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SUMMARY

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Rising global temperatures are associated with increasingly frequent and intense climate change impacts. Scientific consensus finds that stabilizing global temperatures is necessary to avoid increased climate impacts. Studies suggest that such stabilization requires human-caused carbon dioxide (CO_2) emissions to be balanced by CO_2 removals from the atmosphere, a condition known as *net-zero carbon dioxide (CO_2) emissions*. While reductions in human-caused emissions of CO_2 would be necessary to stabilize global temperatures, they may not be sufficient. This is due in part to the difficulty in eliminating emissions from some key economic sectors that are harder to decarbonize, including the steel and cement industries. These emissions are likely to persist after a program of emissions reductions and are known as *residual emissions*.

Methods of further removing CO_2 from the atmosphere may be necessary to counterbalance residual emissions. Researchers are enhancing nature-based techniques for increasing the uptake of CO_2 from the atmosphere by the land surface and oceans, known as *carbon sinks*, as well as with recently developed technological methods. These are known collectively as *carbon dioxide removal (CDR)*. Almost all the climate scenarios assessed by the Intergovernmental Panel on Climate Change that met specific global temperature stabilization levels used CDR to remove more CO_2 from the atmosphere than is being added by emissions.

CO_2 is not the only greenhouse gas (GHG) with a climate effect. The influence of GHGs on global temperatures is the combined effect of CO_2 and the other non-CO_2 GHGs. Human-caused emissions of other GHGs—including methane (CH_4), nitrous oxide (N_2O), and hydrofluorocarbons (HFCs)—also increase global temperatures. No commercially available method for removing non-CO_2 GHGs from the atmosphere exists. Therefore, to balance emissions of non-CO_2 GHGs that cannot be abated, additional removals of CO_2 from the atmosphere would be needed.

There are several types and categories of CDR. Some CDR methods increase the uptake of CO_2 on land by increasing forested area or increasing carbon sequestered in soils. Other methods have been proposed that increase the uptake of CO_2 by the oceans through biological or chemical methods. A third category of CDR uses engineering methods such as chemically capturing CO_2 from the air or from the combustion of biofuel energy crops and storing it in geological formations.

Although almost all climate scenarios find that CDR would be necessary to meet global temperature goals, some researchers have raised concerns about relying on CDR to stabilize global temperatures. These concerns include uncertainties about the effectiveness, feasibility, and side effects of the deployment of certain CDR approaches at a scale necessary for such stabilization. For example, with CDR using forestry or soil carbon enrichment, there is concern that carbon could return to the atmosphere through forest fires or changes in tillage practices. As another example, for forestry and biofuel CDR, there is concern that the land area needed could impinge on food production. The possible ecological side effects of enhancing ocean uptake of CO_2 have also caused concern. At the same time, researchers have noted potential co-benefits associated with certain CDR approaches, including improved crop production through increased levels of soil organic matter and reductions in ocean acidification through changes in ocean alkalinity.

Laws enacted in the 117th Congress included funding for federal CDR research and development. For example, the 117th Congress passed the Infrastructure Investment and Jobs Act (IIJA; P.L. 117-58), the CHIPS Act of 2022 (P.L. 117-167), and the measure commonly known as the Inflation Reduction Act of 2022 (IRA; P.L. 117-169). Legislation to support the research, development, and implementation of CDR has been introduced in the 118th Congress. As the CDR programs and provisions supported by enacted legislation are implemented under congressional oversight, Congress may consider the future direction of federal CDR policy.

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Introduction

Rising global temperatures are associated with increasingly frequent and intense climate change impacts.[1] A 2021 scientific consensus report found that some climate change impacts are already occurring due to global warming and that stabilizing global temperatures is necessary to avoid increased impacts.[2] According to that report and other studies, such stabilization requires that human-caused (anthropogenic) carbon dioxide (CO_2) emissions are balanced by CO_2 removals from the atmosphere, a condition known as *net-zero carbon dioxide (CO_2) emissions*.[3]

CO_2 is not the only greenhouse gas (GHG) with a climate effect; the influence of GHGs on global temperatures is the combined effect of CO_2 and the other non-CO_2 GHGs. Human-caused emissions of other GHGs—including methane (CH_4), nitrous oxide (N_2O), and hydrofluorocarbons (HFCs)—also increase global temperatures.[4] These various GHGs have different warming effects. For example, methane is 27-30 times stronger as a GHG than CO_2 over a 100-year time horizon.[5] The combined influence of all GHGs may be calculated by normalizing the global warming potentials of the GHGs to the global warming potential of CO_2.[6] This results in a metric of CO_2 equivalent (CO_2e) to compare across GHGs.

Net-zero GHG means that the combined net emissions of all GHGs must be zero. It is achieved when CO_2e emissions of all GHGs are equal to CO_2e removals from the atmosphere through removals of CO_2. According to a consensus of scientific reports, achieving net-zero emissions would likely require supplementing the natural removal of CO_2 from the atmosphere by the oceans and land surfaces with anthropogenic removal. This is known as *carbon dioxide removal (CDR)*.[7] No commercially available method for removing non-CO_2 GHGs from the atmosphere currently exists. This means that to balance emissions of non-CO_2 GHGs that cannot be abated, additional removals of CO_2 from the atmosphere would be needed.

This report analyzes the role of CDR in global temperature stabilization. In doing so, the report describes some CDR approaches/methods and illustrates the relationship between emissions reductions and CDR in achieving such stabilization. This report does not serve as a comprehensive overview of all CDR approaches.[8] The report also includes a discussion of some of the potential risks and uncertainties of CDR, as well as the potential co-benefits, and some

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[1] Intergovernmental Panel on Climate Change (IPCC), "Summary for Policymakers," in *Climate Change 2021: The Physical Science Basis—Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, 2021 (hereinafter IPCC SPM WGI 2021).

[2] IPCC SPM WGI 2021. See also U.S. Global Change Research Program (USGCRP), "Chapter 2: Climate Trends," in *Fifth National Climate Assessment*, 2023. p. 2-21 (hereinafter NCA5 2023).

[3] IPCC SPM WGI 2021, p. 30: "Achieving global net zero CO2 emissions, with anthropogenic CO2 emissions balanced by anthropogenic removals of CO2, is a requirement for stabilizing CO2-induced global surface temperature increase." See also NCA5 2023, p. 2-21; and CRS In Focus IF12753, *Climate Change: What Are Net-Zero Emissions?*, by Jonathan D. Haskett.

[4] U.S. Environmental Protection Agency (EPA), "Overview of Greenhouse Gases," https://www.epa.gov/ghgemissions/overview-greenhouse-gases.

[5] EPA, "Climate Change Indicators: Greenhouse Gases," https://www.epa.gov/climate-indicators/greenhouse-gases.

[6] The method of calculating the combined influence of all GHG emissions is described in 40 C.F.R. §98.2 (b)(4).

[7] The term *anthropogenic removal* refers to both the enhancement of ocean and terrestrial carbon uptake by human activity and the use of recently developed mechanical carbon removal technologies.

[8] S. M. Smith et al., *The State of Carbon Dioxide Removal, 1st Edition*, 2023. See also T. Terlouw et al., "Life Cycle Assessment of Carbon Dioxide Removal Technologies: A Critical Review," *Energy & Environmental Science*, vol. 14, no. 4 (2021), pp. 1701-1721.

actions Congress has taken with respect to CDR technologies.[9] The report concludes with considerations for policymakers. This report provides an overview of this complex topic rather than a comprehensive review, which is beyond the scope of the report.

The Role of Carbon Dioxide Removal (CDR) in Balancing Emissions and Stabilizing Temperature

Stabilizing global temperatures to avoid increases in adverse climate effects is a central goal of climate change mitigation. Anthropogenic emissions are increasing the levels of heat-trapping GHGs in the atmosphere, thereby increasing global temperatures. According to recent scientific climate assessments, adverse climate effects increase with increasing temperatures; temperature stabilization is necessary to avoid these increases.[10] These assessments have found that to achieve temperature stabilization, atmospheric levels of CO_2e must stop increasing and stabilize through a balance of CO_2e emissions and removals of CO_2.[11] It may be technologically possible to achieve this balance by mid-century through a combination of emissions reductions and CO_2 removal, although there are uncertainties with respect to implementation.[12] This section describes the relationship between temperature stabilization and the balance known as *net-zero emissions*. It then describes the role of CDR in achieving net-zero emissions by compensating for residual emissions.

Temperature Stabilization and Net-Zero Carbon Dioxide (CO_2) Emissions

According to the current scientific consensus, in order to halt increases in climatic extremes associated with global warming, it is necessary to stop global temperatures from increasing.[13] This condition, known as *temperature stabilization,* means "limiting human-induced global warming to a specific level."[14]

Emissions of GHGs to the atmosphere increase the levels of GHGs in the atmosphere. When anthropogenic CO_2e emissions, as the sum of all GHGs, are balanced by removals of CO_2 from the atmosphere, no net addition of CO_2e occurs. When this balance is achieved, the net addition of GHGs to the atmosphere is zero, and atmospheric concentrations of CO_2e do not increase. The *Intergovernmental Panel on Climate Change Sixth Assessment Report*, a document frequently cited in the U.S. Global Change Research Program's (USGCRP's) *Fifth National Climate*

[9] For example, Congress included provisions for the research and development of CDR, as well as deployment of commercial technologies for some types of CDR, in the appropriations for the Infrastructure Investment and Jobs Act (IIJA; H.R. 3684), the CHIPS Act of 2022 (P.L. 117-167), and in some of the tax provisions of the Inflation Reduction Act (IRA; P.L. 117-169). See also additional discussion of CDR in CRS In Focus IF11861, *DOE's Carbon Capture and Storage (CCS) and Carbon Removal Programs*, by Ashley J. Lawson.

[10] IPCC SPM WGI 2021; NCA5 2023.

[11] IPCC SPM WGI 2021; NCA5 2023.

[12] National Academies of Sciences, Engineering and Medicine (NASEM), "Is It Possible to Achieve Net-Zero Emissions?" https://www.nationalacademies.org/based-on-science/is-it-possible-to-achieve-net-zero-emissions. See also NASEM, *Accelerating Decarbonization of the U.S. Energy System* (Washington, DC: National Academies Press, 2021), p. 81, which states, "Concurrent with the abatement measures [emissions reductions] above, implementation of negative emission technologies (NETs) and strategies is necessary to achieve net-zero emissions by 2050."

[13] IPCC SPM WGI 2021; NCA5 2023.

[14] IPCC SPM WGI 2021, p. 27.

Assessment report (NCA5), states that achieving net-zero CO_2 is necessary to achieve global temperature stabilization:

> From a physical science perspective, limiting human-induced global warming to a specific level requires limiting cumulative CO_2 emissions, reaching at least net zero CO_2 emissions, along with strong reductions in other greenhouse gas emissions.[15]

The Role of CDR in Temperature Stabilization

The Intergovernmental Panel on Climate Change (IPCC) examined a wide range of climate scenarios with varying socioeconomic assumptions and levels of climate change mitigation and found, "For virtually all scenarios assessed by the IPCC, CDR is necessary to reach both global net-zero CO_2 emissions and net-zero GHG emissions."[16] The USGCRP examined pathways that would limit global temperature increase to 2.0°C above preindustrial levels and published a similar finding:

> There is a limited range of pathways which enable the world to remain below 3.6°F (2°C) of warming ... and almost all ... are heavily reliant on the implementation of CO_2 removal from the atmosphere later in the century or other climate intervention ...[17]

The findings of the IPCC and the USGCRP both support a role for CDR in stabilizing global temperatures to mitigate the risk of greater climate impacts associated with temperatures above such stabilization.

Climate scenarios represent a combination of projected socioeconomic, emissions, and climate factors associated with a specific outcome, such as keeping global average temperature at or below a selected threshold.[18] Scientists use climate simulation models to determine which scenarios may result in net-zero GHG emissions and temperature stabilization. These scenarios can include CDR as an option, where anthropogenic methods supplement natural carbon removal from the atmosphere.

If temperature stabilization were achieved, it would not halt all climate impacts already under way. Other parts of the climate system may respond more slowly than temperature. For example, studies estimate that it would take decades to reverse the decline in permafrost, and centuries to halt sea-level rise.[19]

To stabilize global temperatures at a specific level, atmospheric CO_2e levels must also stabilize at the level that corresponds to that temperature. For example, stabilizing global temperatures at specific warming levels, such as 1.5°C or 2.0°C, requires limiting the level of CO_2e in the atmosphere to a level that corresponds to that temperature. As a result, emissions reductions and CDR are linked in the effort to stay at or below that CO_2e level. The more CO_2e emissions are

[15] IPCC SPM WGI 2021, p. 27.

[16] IPCC, "Framing, Context, and Methods," in *Climate Change 2021: The Physical Science Basis—Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, 2021, Box 1.4, p. 242 (hereinafter AR6 WGI 2021, Chapter 1). *Net-zero GHG emissions* refers to a balance of global warming potential between the removal of CO_2 from the atmosphere and the emission of all greenhouse gases, some of which, like methane, have a greater warming effect than CO_2.

[17] USGCRP, "Chapter 2: Climate Trends," in *Fourth National Climate Assessment*, 2017, p. 399 (hereinafter USGCRP NCA4, 2017).

[18] A. Pirani et al., "Scenarios in IPCC Assessments: Lessons from AR6 and Opportunities for AR7," *npj Climate Action*, vol. 3, no. 1 (2024), p. 1.

[19] IPCC, "Global Carbon and Other Biogeochemical Cycles and Feedbacks," in *Climate Change 2021: The Physical Science Basis—Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, 2021, FAQ 5.3, pp. 775-776 (hereinafter AR6 WGI 2021, Chapter 5).

reduced, the less CDR is required to stay below the CO_2e concentration level needed for global temperature stabilization at a specific level. In addition, if emissions reductions are delayed, a greater use of CDR is needed to stabilize temperatures than if emissions reductions happen earlier.[20]

The Role of CDR in Compensating for Hard-to-Abate Residual Emissions

It may not be possible to achieve net-zero CO_2e emissions through emissions reductions alone, as it may not be possible to eliminate all anthropogenic emissions of CO_2 and other GHGs. The hard-to-abate emissions remaining after emissions reduction efforts are known as *residual emissions*. Some industries, such as steel and cement, are difficult to decarbonize due to industry-specific heat, materials, and process requirements, which result in CO_2 emissions.[21] Steel is an alloy that includes carbon and iron, requiring a carbon source and extremely high temperatures for its manufacture, a process that emits CO_2.[22] The production of cement requires *clinker*, a substance produced from limestone in a process that emits CO_2.[23] In the case of both steel and cement, CO_2 emissions are part of the chemical process of production.

Emissions from a range of industries and economic sectors may be difficult to eliminate and may require CDR to achieve net-zero CO_2e emissions. Methods to eliminate emissions from the steel and cement industries are expensive, not fully developed, or as yet unknown.[24] There are also economic and regulatory difficulties in reducing emissions from the agricultural sector.[25] Thus, emissions from these industries and the agricultural sector may persist as residual emissions. CDR may be necessary to balance these residual emissions and achieve net-zero CO_2e emissions.[26] In addition, some emissions from other economic sectors, including some involving

[20] J. Strefler et al., "Between Scylla and Charybdis: Delayed Mitigation Narrows the Passage Between Large-Scale CDR and High Costs," *Environmental Research Letters*, vol. 13, no. 4 (2018), p. 044015. See also K. Riahi et al., "Locked into Copenhagen Pledges—Implications of Short-Term Emission Targets for the Cost and Feasibility of Long-Term Climate Goals," *Technological Forecasting and Social Change*, vol. 90 (2015), p. 8.

[21] Samantha Gross, *The Challenge of Decarbonizing Heavy Industry*, Brookings Institution, June 24, 2021, https://www.brookings.edu/research/the-challenge-of-decarbonizing-heavy-industry/. This source provides examples of industry feedstocks that produce emissions: "Steelmaking uses coal both as a source of heat and as part of the chemical process of converting iron ore to elemental iron. Both of these uses produce carbon dioxide." The report also notes, "Cement production also releases CO_2 as part of the chemical process, in this case when limestone is heated to very high temperature to produce calcium oxide 'clinker,' the cement's primary component."

[22] Warren Cornwall, "Steel Industry Emissions Are a Big Contributor to Climate Change. Can It Go Green?" *Science*, vol. 384, no. 6695 (2024), https://www.science.org/content/article/steel-industry-emissions-big-contributor-climate-change-can-go-green#:~:text=Steelmaking%2C%20the%20fiery%20process%20that%20undergirds%20modern%20life%2C,releases%20a%20second%2C%20bigger%20surge%20of%20carbon%20dioxide.

[23] British Broadcast Corporation, "Climate Change: The Massive CO_2 Emitter You May Not Know About," https://www.bbc.com/news/science-environment-46455844.

[24] AR6 WGI 2021, Chapter 1, p. 242.

[25] Sinead Leahy et al., "Challenges and Prospects for Agricultural Greenhouse Gas Mitigation Pathways Consistent with the Paris Agreement," *Frontiers in Sustainable Food Systems*, vol. 4 (2020). This publication states the following:

> While substantial reductions in agricultural emissions could in theory be achieved through the widespread introduction of price-based policies, or through equally ambitious regulations or other measures with an implicit price, current evidence suggests considerable reluctance to apply stringent climate policies to agriculture even in developed countries.

[26] IPCC, "Cross Sectoral Perspectives," in *Climate Change 2022: Mitigation of Climate Change, Working Group III Contribution to the IPCC Sixth Assessment Report*, 2022, pp. 12-33 (hereinafter IPCC AR6 WGIII 2022).

non-CO_2 GHGs, may continue after emissions reduction efforts, resulting in the need for CDR to balance these remaining residual emissions as well.[27]

Types of CDR

As part of the earth's carbon cycle, the oceans and the land surface both emit CO_2 and absorb CO_2, thereby exchanging CO_2 with the atmosphere. When emitting CO_2, they are referred to as *sources*, and when absorbing CO_2, they are referred to as *sinks.* For about the last 10,000 years—until the addition of anthropogenic emissions starting with the industrial revolution—these natural sources and sinks were approximately in balance.[28] To restore the pre-industrial-revolution balance between CO_2 emissions and absorption, the additional anthropogenic CO_2 emissions would need to be removed. CDR might be used for this removal through increasing the absorption and storage of CO_2 by the terrestrial (land) sink, increasing absorption and storage of CO_2 by the ocean sink, or developing new human-created sinks.

The enhancement of the land sink, which occurs by increasing the absorption of CO_2 through agriculture, forestry, and other land uses (AFOLU), is sometimes referred to as a form of *nature-based* CDR.[29] The creation of new anthropogenic sinks by technological means, such as *direct air capture* (DAC) and *bioenergy carbon capture and storage* (BECCS), are sometimes referred to as *technological* CDR.[30] Ocean-based CDR includes both nature-based and technological CDR. Some types of CDR, such as *biochar* and *enhanced weathering*, are less mature and may be referred to as *emerging* CDR approaches. A comprehensive discussion of the full range of all types of CDR is a specialized topic and beyond the scope of this report.

Nature-Based CDR Using Agriculture and Forestry

One method of removing CO_2 from the atmosphere would be to increase its absorption or uptake on land in terrestrial carbon sinks, such as forests and soils. This can be done through agriculture-based CDR or forestry-based CDR.

Agriculture-Based CDR

Agricultural CDR involves increasing the amount of carbon stored in the soil by increasing additions of carbon-rich material, such as crop residue or animal manure, to the soil and reducing losses of soil organic matter.[31] These techniques include the use of cover crops, the reduction of tillage, and the addition of organic material. According to researchers, these are mature agricultural techniques that are well understood and currently available for use at the scale necessary to increase carbon storage.[32]

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[27] IPCC AR6 WGIII 2022, pp. 12-33.

[28] IPCC, *Climate Change 2007: The Physical Science Basis—Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, 2007, p. 514.

[29] IPCC AR6 WGIII 2022, pp. 774.

[30] G. Erbach and G. A. Victoria, "Carbon Dioxide Removal: Nature-Based and Technological Solutions," *Briefing: Towards Climate Neutrality*, European Parliamentary Research Service, 2021, https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/689336/EPRS_BRI(2021)689336_EN.pdf#page=5.

[31] See CRS In Focus IF11693, *Agricultural Soils and Climate Change Mitigation*, by Megan Stubbs. See also CRS In Focus IF11404, *Greenhouse Gas Emissions and Sinks in U.S. Agriculture*, by Megan Stubbs.

[32] K. Paustian et al., "Soil C Sequestration as a Biological Negative Emission Strategy," *Frontiers in Climate*, vol. 1 (2019).

Forestry-Based CDR

As trees grow, they absorb CO_2 from the atmosphere and store the carbon in their biomass.[33] Increasing the terrestrial carbon sink through forestry involves increasing tree biomass on the landscape. Techniques for increasing tree biomass include

- *afforestation* to increase the forested area in new, previously unforested locations;
- *reforestation* to increase the forested area in previously forested locations; and
- *forest management* to increase the amount of carbon per unit area stored in currently forested areas.

Forest-based CDR techniques are mature, well understood, and currently available for use at the scale necessary to increase carbon storage.[34] Additional techniques based on land management include sustaining forest ecosystem functions and lessening forest carbon emissions from wildfires and other disturbances.[35]

Ocean-Based CDR

The ocean's natural uptake of CO_2 from the atmosphere takes place by chemical and biological mechanisms.[36] Enhancing the biological and chemical mechanisms for increasing the ocean sink are areas of CDR research, but these methods are not currently deployed at a large scale.[37]

Ocean fertilization is an example of ocean-based CDR using biological mechanisms. It enhances biological processes on the ocean surface by applying appropriate nutrients to promote phytoplankton growth. These phytoplankton, in turn, remove CO_2 from the atmosphere by photosynthesis.[38] Research on this approach suggests that ocean fertilization would reduce the level of atmospheric CO_2, as a portion of the carbon removed by photosynthesis would remain in the ocean.[39]

Ocean alkalinity enhancement is an example of ocean-based CDR using chemical mechanisms. In this method, alkalinity is increased in the ocean through the addition of minerals alone or in

[33] For an overview of forest carbon accumulation, see CRS Report R46312, *Forest Carbon Primer*, by Katie Hoover and Anne A. Riddle.

[34] S. M. Smith et al., *The State of Carbon Dioxide Removal—2nd Edition*," 2024, states the following:

> Around 2 GtCO2 per year of CDR is taking place already. Almost all of this comes from conventional CDR methods—those methods that are well established and widely reported by countries as part of land use, land-use change and forestry (LULUCF) activities principally through afforestation/reforestation.

[35] T. A. Ontl et al., "Forest Management for Carbon Sequestration and Climate Adaptation," *Journal of Forestry*, vol. 118, no. 1 (2020).

[36] National Aeronautics and Space Administration (NASA) Earth Observatory, "The Ocean's Carbon Balance," accessed March 1, 2024, https://earthobservatory.nasa.gov/features/OceanCarbon.

[37] Committee on a Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration, Ocean Studies Board, Division on Earth and Life Studies, and National Academies of Sciences, Engineering, and Medicine, *A Research Strategy for Ocean-Based Carbon Dioxide Removal and Sequestration* (Washington, DC: National Academies Press, 2022).

[38] CRS Report R47172, *Geoengineering: Ocean Iron Fertilization*, by Caitlin Keating-Bitonti.

[39] P. W. Boyd, "Ocean Fertilization for Sequestration of Carbon Dioxide from the Atmosphere," in *Geoengineering Responses to Climate Change*, ed. T. Lenton and N. Vaughan (New York: Springer, 2013).

combination with electrochemical means.[40] This increase in alkalinity increases the ocean's uptake of CO_2 from the atmosphere.

Technology-Based CDR

In addition to enhancing the existing ocean and terrestrial carbon sinks, a range of stakeholders are developing and refining technology-based CDR methods. These include DAC, BECCS, and the emerging technologies of *enhanced weathering (EW)* and *biochar*. These methods are examples of human design and development to complement the natural processes that remove CO_2 from the atmosphere.

Direct Air Capture

Public- and private-sector stakeholders have demonstrated interest in DAC technologies, which use chemical processes to remove CO_2 directly from ambient air.[41] The removed CO_2 can subsequently be injected for sequestration in geological formations or used in industrial processes such as the production of concrete, plastics, and carbon fibers.[42] The technology is under development, and facilities are planned at several locations, in addition to an operational plant in Iceland.[43]

Separating gases from ambient air requires energy. The net removal of CO_2 varies depending on the energy source.[44] There is greater net removal of CO_2 by DAC if a lower-carbon energy source like wind, solar, or geothermal is used, and less if a higher-carbon energy source, like coal or natural gas, is used.[45]

Bioenergy Carbon Capture and Storage

BECCS removes CO_2 from the atmosphere through photosynthesis by trees and bioenergy crops, such as maize, sugarcane, and sugar beet. Energy is produced by burning biomass directly to

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[40] U.S. Geological Survey (USGS) defines *alkalinity* as follows: "The buffering capacity of a water body; a measure of the ability of the water body to neutralize acids and bases and thus maintain a fairly stable pH level." See USGS, "Alkalinity and Water," https://www.usgs.gov/special-topics/water-science-school/science/alkalinity-and-water.

[41] CRS In Focus IF11501, *Carbon Capture Versus Direct Air Capture*, by Ashley J. Lawson. Some exploratory studies are also examining the processes for capturing CO_2 from seawater instead of the atmosphere. These processes are sometimes called *direct ocean capture*, or DOC. See ARPA-E, "Direct Removal of Carbon Dioxide from Ocean Water," accessed March 1, 2024, https://arpa-e.energy.gov/technologies/exploratory-topics/direct-ocean-capture.

[42] A. Bashir et al., "Comprehensive Review of CO_2 Geological Storage: Exploring Principles, Mechanisms, and Prospects," *Earth-Science Reviews*, vol. 249 (2024), p. 104672. See also Marcileia Zanatta, "Materials for Direct Air Capture and Integrated CO2 Conversion: Advancement, Challenges, and Prospects," *ACS Materials Au*, vol. 3, no. 6 (2023), p. 576.

[43] Department of Energy (DOE), "Biden-Harris Administration Announces Up To $1.2 Billion For Nation's First Direct Air Capture Demonstrations in Texas and Louisiana," August 11, 2023, https://www.energy.gov/articles/biden-harris-administration-announces-12-billion-nations-first-direct-air-capture. See also M. Ozkan et al., "Current Status and Pillars of Direct Air Capture Technologies," *Science*, vol. 25, no. 4 (2022). See also *The Economist*, "The World's Biggest Carbon-Removal Plant Switches On," September 18, 2021, https://www.economist.com/science-and-technology/2021/09/18/the-worlds-biggest-carbon-removal-plant-switches-on.

[44] NASEM, *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*, 2019, p. 189 (hereinafter NASEM NET 2019).

[45] Using a carbon-based energy source such as coal results in CO_2 emissions that offset the CO_2 by DAC, reducing the net removal. See also NASEM NET 2019, p. 194. Geothermal energy is currently in use with a DAC installation in Iceland; see *The Economist*, "The World's Biggest Carbon-Removal Plant Switches On," September 18, 2021, https://www.economist.com/science-and-technology/2021/09/18/the-worlds-biggest-carbon-removal-plant-switches-on.

make electricity and by converting biomass to biofuels such as ethanol.[46] The CO_2 can then be put into long-term storage in geological formations.[47] While at least one BECCS facility was operational in the United States as of 2022, with other facilities and pilot projects planned, large-scale deployment of BECCS technology has not yet occurred.[48]

Emerging CDR Approaches

Biochar and enhanced weathering are less-mature technologies with respect to the potential for large-scale deployment for CDR. In EW, crushed and finely ground carbonate and silicate minerals are applied to soils. The weathering of these minerals removes CO_2 from the atmosphere.[49] This technique is in development as an active area of research, with one research group finding that EW's "potential to contribute large-scale CDR requires further integration of nation-by-nation quantitative analysis, together with large-scale pilot demonstrations supported by fundamental process studies and public engagement."[50] Biochar is a stable high-carbon material that can be applied to the soil and is produced from biomass using high temperature pyrolysis.[51]

Potential Effectiveness, Feasibility, Side Effects, and Co-benefits of CDR

The scientific discussion of the risks of CDR is complex, as experts have stated that there are risks associated with reliance on CDR as well as climate risks associated with implementation of what some regard as an insufficient level of CDR. This section presents illustrative information on the potential effectiveness, feasibility, side effects, and co-benefits of CDR. The information should not be considered comprehensive, as such a presentation is beyond the scope of this report.

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[46] M. A. Hayat et al., "Which Bioenergy with Carbon Capture and Storage (BECCS) Pathways Can Provide Net-Negative Emissions?" *International Journal of Greenhouse Gas Control*, vol. 135 (2024), p. 104164, states the following:

> In essence, BECCS is a process of capturing and storing CO_2 from a bioenergy conversion process that uses biomass feedstock to produce heat, electricity, or biofuels. Bioenergy conversion processes include combustion, anaerobic digestion, and fermentation.

[47] CRS Report R46807, *Greenhouse Gas Emissions Scenarios: Background, Issues, and Policy Relevance*, by Michael I. Westphal; Etsushi Kato and Yoshiki Yamagata, "BECCS Capability of Dedicated Bioenergy Crops Under a Future Land-Use Scenario Targeting Net Negative Carbon Emissions," *Earth's Future*, vol. 2, no. 9 (2014), pp. 421–39.

[48] Energy and Environmental Research Center, "Red Trail Energy CCS: First Operational Commercial-Scale CO_2 Capture and Storage Project in North Dakota," accessed February 23, 2024, https://undeerc.org/research/projects/redtrailenergyccs.html#discover-more. See also International Energy Agency (IEA), "Bioenergy with Carbon Capture and Storage," accessed February 23, 2024, https://www.iea.org/reports/bioenergy-with-carbon-capture-and-storage.

[49] D. J. Beerling et al., "Potential for Large-Scale CO2 Removal via Enhanced Rock Weathering with Croplands," *Nature*, vol. 583, no. 7815 (2020), p. 242 (hereinafter Beerling 2020).

[50] Beerling 2020.

[51] The U.S. Department of Agriculture (USDA) defines *pyrolysis* as follows: "Pyrolysis is the heating of an organic material, such as biomass, in the absence of oxygen." USDA, Agricultural Research Service, "What is Pyrolysis?" accessed March 1, 2024, https://www.ars.usda.gov/northeast-area/wyndmoor-pa/eastern-regional-research-center/docs/biomass-pyrolysis-research-1/what-is-pyrolysis/.

Risks to Effectiveness

One category of risk with respect to CDR is associated with its effectiveness, generally, and with specific reference to the category of agriculture, forestry, and other land uses CDR. As noted above, some have stated that CDR is essential, in combination with large-scale decarbonization, in order to achieve net-zero GHG emissions by 2050 and to limit the risk of harm from adverse climate impacts.[52] Other researchers have stated that there are risks to relying on CDR for this purpose. The IPCC states, for example, that "CDR deployed at scale is unproven, and reliance on such technology is a major risk in the ability to limit warming to 1.5°C."[53]

Some have stated the concern that such reliance might lead to delaying or avoiding current emissions reductions on the assumption that the effect of the CO_2 emitted will be counteracted through future CDR.[54] These researchers have stated the concern that it may be difficult to deploy a sufficient amount of CDR to balance the emissions under these circumstances.[55] If CDR does not function as anticipated, the risk of climate impacts could increase, and the range of mitigation options to avoid such impacts might be limited.[56] Some have questioned the future technical and economic viability of CDR and state that such a delay may create risks for communities that are more vulnerable to the effects of climate change.[57]

Some researchers have stated concerns regarding effectiveness that are specific to AFOLU CDR. One concern is the durability of carbon removal, a concern for AFLOU CDR, as forests and soils can act as either sources or sinks for atmospheric CO_2.[58] A forest fire or a change in agricultural tillage practices could return carbon to the atmosphere, and the CDR benefit from the soils and forests would then be lost. Some have stated an additional concern that efforts to enhance forest carbon stocks in one location will displace deforestation to a different location in a process known as *leakage.* Such leakage could reduce the climate mitigation effectiveness of the AFOLU CDR.[59]

Feasibility Concerns

Some have expressed a range of concerns about the feasibility of CDR. These have included concerns about the costs, scalability, and economic viability of some CDR methods. In particular, there is concern that such economic or biophysical constraints may cause CDR methods to fail to

[52] DOE, Office of Fossil Energy and Carbon Management, "Is CDR Necessary to Achieve Net-Zero by 2050?" in *Carbon Dioxide Removal Frequently Asked Questions*, https://www.energy.gov/sites/default/files/2021-11/Carbon-Dioxide-Removal-FAQs.pdf#page=5.

[53] IPCC, "Chapter 2: Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development," in *Global Warming of 1.5°C: An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*, 2018, p. 96.

[54] N. Grant et al., "The Policy Implications of an Uncertain Carbon Dioxide Removal Potential," *Joule,* vol. 5, no. 10 (2021), p. 2593.

[55] N. Grant et al., "Confronting Mitigation Deterrence in Low-Carbon Scenarios," *Environmental Research Letters*, vol. 16, no. 6 (2021), p. 064099 (hereinafter Grant 2021).

[56] Grant 2021.

[57] Kevin Anderson and Glen Peters, "The Trouble with Negative Emissions," *Science*, vol. 354, no. 6309 (2016), p. 182.

[58] T. Bhattacharyya et al., "Soil as Source and Sink for Atmospheric CO_2," in *Carbon Utilization: Applications for the Energy Industry*, ed. Malti Goel and M. Sudhakar (Singapore: Springer, 2017), p. 61. See also CRS Report R46312, *Forest Carbon Primer*, by Katie Hoover and Anne A. Riddle.

[59] Charlotte Streck, "REDD+ and Leakage: Debunking Myths and Promoting Integrated Solutions," *Climate Policy,* vol. 21, no. 6 (2021), p. 843.

achieve the CO_2 removal capacity necessary to stabilize the climate.[60] For some CDR methods, such as BECCS and ocean alkalinity enhancement, some have stated concerns that their implementation may be constrained by requirements for land, fertilizer resources, water, or mined minerals. For other CDR methods, such as biochar and EW, there are concerns regarding limited capacity to produce the carbon residue and the crushed rock necessary for these methods.

Some researchers have questioned the feasibility of stabilizing global temperatures using BECCS, as it has not been implemented at a commercial scale and there are uncertainties regarding scale-up and cost.[61] Some studies have scrutinized the implementation and the timeline for using BECCS.[62] Other studies indicate that the resources required to support BECCS could rival the requirements of current global food production.[63] Using BECCS to stabilize global temperature increases at or below 2°C is estimated to require the removal, by BECCS, of 3.3 gigatons of carbon per year by 2100.[64] The IPCC *Special Report on Global Warming of 1.5°C* found that this level of BECCS could require 25%-46% of the world's cropping area by 2100.[65] A study of this level of BECCS found that it is comparable to current U.S. and global agricultural resource requirements:

> [R]emoving 3.3 Gt of carbon per year from the atmosphere using BECCS would require the annual mobilisation of ... 60 to 371 Mt of nutrients (N and P_2O_5), 1250 to 2490M ha of marginal land in the US, and 7800 to 15700B m^3 of water. As a means of comparison, 17 Mt of N and P_2O_5 nutrients are used annually in the US, 721M ha of land are harvested for cereal production in the world ... and 7980B m^3 of water is withdrawn—including green water—for the world agriculture.[66]

Ocean-based CDR has not been implemented at a commercial scale, and there are uncertainties regarding scale-up and cost.[67] Some researchers have questioned the feasibility of ocean alkalinity enhancement at scale, due to the magnitude of mining the required minerals. A National Academies of Sciences, Engineering, and Medicine (NASEM) report estimated that the required mining effort would be equivalent to that of the global cement industry.[68]

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[60] P. Smith et al., "Biophysical and Economic Limits to Negative CO2 Emissions," *Nature Climate Change*, vol. 6, no. 1 (2016), p. 42. See also S. Fuss et al., "Betting on Negative Emissions," *Nature Climate Change*, vol. 4, no. 10 (2014), p. 850 (hereinafter Fuss 2014).

[61] Fuss 2014.

[62] G. F. Nemet et al., "Negative Emissions—Part 3: Innovation and Upscaling," *Environmental Research Letters*, vol. 13, no. 6 (2018).

[63] IPCC, *Global Warming of 1.5°C: An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*, 2018. On page 343 this report states the following:

> The average amount of BECCS in these pathways requires 25–46% of arable and permanent crop area in 2100. Land area estimates differ in scale and are not necessarily a good indicator of competition with, for example, food production, because requiring a smaller land area for the same potential could indicate that high-productivity agricultural land is used.

[64] P. Smith et al., "Biophysical and Economic Limits to Negative CO2 Emissions," *Nature Climate Change*, vol. 6, no. 1 (2016), p. 42.

[65] IPCC SR1.5 2018, p. 343.

[66] Mathilde Fajardy and Niall MacDowell, "Can BECCS Deliver Sustainable and Resource Efficient Negative Emissions?" *Energy & Environmental Science*, vol. 10, no. 6 (2017), p. 1389.

[67] Committee on a Research Strategy for Ocean-Based Carbon Dioxide Removal and Sequestration, Ocean Studies Board, Division on Earth and Life Studies, and NASEM, *A Research Strategy for Ocean-Based Carbon Dioxide Removal and Sequestration*, 2022, p. 17 (hereinafter NASEM OBCDR 2022).

[68] NASEM OBCDR 2022, p. 195.

Some researchers have raised concerns about the economic feasibility of direct air capture due to the wide range of estimates of potential costs associated with this developing technology.[69] Cost estimates vary based on the type of DAC technology used and whether the energy comes from a fossil fuel or renewable energy source.[70] Reliance on DAC would require a large scale-up, and there is uncertainty about the potential rate of implementation.[71]

Some researchers have also stated concerns about the feasibility of biochar and enhanced weathering. Although the methods of biochar pyrolysis and crushing stone for EW are well understood, these technologies have not been deployed on a large scale for CDR. There are potential limitations on production capacity for both methods and uncertainties regarding cost.[72]

Potential Side Effects

Some have raised concerns that different types of CDR may have unintended potential side effects. These side effects may be biophysical, such as changes to landscapes and ecosystems, or economic, such as changes to the cost of food.

Some researchers have expressed concerns about potential side effects of ocean-based methods of CDR. For ocean alkalinity enhancement, some researchers have raised concerns about the environmental impacts of the mining associated with this method of CDR. In addition, some researchers have stated concerns regarding potential unintended ecological effects to the ocean ecosystem of both ocean fertilization and the chemical mechanisms of ocean alkalinity enhancement.[73]

Both biochar and EW CDR methods involve the addition of materials to soils, which some researchers believe could lead to the potential addition of toxic substances. Some researchers have stated that the EW CDR method could result in the addition of heavy metals such as nickel and chromium to soils.[74] Nickel and chromium can have toxic effects on plants.[75] Some researchers have stated concerns that biochar could be a source of organic contaminants when added to soils, including polycyclic aromatic hydrocarbons (PAHs), and dioxins, as well as heavy metals.[76]

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[69] K. Sievert et al., "Considering Technology Characteristics to Project Future Costs of Direct Air Capture," *Joule*, vol. 8, no. 4 (2024), p. 979.

[70] The two main types of DAC technology are solid sorbent and liquid solvent approaches with energy sources that include natural gas and renewable hydrogen. See NASEM NET 2019, p. 223; see also S. Shayegh et al., "Future Prospects of Direct Air Capture Technologies: Insights From an Expert Elicitation Survey," *Frontiers in Climate*, vol. 3 (2021) (hereinafter Shayegh 2021).

[71] Shayegh 2021. See also NASEM, *Accelerating Decarbonization in the United States: Technology, Policy, and Societal Dimensions* (Washington, DC: The National Academies Press, 2024) (hereinafter NASEM 2024), which states on p. 424 that "technological options like BECCS and DAC are unlikely to be deployed at levels that would materially affect 2030 emissions, carbon sinks in the United States through 2030."

[72] J.C. Minx et al., "Negative Emissions—Part 1: Research Landscape and Synthesis," *Environmental Research Letters*, vol. 13, no. 6 (2018), p. 063001.

[73] NASEM OBCDR 2022, p. 195. See also p. 8.

[74] Fatima Haque, Yi Wai Chiang, and Rafael M. Santos, "Risk Assessment of Ni, Cr, and Si Release from Alkaline Minerals during Enhanced Weathering," *Open Agriculture*, vol. 5, no. 1 (2020), p. 166.

[75] S. Kumar et al., "Nickel Toxicity Alters Growth Patterns and Induces Oxidative Stress Response in Sweetpotato," *Frontiers in Plant Science*, vol. 13 (2022), p. 1054924. See also M. Shahid et al., "Chromium Speciation, Bioavailability, Uptake, Toxicity and Detoxification in Soil-Plant System: A Review," *Chemosphere*, vol. 178 (2017), p. 513.

[76] M. Brtnicky et al., "A Critical Review of the Possible Adverse Effects of Biochar in the Soil Environment," *Science of The Total Environment*, vol. 796 (2021), p. 148756.

Some researchers have suggested that the land area required for AFOLU CDR could compete with food production. The cost of food could increase as agricultural land is converted to forest, although price increases could be lower when afforestation occurs only in tropical areas rather than worldwide.[77]

Similarly, some researchers have stated the concern that implementation of BECCS as a CDR method could have the side effect of competition for agricultural resources, including arable land and water for crop production.[78] Some have proposed that in scenarios that include a range of CDR methods, possible competition for arable land and resources resulting from the implementation of BECCS might be avoided.[79] This might be accomplished by limiting BECCS feedstocks to waste forestry and agricultural biomass and limiting land use to areas already producing corn ethanol.[80]

Potential Advantages and Co-benefits

There are potential advantages and co-benefits associated with different types of CDR that are related to the particular implementation of each CDR mechanism. Some of these are specific to particular types of CDR and others are associated with more than one type. Some of the advantages and co-benefits of CDR are presented in this section.

AFOLU CDR may facilitate climate adaptation and biodiversity co-benefits.[81] Sequestering carbon in soils in the form of soil organic matter, a type of AFOLU CDR, can increase the amount of water available to plants.[82] This can be a climate change adaptation strategy, allowing crops to be less vulnerable to drought. In addition, some increases in soil organic matter are associated with crop yield increases in maize and wheat.[83]

BECCS has the unique co-benefit among types of CDR that it also produces energy, in addition to removing CO_2 from the atmosphere.[84] BECCS can be used to produce heat or electricity by combustion. It can also be used to produce biomass-derived hydrogen.[85]

Ocean alkalinity enhancement has the potential co-benefit of reducing ocean acidification that is driven by increased atmospheric CO_2 concentrations.[86] Reducing ocean acidification would have

[77] IPCC, *Climate Change 2014: Mitigation of Climate Change Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 2014, p. 841. See also U. Kreidenweis et al., "Afforestation to Mitigate Climate Change: Impacts on Food Prices Under Consideration of Albedo Effects," *Environmental Research Letters*, vol. 11, no. 8 (2016), p. 085001; and M. Wise et al., "Implications of Limiting CO_2 Concentrations for Land Use and Energy," *Science*, vol. 324, no. 5931 (2009), p. 1183.

[78] M. Bonsch et al., "Trade-Offs Between Land and Water Requirements for Large-Scale Bioenergy Production," *GCB Bioenergy*, vol. 8, no. 1 (2016), p. 11.

[79] NASEM, *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda* (Washington, DC: The National Academies Press, 2019), p. 8.

[80] NASEM 2024, p. 428.

[81] P. C. Buotte et al., "Carbon Sequestration and Biodiversity Co-Benefits of Preserving Forests in the Western United States," *Ecological Applications*, vol. 30, no. 2 (2020).

[82] Rattan Lal, "Soil Organic Matter and Water Retention," *Agronomy Journal*, vol. 112, no. 5 (2020), pp. 3265-3277.

[83] E. E. Oldfield et al., "Global Meta-Analysis of the Relationship Between Soil Organic Matter and Crop Yields," *SOIL*, vol. 5, no. 1 (2019).

[84] IEA, "Bioenergy with Carbon Capture and Storage," https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/bioenergy-with-carbon-capture-and-storage.

[85] M. Bui et al., "Delivering Carbon Negative Electricity, Heat and Hydrogen with BECCS—Comparing the Options," *International Journal of Hydrogen Energy*, vol. 46, no. 29 (2021), p. 15298.

[86] NASEM OBCDR 2022, p. 196. See also CRS Report R47300, *Ocean Acidification: Frequently Asked Questions*, by Caitlin Keating-Bitonti and Eva Lipiec.

a beneficial effect on some marine organisms that produce calcium carbonate to make shells and other skeletal structures.[87]

Both the biochar and EW CDR methods involve adding materials to soils. Some researchers have found that both methods may have co-benefits in promoting soil fertility.[88] Biochar may provide a source of plant nutrients in soil and may increase soil water-holding capacity.[89] EW CDR methods can increase soil pH, increasing nutrient availability for corn and soybean crops.[90]

DAC has the advantage of flexibility in terms of siting that could allow it to be implemented near favorable geological formations for carbon sequestration, reducing the need for pipeline transport.[91]

CDR and U.S. International Climate Commitments

The United States is a signatory to international climate agreements, and CDR is included in U.S. commitments under these agreements. The United Nations Framework Convention on Climate Change (UNFCCC) is the principal international treaty to acknowledge and address anthropogenic climate change. The United States ratified the treaty in 1992.[92] Pursuant to the 2015 Paris Agreement (PA), the second major subsidiary agreement under the UNFCCC,[93] countries must submit GHG emission reduction pledges referred to as nationally determined contributions (NDCs). Targets and actions pledged in the NDCs are nonbinding. The U.S. NDC is economy-wide and includes all anthropogenic GHG emissions and removals. In the 2021 NDC, the United States pledged to reduce net GHG emissions by 50%-52% below 2005 levels by 2030.[94]

In 2021 the Biden Administration published *The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050*, which included a policy goal consistent with the U.S. NDC.[95] A key aspiration of the Biden Administration's strategy is to achieve a 50%-52% GHG emissions reduction by 2030 (compared with 2005 levels). This goal is consistent with the PA to reduce the risks and impacts of climate change and with the NDC of the United States. The strategy includes scenarios that achieve these goals through a combination of

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[87] NASEM OBCDR 2022, p. 200.

[88] D. J. Beerling et al., "Potential for Large-Scale CO2 Removal via Enhanced Rock Weathering with Croplands," *Nature*, vol. 583, no. 7815 (2020), p. 242. See also S. Kuppusamy et al., "Agronomic and Remedial Benefits and Risks of Applying Biochar to Soil: Current Knowledge and Future Research Directions," *Environment International*, vol. 87, (2016), p. 1.

[89] Y. Ding et al., "Biochar to Improve Soil Fertility. A Review," *Agronomy for Sustainable Development*, vol. 36, no. 2 (2016), p. 36.

[90] D. J. Beerling et al., "Enhanced Weathering in the US Corn Belt Delivers Carbon Removal with Agronomic Benefits," *Proceedings of the National Academy of Sciences*, vol. 121, no. 9 (2024), p. e2319436121.

[91] NASEM, "Chapter 5: Direct Air Capture," in *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*, 2018. The report states, "Direct air capture systems benefit from their inherent flexibility of placement, which can reduce the need for pipelines from the capture site to the sequestration reservoir" (p. 189).

[92] U.S. Treaty Number 102-38.

[93] See CRS Report R46204, *The United Nations Framework Convention on Climate Change, the Kyoto Protocol, and the Paris Agreement: A Summary*, by Richard K. Lattanzio.

[94] The United States of America, "The United States' Nationally Determined Contribution Reducing Greenhouse Gases in the United States: A 2030 Emissions Target," submitted by the United States to the UNFCCC Secretariat on April 22, 2021, https://unfccc.int/NDCREG.

[95] U.S. Department of State and U.S. Executive Office of the President, "The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050," November 2021.

emissions reductions and CDR. CO_2 removal by CDR methods accounts for between 10% and 20% of total net-zero GHG emissions reduction in these scenarios.

Congressional Actions

This section provides a description of congressional actions regarding carbon dioxide removal in the 117th and 118th Congresses and a brief description of earlier congressional action in support of CDR. This summary of congressional activity is not a comprehensive review of climate-related legislation, which is beyond the scope of this report.

Early Congressional Action in Support of CDR

Early congressional action in support of CDR included research and development funds specifically for CDR, as well as incentives to support CDR.[96] The Energy Act of 2020 (enacted as Division Z of P.L. 116-260) included support for research and development of CDR methods including direct air capture; bioenergy carbon capture and storage; agriculture, forestry, and other land uses; enhanced weathering; and other CDR-related activities.[97]

In addition to supporting research, and development of specific approaches to CDR, some in Congress have expressed interest in the potential for CDR to contribute to achieving net-zero CO_2 emissions by 2050 and federal actions that may be needed to promote this outcome. Section 5002 of the Energy Act of 2020 directed the Secretary of Energy to prepare a report on CDR that would[98]

- estimate the amount of CO_2 that would need to be removed from the atmosphere to reach the net-zero emissions by 2050 climate goal;
- inventory the types of CDR methods available and under development and assess their advantages and disadvantages; and
- identify policy tools the federal government could use to advance the deployment of CDR projects to achieve the level of removal of CO_2 consistent with the net-zero emissions by 2050 climate goal. These policy tools include grants, loans, loan guarantees, public-private partnerships, direct procurement incentives that include federal financing mechanisms available to project developers, advance market commitments, and regulations.

The 117th Congress

In 2022, the 117th Congress passed the Infrastructure Investment and Jobs Act (IIJA),[99] the CHIPS Act of 2022,[100] and the measure commonly known as the Inflation Reduction Act of 2022 (IRA).[101] These laws provided funding and support for CDR. The IRA was the most

[96] For information about appropriations to CDR R&D at DOE, see CRS In Focus IF11861, *DOE's Carbon Capture and Storage (CCS) and Carbon Removal Programs*, by Ashley J. Lawson. For information about federal tax incentives for DAC, see CRS In Focus IF11861, *DOE's Carbon Capture and Storage (CCS) and Carbon Removal Programs*, by Ashley J. Lawson.

[97] P.L. 116-260.

[98] As of February 28, 2024, this report was in preparation by DOE. CRS requested a status update regarding this report on August 16, 2024; as of November 4, 2024, no update had been provided.

[99] P.L. 117-58.

[100] P.L. 117-167.

[101] P.L. 117-169.

comprehensive and fiscally largest climate legislation in U.S. history.[102] The IIJA and the CHIPS Act provided additional appropriations for climate provisions supporting CDR.

The IIJA provides appropriations for a range of CDR programs and approaches. Some programs are funded through the U.S. Department of Energy (DOE), including some new programs.[103] These programs include the following:

- **Regional Direct Air Capture Hubs.** The IIJA includes $3.5 billion in funding opportunities for eligible applicants, for the development of four Regional Direct Air Capture Hubs that would each have the capacity to capture, store, and/or utilize at least 1 million tons of atmospheric CO_2 each year.[104] These hubs are to be preferentially sited in industrial areas or in areas of fossil fuel production.[105]
- **Carbon Dioxide Transportation Infrastructure.** DOE programs funded by the IIJA support the development of the transportation and storage components that could be part of a complete CDR system using either DAC or BECCS. The Carbon Dioxide Transportation Infrastructure Finance and Innovation (CIFIA) program finances common carrier transport projects to "move CO_2 from points of capture to conversion facilities and/or storage wells."[106] This $2.1 billion program is intended to provide capital to CO_2 pipeline projects as well as other means of CO_2 transportation.
- **Commercial-Scale Carbon Storage.** The IIJA also funds DOE research, development, and deployment of commercial-scale carbon storage projects that could receive captured CO_2 from multiple sources and locations.[107] These programs seek to support the construction of infrastructure that could be used for transporting and sequestering CO_2. DAC facilities have siting flexibility that could facilitate collocation near storage sites; in other instances, they could be situated near other carbon capture facilities and share transportation infrastructure.[108]

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[102] U.S. Department of the Treasury, "The Inflation Reduction Act: Pro-Growth Climate Policy," November 13, 2023, https://home.treasury.gov/news/featured-stories/the-inflation-reduction-act-pro-growth-climate-policy#:~:text=The%20 Inflation%20Reduction%20Act%20 (IRA,investment%20in%20our%20economic%20growth.

[103] CRS In Focus IF11861, *DOE's Carbon Capture and Storage (CCS) and Carbon Removal Programs*, by Ashley J. Lawson. See also DOE, "The Infrastructure Investment and Jobs Act: Opportunities to Accelerate Deployment in Fossil Energy and Carbon Management Activities," accessed March 1, 2024, https://www.energy.gov/sites/default/ files/2022-09/FECM%20Infrastructure%20Factsheet-revised%209-27-22.pdf.

[104] Eligible applicants include institutions of higher education, for-profit entities, nonprofit entities, state and local governmental entities, and tribal nations. For a description of the program, see DOE Office of Clean Energy Demonstrations, "Regional Direct Air Capture Hubs Update," https://www.energy.gov/oced/regional-direct-air-capture-hubs-update.

[105] 42 U.S.C. §16298d.

[106] DOE, "Carbon Dioxide Transportation Infrastructure," accessed March 1, 2024, https://www.energy.gov/lpo/ carbon-dioxide-transportation-infrastructure.

[107] CRS In Focus IF11861, *DOE's Carbon Capture and Storage (CCS) and Carbon Removal Programs*, by Ashley J. Lawson. See also description of the funding opportunity, including a list of eligible applicants, in DOE Office of Fossil Energy and Carbon Management, "Funding Notice: Bipartisan Infrastructure Law: Carbon Storage Validation and Testing," https://www.energy.gov/fecm/funding-notice-bipartisan-infrastructure-law-carbon-storage-validation-and-testing.

[108] M. Batres et al., "Environmental and Climate Justice and Technological Carbon Removal," *The Electricity Journal, Special Issue: Carbon Capture and Storage Today: Applications, Needs, Perceptions and Barriers*, vol. 34, no. 7 (2021), p. 107002.

Congress has also enacted legislation and funding to support the development and deployment of projects related to carbon capture and storage (CCS). These include carbon storage, such as targeted appropriations to federal agencies for development and deployment of carbon storage sites, and federal tax credits designed to incentivize development of DAC, geologic sequestration of CO_2, and other CCS-related projects. Provisions in the IRA support DAC facilities by increasing the federal tax credit for CO_2 captured and stored using DAC and reducing the threshold capture level of CO_2, thereby making the tax credit available to smaller, pilot-phase facilities.[109] The IRA increases the tax credit available for DAC from $50 per ton to $180 per ton of permanently stored CO_2.[110]

Both the IIJA and the IRA provide funding for AFOLU CDR through a variety of programs and approaches. IIJA Section 70301 (the Repairing Existing Public Land by Adding Necessary Trees [REPLANT] Act) increased resources for reforestation by removing the annual $30 million funding limit on the Reforestation Trust Fund.[111] The IRA provides funding for conservation practices that sequester carbon through the U.S. Department of Agriculture's Environmental Quality Incentives Program, the Regional Conservation Partnership Program, the Agricultural Conservation Easement Program, and the activities of the Natural Resources Conservation Service.[112]

The CHIPS Act of 2022 includes a $1 billion appropriation for research and development of carbon removal.[113] Part of the research allocation is for basic research on the subsurface sequestration of CO_2.

The 118th Congress

Some Members have introduced legislation in the 118th Congress associated with carbon dioxide removal. This includes legislation that would support the implementation of mechanical and nature-based CDR, as well as legislation that would support research and development of CDR. Legislation has also been introduced to reverse previously enacted tax incentives for CDR.

Examples of CDR legislation introduced in the 118th Congress are presented here. This is not a comprehensive presentation of such proposed legislation, as that would be beyond the scope of this report.

Legislation has been introduced in the 118th Congress that would support CDR implementation by

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109 CRS Report R47262, *Inflation Reduction Act of 2022 (IRA): Provisions Related to Climate Change*, coordinated by Jane A. Leggett and Jonathan L. Ramseur. See also IEA, "Section 45Q Credit for Carbon Oxide Sequestration," accessed March 1, 2024, https://www.iea.org/policies/4986-section-45q-credit-for-carbon-oxide-sequestration. The carbon sequestration tax credit increase applies to certain facilities that meet criteria for date of start of construction and wage and apprenticeship requirements.

110 CRS In Focus IF11501, *Carbon Capture Versus Direct Air Capture*, by Ashley J. Lawson. See also IEA, "Section 45Q Credit for Carbon Oxide Sequestration," accessed March 1, 2024, https://www.iea.org/policies/4986-section-45q-credit-for-carbon-oxide-sequestration. For more information on the 45Q tax credit, see CRS In Focus IF11455, *The Section 45Q Tax Credit for Carbon Sequestration*, by Angela C. Jones and Donald J. Marples.

111 CRS Report R47263, *Ecosystem Restoration in the Infrastructure Investment and Jobs Act: Overview and Issues for Congress*, coordinated by Anna E. Normand and Pervaze A. Sheikh. See also P.L. 117-58 §70302.

112 CRS Report R47262, *Inflation Reduction Act of 2022 (IRA): Provisions Related to Climate Change*, coordinated by Jane A. Leggett and Jonathan L. Ramseur. See also U.S. Department of Agriculture, "Climate-Smart Agriculture and Forestry," accessed March 1, 2024, https://www.farmers.gov/conservation/climate-smart.

113 P.L. 117-167 §10771 (6)(c): "$1,000,000,000 to carry out carbon removal research, development, and demonstration activities."

- directing the Secretary of Energy to implement the removal of CO_2 from ambient air or seawater using a variety of technologies, excluding nature-based technologies reliant on photosynthesis (H.R. 7054);
- promoting carbon sequestration in soils and forests through revegetation projects (S. 2991) including on federal, nonfederal, and abandoned mine land;
- providing incentive payments for the adoption of soil conservation practices for carbon sequestration (H.R. 5043), with priority for small producers, those in rural areas, and socially disadvantaged farmers;
- providing grants for proposals to sequester carbon on agricultural land and increase resilience to extreme weather and climate conditions (H.R. 7146); and
- providing incentive payments to private landowners to adopt forestry practices that increase carbon sequestration with credit for the carbon benefits of harvested wood products (S. 1366).

Multiple bills introduced in the 118th Congress include components that would support research and development of CDR methods as well as CDR pilot projects. Examples include the following:

- One bill (H.R. 5457) would include support for CDR research in a range of federal agencies and support for research on a range of types of CDR and related topics. The topics include direct air capture, bioenergy carbon capture and storage, enhanced weathering, biochar, soil carbon sequestration, forest management, coastal marine carbon research, alkalinity research, ocean fertilization, mined land restoration, carbon sequestration in cement, social impacts of CDR, preservation of harvested wood, and genetic research to improve carbon uptake.
- Several bills would support research specifically on soil carbon sequestration, including H.R. 2241 and H.R. 6232. The latter also would support the creation of an interagency committee to develop a cross-agency research plan for soil carbon measurement and monitoring technologies.
- S. 732 would provide specific support for research on biochar through the establishment of a biochar research network administered by the Agricultural Research Service.
- H.R. 7797 would promote research on ocean fertilization through a pilot program that includes applied research and ecosystem monitoring through the use of demonstration projects.

Other proposed legislation could reduce support for CDR. H.R. 2811 would reverse the tax credit for removing carbon emissions through changes to the Qualifying Advanced Energy Project Credit (26 U.S.C. §48C). Such a change could reduce the tax incentives available for CDR projects, if they fall in this category.

Considerations for Congress

Congress has passed legislation that includes provisions to support a range of carbon dioxide removal activities and approaches. Congress may wish to obtain information on the full scope of federal CDR activities. As stated above, Section 5002 of the Energy Act of 2020 directed the Secretary of Energy to prepare a report on CDR.[114] The report is to include information on the estimated amount of CO_2 removal needed to reach the net-zero emissions by 2050 climate goal, an inventory of CDR methods, and identification of federal policy tools to advance CDR deployment. NASEM has published a report that includes some of these aspects in a broader analysis of decarbonization in the United States.[115] Requiring a future report complementing these reports, with information on the allocation of the federal resources of the federal CDR effort and projected CDR funding required to maintain the trajectory to achieve net-zero GHG emissions, may be considered by Congress.

A recent NASEM report, *Accelerating Decarbonization in the United States: Technology, Policy, and Societal Dimensions*, included the results of an analysis of the potential for CDR to contribute to the United States achieving the climate goal of net-zero emissions by 2050.[116] The report examined greenhouse gas emissions scenarios that would allow the United States to achieve net-zero GHG emissions by 2050 and found that most of these scenarios would include a combination of CDR methods.[117] The report states that funding for CDR under the Inflation Reduction Act, specifically for forestry programs, is theoretically consistent with a net-zero trajectory, but that there is a high degree of uncertainty regarding the success of this implementation.[118]

With respect to components of the report specified in Section 5002 of the Energy Act of 2020 and noted earlier, the NASEM report addresses some components and not others. The report provides a range of estimates of the amount of CO_2 removal needed to reach the net-zero emissions by 2050 climate goal. The NASEM report describes some types of CDR, such as BECCS and afforestation, but does not inventory all CDR methods under development or assess their advantages and disadvantages. The report makes general policy recommendations regarding BECCS and some AFOLU CDR, but does not include all of the specific policy tools listed in Section 5002 of the Energy Act of 2020.

While the NASEM report provides an assessment of CDR in the context of the goal of net-zero GHG emissions by 2050, and although the DOE report is intended to provide an inventory of federal policy tools to advance CDR deployment, these reports may not be comprehensive. They may not fully evaluate the effectiveness, feasibility, side-effects, co-benefits, and allocation of

[114] P.L. 116-260.

[115] NASEM 2024.

[116] NASEM 2024.

[117] NASEM 2024, p. 423. "Most net-zero emissions budgets for the United States assume midcentury sinks totaling 1 GtCO2/y plus or minus several hundred MtCO2/y from a mix of forestry, agriculture, and industrial carbon removal methods like BECCS and direct air capture (DAC)."

[118] NASEM 2024, p. 438, states the following:

> The $5 billion of forestry funding in the IRA is theoretically sufficient to create additional terrestrial carbon sinks as large as those in simple net-zero trajectories. There is sufficient land available to stay well within the safe limits proposed by the National Academies, and to avoid likely impediments caused by low landowner adoption rates. However, the actual performance of the terrestrial sink provisions in the IRA is still highly uncertain for several reasons, including unpredictable climate, demand for fuel and food, and changes in afforestation, reforestation, and development.

federal resources for the federal CDR effort (encompassing all federal CDR programs) in contributing to achieving net-zero GHG emissions by 2050 and an evaluation of additional resources that may be needed to achieve this goal. A report to address such knowledge gaps could include an evaluation of the projected CDR funding required to maintain the trajectory to achieve net-zero GHG emissions by 2050. This could include options for funding beyond 2030 and the end of funding under the IRA. Congress may choose to direct research on any or all of these or other knowledge gaps or direct the preparation of a report on CDR that includes all of the currently proposed types of CDR.

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