funders.

About Rhodium Group

Rhodium Group is an independent research provider with deep expertise in policy and economic analysis. We help decision-makers in both the public and private sectors navigate global challenges through objective, original, and data-driven research and insights. Our key areas of expertise are China's economy and policy dynamics, and global climate change and energy systems. More information is available at www.rhg.com.

Acknowledgments

The authors would like to thank our interviewees for their input and expertise related to carbon dioxide removal and policy. Key aspects that our interviewees assisted with include carbon dioxide removal policy insights, permitting details, market developments, MRV protocols, and modeling. We would like to thank the following individuals whose expertise contributed to our report:

Roger Aines – Lawrence Livermore National Laboratory
Giana Amador – Carbon Removal Alliance
Savita Bowman – ClearPath
Erin Burns – Carbon180
Jane Flegal – Stripe
Julio Friedmann – Carbon Direct
Lori Guetre – Carbon Engineering
Zeke Hausfather – Stripe
Mary Yap and Jonny Lu – Lithos

We'd also like to thank Carbon Engineering for welcoming members of our team to their Innovation Centre in Squamish, BC. This site visit, as well as the policy discussions that followed, put into perspective the journey CDR approaches must endure to reach full-scale deployment.

Finally, we'd like to thank Rhodium Group's Climate Impact Team for their Finite Amplitude Impulse Response (FaIR) climate modeling. This work provided us with science-based carbon dioxide removal insights to inform our policy guidance. We'd also like to thank Rhodium colleagues Jaspreet Sohal and Maggie Young for their contributions and review.

Disclosures

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