U.S. DEPARTMENT OF ENERGY

# Carbon Dioxide Removal: Purpose, Approaches, and Recommendations

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United States Department of Energy
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# Draft for Public Comment

Section 5002 of the Consolidated Appropriations Act, 2021 (Pub. L. 116-260, Div. Z, Tit. V, codified at 42 U.S.C. § 16298e) directed the Secretary of Energy, "in consultation with the heads of any other relevant Federal agencies, to prepare a report that—

1. Estimates the magnitude of excess carbon dioxide in the atmosphere that will need to be removed by 2050 to achieve net-zero emissions and stabilize the climate;
2. Inventories current and emerging approaches of carbon dioxide removal and evaluates the advantages and disadvantages of each of the approaches; and
3. Identifies recommendations for legislation, funding, rules, revisions to rules, financing mechanisms, or other policy tools that the Federal Government can use to sufficiently advance the deployment of carbon dioxide removal projects in order to meet, in the aggregate, the magnitude of needed removals estimated under paragraph (1), including policy tools, such as—
    a. grants;
    b. loans or loan guarantees;
    c. public-private partnerships;
    d. direct procurement;
    e. incentives, including subsidized Federal financing mechanisms available to project developers;
    f. advance market commitments;
    g. regulations; and
    h. any other policy mechanism determined by the Secretary to be beneficial for advancing carbon dioxide removal methods and the deployment of carbon dioxide removal projects."

The draft report that follows reflects the input of offices across the U.S. Department of Energy (DOE) and several Federal agencies working on carbon dioxide removal. Given how rapidly the carbon dioxide removal field is evolving, DOE is seeking public comment on the report through April 1, 2025 to ensure our analysis is as robust and reasonable as possible. DOE will synthesize feedback and then submit the final report to Congress.

# Executive Summary

Deploying carbon dioxide removal (CDR)—the process of directly removing carbon dioxide ($CO_2$) from the atmosphere—at scale is crucial for meeting domestic and global climate targets while boosting American economic competitiveness and energy security. The field is rapidly expanding today, with tremendous innovation coming from hundreds of new companies offering many approaches. The promise is great, but the work is just beginning. Most CDR efforts today have yet to remove $CO_2$ from the air beyond the small pilot size scale. Further research, including carefully controlled field trials, is needed to comprehensively evaluate the efficacy and potential impacts of various CDR approaches if deployed at large scale. Without increased support and research, solutions will not scale at the necessary pace. Further policy action can support the development of additional frameworks to ensure that CDR innovation and deployment enhances U.S. economic competitiveness, creates high quality jobs and investment opportunities across the nation, and advances environmental protection in communities where CDR is deployed.

In recognition of CDR's importance and the challenges it faces, Congress directed the U.S. Department of Energy (DOE) to deliver a report on CDR.[1] To inform this report, DOE organized an Interagency CDR Task Force to collect insights on CDR approaches, policies, and options from Federal staff representing ten agencies (see Appendix A. Summary of Federal Agency Activities Relevant to Carbon Dioxide Removal for more details).

Based on insights from the interagency team and published literature, this report identifies likely needs for future research and deployment of CDR, outlines current and emerging CDR approaches, provides a high-level assessment of the approaches, and offers insight into potential Federal policies and measures that could significantly contribute to the advancement of CDR deployment.

### *REPORT SCOPE AND STRUCTURE*

This report provides an analytical foundation to understand the U.S. Government's CDR strategy. The development of this report was led by DOE with significant input from multiple agencies. Additionally, the U.S. Department of Agriculture (USDA), the U.S. Department of the Interior (DOI), the U.S. Environmental Protection Agency (EPA), and the National Oceanic and Atmospheric Administration (NOAA) co-chaired the interagency CDR Working Group that contributed to this report.

For this report, CDR is defined as approaches that remove $CO_2$ from the atmosphere—not those that offer emissions reductions only. CDR encompasses a wide array of approaches, including direct air capture with storage, soil carbon sequestration, biomass carbon removal and storage (BiCRS), enhanced mineralization, marine CDR, and afforestation/reforestation. CDR does

[1] Section 5002(e) of the Energy Act of 2020 (Pub. L. No. 116-260, Div. Z, Title V, codified at 42 U.S.C. § 16298e(e)), also requires the Secretary to establish a CDR Task Force to assist in preparing the report, among other duties. In response, the Secretary established the CDR Working Group to preliminarily examine the matters identified in section 5002(e). Over time, the CDR Working Group may develop into a more formal CDR Task Force that will include non-government stakeholders.

not refer to point source carbon capture for industry or power generation. Paired with the simultaneous deployment of mitigation measures and other carbon management practices, CDR serves as a tool to address emissions from the hardest-to-decarbonize sectors, such as agriculture and transportation, and eventually remove legacy $CO_2$ emissions from the atmosphere.

This report relies primarily on existing literature and analyses, incorporating further analysis from DOE's Pacific Northwest National Laboratory on the need for CDR[2]. The report is not intended to be a comprehensive examination of CDR approaches nor a comprehensive analysis of benefits, impacts, or policies. This report also offers a menu of options for policymakers to expand support for responsible CDR development and deployment in the future, but these options do not necessarily reflect the Biden Administration's current policy.

Furthermore, although CDR overlaps with other biomass, nature-based, and point source carbon capture, use, and storage solutions, this report focuses specifically on technologies that generate net-removals of $CO_2$ from the air. While there is significant technological overlap between many carbon capture, use, and storage approaches, bioenergy technologies, and ecosystem conservation strategies, this report does not evaluate those fields comprehensively. See Table 1 for a detailed overview of this report's structure and coverage.

[2] M. Browning et al., Net-zero $CO_2$ by 2050 scenarios for the United States in the Energy Modeling Forum 37 study, Energy and Climate Change, Volume 4, 2023, 100104, ISSN 2666-2787, https://doi.org/10.1016/j.egycc.2023.100104

**Table 1: Overview of Covered and Excluded Topics in CDR Report**

| Overview of Covered and Excluded Topics in CDR Report | | | |
|---|---|---|---|
| | **Carbon Capture, Use, and Storage** | **Biomass** | **Nature-based solutions** |
| **In scope** | • Direct air capture<br>• Net-negative greenhouse gas emissions bioenergy + carbon capture, use, and storage<br>• Utilization with permanent storage (e.g., building materials) | • Net-negative greenhouse gas emissions bioenergy + carbon capture and storage<br>• Biomass burial | • Afforestation<br>• Reforestation<br>• Net-negative soil carbon storage<br>• Coastal ecosystem restoration |
| **Out of scope** | • Carbon capture, use, and storage in industry and power generation<br>• Lower-greenhouse gas emissions bioenergy + carbon capture, use, and storage<br>• Utilization for short-lived storage (e.g., chemicals and fuels) | • Lower-greenhouse gas emissions bioenergy + carbon capture and storage | • Avoided deforestation<br>• Avoided agriculture emissions<br>• Avoided coastal ecosystem emissions |

***A note on point source carbon capture, use, and storage***:

While the full carbon capture, use, and storage value chain is out of scope for this report, carbon capture, use, and storage are essential. DOE recently published a draft Carbon Management Strategy for public comment, which outlines how DOE is approaching the development of the carbon management industry in the United States. Many aspects of carbon capture, use, and storage are directly relevant to CDR solutions. In particular, the development of point source capture technologies has direct relevance to carbon-negative bioenergy carbon capture, use, and storage projects. The transport and storage infrastructure built to support point source carbon capture, use, and storage projects can also support CDR projects in the future. CDR projects can also benefit from the workforce, finance, and regulatory systems pioneered by point source carbon capture, use, and storage projects.

This report groups CDR strategies into two main categories: (1) technological approaches and (2) land management approaches. Technological approaches are further divided into:

- Direct air capture
- Biomass with carbon removal
- $CO_2$ mineralization
- Marine CDR

Land management approaches are further divided into:

- Forestry (including afforestation and reforestation)
- Agricultural soil carbon

This report also focuses only on atmospheric $CO_2$ removal, not the removal of other greenhouse gases from the atmosphere.

**Note:** For all the solutions listed above, the technologies in the categories listed will not inherently produce negative emissions. For example, direct air capture systems without secure geologic storage or its equivalent can produce near-zero, but not negative emissions. Similarly, biomass used in CDR processes must be produced with low- or zero- greenhouse gas emissions for systems to generate negative emissions.

## Need for Decarbonization and Carbon Dioxide Removal

Achieving net-zero emissions by midcentury will require rapidly decarbonizing the global economy and reducing emissions from the power, transportation, industrial, commercial, and residential sectors.

For virtually all scenarios assessed by the Intergovernmental Panel on Climate Change (IPCC) in Working Group III's contribution to the Sixth Assessment Report, CDR is necessary to reach global net-zero greenhouse gas emissions.[3] However, in no scenario is large-scale CDR a cost-effective or scientifically feasible replacement for rapid emissions cuts. As a result, policy to support the emergence of CDR should be designed to complement, not substitute, emissions avoidance or reduction. While this report focuses on how much CDR is needed in the United States to achieve emissions targets by 2050, it is important to note that CDR is the only way to reverse an "overshoot" of emissions (when global warming exceeds a threshold) if the world does not achieve net-zero greenhouse gas emissions in time to limit warming to 1.5° or 2°C.[4]

The total amount of CDR needed in the United States to meet future emissions targets is difficult to predict. It will depend on three factors: 1) the amount of current and future greenhouse

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3 *Climate Change 2022: Mitigation of Climate Change*. Intergovernmental Panel on Climate Change (2022). Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/ar6/wg3/

4 42 U.S.C. § 16298e(b)(1)

gas emissions that cannot feasibly be completely eliminated and/or that arise from feedback loops triggered by present and future emissions, such as agricultural nitrous oxide emissions from fertilizer (so-called residual emissions); 2) the speed and scale of emissions avoidance and reduction between now and 2050, which in turn depends on uncertain rates of technology innovation, economic growth, and policy change around the world; and 3) choices the United States may make for economic or policy reasons to continue emitting, such as continuing the use of some petroleum-based fuels. Beyond these 2050 goals, the United States may choose to conduct additional CDR operations to actively reduce $CO_2$ levels in the air.

Taking these factors into account, an analysis conducted by Pacific Northwest National Laboratory for this report projects that the United States may need to deploy enough CDR to remove between 0.5 and 2.4 billion metric tonnes of $CO_2$ per year (GT $CO_2$/year) to achieve net-zero emissions by 2050.[5] Pathways examined in the White House's *The Long-Term Strategy of the United States to Reach Net-Zero Greenhouse Gas Emissions by 2050*[6] provide an estimate for the likely residual emissions of approximately 0.5 GT $CO_2$/year. Without knowing exactly how effective, and how fast, overall U.S. emissions reduction strategies will be, it is necessary to create a policy and technical landscape that can deliver CDR solutions anywhere within the rating range of 0.5 (nearly perfect other greenhouse gas control activities) to 2.4 (multiple delays in other activities) GT $CO_2$/year by 2050.

The United States is a global leader in CDR technologies today, thanks to provisions in the Infrastructure Investment and Jobs Act (more commonly referred to as the Bipartisan Infrastructure Law or BIL),[7] the Inflation Reduction Act, the CHIPS and Science Act, as well as annual appropriations for CDR-funded activities by DOE and other agencies. Moving forward, CDR represents a new frontier for U.S. leadership in technology commercialization, workforce development, and advanced manufacturing, and potentially in exporting CDR credits to help other countries achieve their emissions targets as quickly and cost-effectively as needed.

A more detailed discussion of the U.S. Government's strategy for scaling CDR is included in subsequent sections of this Executive Summary and the main report that follows. Rigorously pursuing the fundamental research and establishing policy frameworks to support these activities is needed not only to address climate change, but also to advance U.S. national security, and scientific and economic leadership.

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[5] M. Browning *et al*., Net-zero $CO_2$ by 2050 scenarios for the United States in the Energy Modeling Forum 37 study, Energy and Climate Change, Volume 4, 2023, 100104, ISSN 2666-2787, https://doi.org/10.1016/j.egycc.2023.100104

[6] *The Long-term Strategy of the United States - Pathways to Net-Zero Greenhouse Gas Emissions by 2050*. The White House. (2021). https://www.whitehouse.gov/wp-content/uploads/2021/10/US-Long-Term-Strategy.pdf

[7] Infrastructure Investment and Jobs Act, Public Law 117-58 (November 15, 2021). https://www.congress.gov/bill/117th-congress/house-bill/3684 This report uses the more common name Bipartisan Infrastructure Law (BIL).

## Short Term (by 2030) Targets for Carbon Dioxide Removal Solutions

At present, only some land management approaches to CDR are included in the U.S. national greenhouse gas emissions inventory[8] (e.g., greenhouse gas emissions flux estimates associated with emerging approaches like enhanced weatherization are not included in national greenhouse gas inventories). While the United States does not have a dedicated near-term target for land-based CDR volumes, existing approaches such as reforestation and cover cropping are included in broader plans to mitigate land sector emissions and increase natural carbon sinks, as outlined in the White House's *Opportunities to Accelerate Nature-Based Solutions: A Roadmap for Climate Progress* (2022).[9] Furthermore, according to the Lawrence Livermore National Laboratory's Roads to Removal report,[10] there is capacity for over 100Mt/y of additional CDR from forests and soils across the United States accessible by 2030 with sufficient incentive and financing mechanisms, and more than 800Mt/y if farmers are paid $100/tonne for soil carbon storage. Given the broader integration of nature-based CDR approaches into land sector decarbonization efforts in the United States, this report does not set an explicit short-term deployment target for nature-based solutions.

For all types of CDR solutions not widely adopted at commercial scale today, it is important to set dual innovation investment and deployment targets in the near-term. Third-party analyses from groups like the National Academies of Sciences,[11] Rocky Mountain Institute,[12] and the Rhodium Group[13] suggest an innovation investment target of at least $10 billion cumulative new funding by 2030 will be needed to catalyze breakthroughs from soil carbon to direct air capture, and build the measurement, monitoring, reporting, and verification (MMRV) infrastructure needed to account for CDR activities accurately.

For technological CDR approaches, one recent analysis[14] sheds light on how quickly we may need to scale deployment of these solutions to be on track to deliver CDR at the scale required by midcentury. That analysis identifies two critical phases of technology growth: an early phase of

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[8] EPA (2024). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2022 U.S. Environmental Protection Agency, EPA 430R-24004. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2022

[9] *Opportunities to Accelerate Nature-Based Solutions: A Roadmap for Climate Progress, Thriving Nature, Equity, & Prosperity – A Report to the National Climate Task Force. (2022)*. https://www.whitehouse.gov/wp-content/uploads/2022/11/Nature-Based-Solutions-Roadmap.pdf

[10] *Roads to Removal – Options for carbon dioxide removal in the US.* Lawrence Livermore National Laboratory. https://roads2removal.org/

[11] *Developing a Research Agenda for Carbon Dioxide Removal and Reliable Sequestration*. National Academies of Science, Engineering, and Medicine. https://www.nationalacademies.org/our-work/developing-a-research-agenda-for-carbon-dioxide-removal-and-reliable-sequestration

[12] *The Applied Innovation Roadmap for CDR*. RMI. https://rmi.org/insight/the-applied-innovation-roadmap-for-cdr/

[13] *The Landscape of Carbon Dioxide Removal and US Policies to Scale Solutions*. Rhodium Group. https://rhg.com/research/carbon-dioxide-removal-us-policy

[14] G. Nemet et al., Dataset on the adoption of historical technologies informs the scale-up of emerging carbon dioxide removal measures. Communications Earth & Environment, 2023 (4) p397. https://doi.org/10.1038/s43247-023-01056-1

accelerating growth where the *improved performance* of the technology is the primary objective (the "formative" phase), and a later phase of growth where *price competitiveness* and *market expansion* are the primary objectives. The combination of these two phases results in an S curve for technology development. The formative phase is typically 2.5% of the final adoption. Given that the demands for CDR by 2050 requires roughly 0.5 billion tonnes of $CO_2$ per year (Bt/y) to 2.4Bt/y, this study implies that a portfolio of technological CDR solutions will be needed at roughly 10Mt/y to 60Mt/y of capacity in the United States by 2030. DOE has set a goal of unlocking at least 25Mt/y of demand for technological-based CDR by 2030, expanding the pipeline of applied early stage to early deployment efforts across the tech-based CDR pathways by at least a factor of ten by 2030.

**Note:** No explicit marine CDR deployment goal is set in this report. The Marine Carbon Dioxide Removal Fast Track Action Committee (MCDR-FTAC) has published the National Marine Carbon Dioxide Removal Research Strategy, which includes research and development guidelines to support subsequent decisions on the deployment of marine CDR technologies.

## State of Carbon Dioxide Removal Solutions

One of the most encouraging aspects of CDR is the large number of methods that are now under development. DOE has organized these solutions in its Carbon Negative Shot initiative, a strategy to provide a portfolio of solutions enabling a capacity of 1 GT $CO_2$/year at a cost of \$100/tonne $CO_2$, into six major technology areas, described in Figure 1 below.

**Figure 1: Carbon Negative Shot pathways for Carbon Dioxide removal**[15]


- **Direct air capture with storage** uses chemical engineering to separate $CO_2$ from ambient air through sorbents, solvents, cryogenic, and other innovative technologies, combined with storage of $CO_2$ geologically or in long-lived products such as building materials. Direct air capture with storage solutions has received significant DOE funding, with initial negotiations under way for the first two 1 million-tonne per year facilities under the Bipartisan Infrastructure Law. Today, there are over 100 companies formed globally to advance a variety of direct air capture with storage approaches. Costs are still high, and

[15] Carbon Negative Shot. https://www.energy.gov/fecm/carbon-negative-shot

this method is expected to remain one of the most costly but straightforward approaches to delivering CDR.

- **Soil carbon storage** involves changes to agricultural practices to increase the net rate of carbon storage in soils. Soil carbon storage approaches are being deployed at scale, and the extent to which they store carbon is under extensive study by USDA and DOE's Office of Science (SC).
- **Biomass carbon removal and storage** (BiCRS) involves converting biomass produced with low or zero greenhouse gas emissions (on a lifecycle basis) into energy or products and capturing and storing the associated process $CO_2$ (also known as bioenergy with carbon capture and storage [BECCS]), as well as directly burying biomass or biomass products with the primary aim of CDR. BiCRS work is underway both from a bioenergy and biomass burial perspective, with innovation support largely funded by DOE. The first large-scale biogenic waste-to-heat and power carbon capture and storage facility (500,000 tonnes per year) is under construction in Denmark. It is important to note that not all biomass-based processes with carbon capture and storage can be considered as CDR (i.e., such systems only can be considered CDR when net negative emissions occur due to the process/product).
- **Enhanced mineralization** involves exposing $CO_2$-reactive alkaline materials with air and/or $CO_2$ rich solutions to accelerate natural processes where $CO_2$ is captured via rock weathering over the course of millennia. Enhanced mineralization approaches are in initial development with U.S. research and development support expanding in 2024 with DOE's Carbon Negative Shot.
- **Marine based CDR (and coastal ecosystem restoration)** methods include open-ocean approaches for separating $CO_2$ out of seawater, enhancing alkalinity of the ocean, and other innovative approaches for enhancing the ability of the ocean to store atmospheric $CO_2$. Marine CDR approaches are receiving significant attention recently with the publication of the White House's Ocean Climate Action Plan and the formation of the MCDR-FTAC, under the Subcommittee on Ocean Science and Technology of the National Science and Technology Council. While this CDR approach is the least developed for potential commercial use, research and innovation work is accelerating significantly, including through research and research funding support from NOAA and DOE. There are CDR-funded programs supported through NOAA's Ocean Acidification Program, DOE's Advanced Research Projects Agency Energy (ARPA-E) and the Water Power Technologies Office (WPTO).
- **Afforestation and reforestation** include tree planting and other types of restoration activities to enhance carbon storage in forests, which are a part of the U.S. Nationally Determined Commitment to the Paris Agreement and have received extensive private and government attention.

External analyses have evaluated the state of the CDR field, including current deployment levels, cost trajectories, and likely scale potential.[16] These analyses show that CDR approaches span varying levels of technological maturity, from the early research stage to those that are in place at commercial scale today. However, all of these solutions face a number of hurdles to making a climatically relevant gigaton-scale impact. Novel pre-commercial solutions must come down

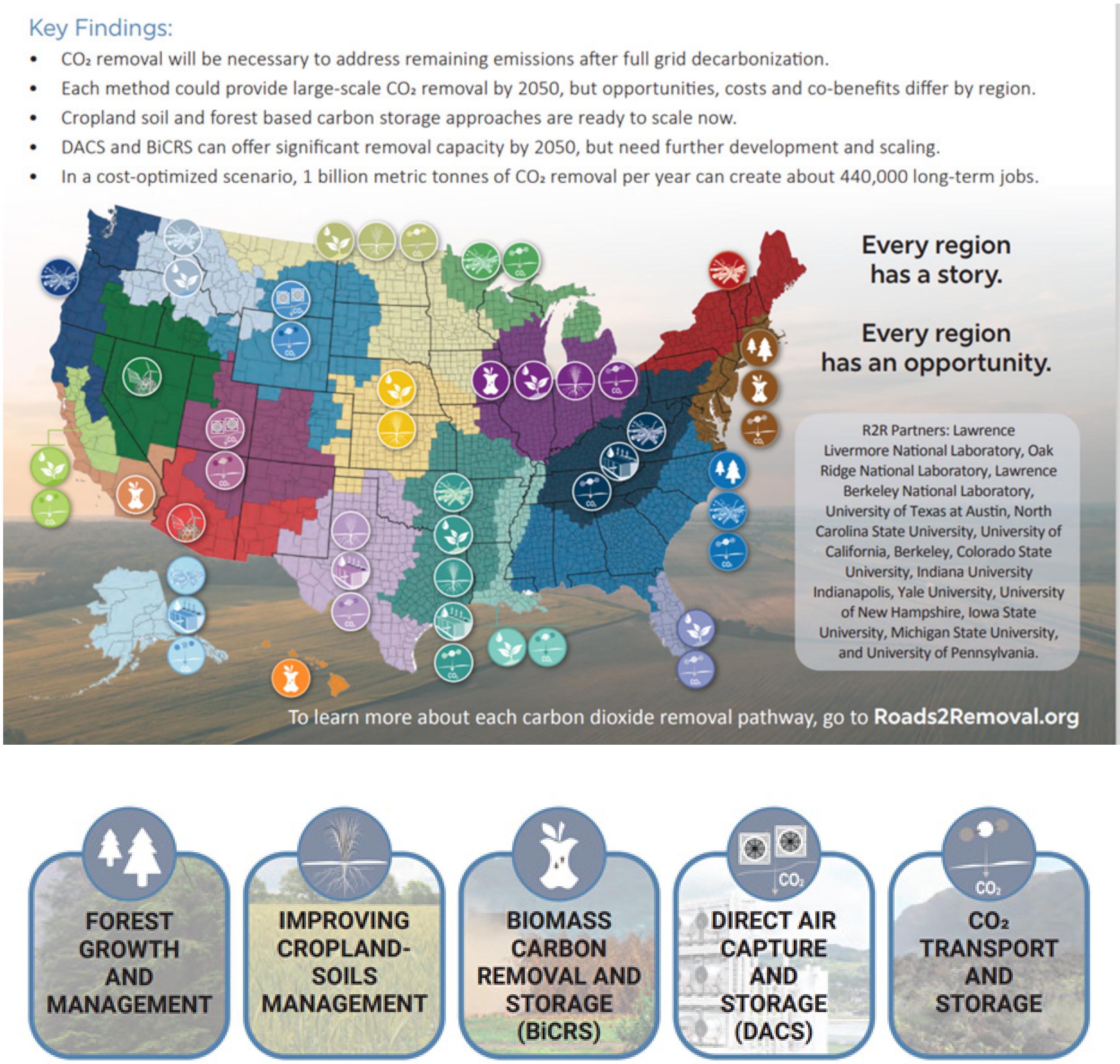
[16] *O. Geden et al., The State of Carbon Dioxide Removal*. https://www.stateofcdr.org/

the cost curve and need advancements in science and technology for measuring carbon fluxes associated with specific CDR projects. More mature solutions face challenges around issues like ensuring permanence of removals and supply chain challenges around biomass, land, and other resource availability at scale. All solutions will need to mitigate any unintended negative environmental impacts at scale, as well as develop models for community and workforce benefits. None of the technological solutions are on pace today to achieve the greater than 15Mt/y scale minimum by 2030, and all of these solutions will need sustained efforts and increased funding in order to scale.

Complementing the wide range of technology approaches, the geographical and social diversity of the United States drives a range of opportunities and challenges. A recent report from a team led by Lawrence Livermore National Laboratory showed that the nation's ability to conduct certain CDR solutions varies widely by region. Each region of the country has different opportunities and limitations. There is unlikely to be a single "silver bullet" CDR solution, but a diversity of solutions hold potential for delivering CDR in different regions to collectively build a portfolio approach to CDR, as shown in the graphic below[17]. Aligning CDR solutions with capacities of local communities can serve as the foundation for strong Federal, state, Tribal, and local government policy support for CDR implementation. Addressing the layered regional partnership and environmental protection aspects of scaling CDR must be a critical pillar of the U.S. Government's approach to advancing CDR.

17 *Roads to Removal – Options for carbon dioxide removal in the US.* Lawrence Livermore National Laboratory. https://roads2removal.org/

**Figure 2: Roads to Removal Summary of Key Findings**




The range of regional opportunities and possible solutions for CDR present an opportunity to craft a robust national CDR program that meets emissions targets, environmental considerations, and safeguards while delivering economic benefits. This can and must be done while strengthening engagement with communities and stakeholders that could participate in or be affected by CDR, including environmental organizations, Tribal nations, labor unions and workforce development entities, industry, and academia.

Additionally, it is essential to accelerate the pace of research, innovation, and demonstration of CDR today to ensure that legislative and regulatory frameworks for a scalable CDR economy in the coming decades are built on a robust scientific foundation. This careful groundwork will help to avoid any unintended consequences of scaling CDR. The Federal Government can seek to support activities to ensure that a diversity of CDR solutions can achieve commercial maturity, and that communities across geographies can be equipped with the information and resources needed to deploy the best CDR solutions for their region while avoiding and minimizing adverse environmental and social impacts.

### *DOE's Carbon Negative Shot Initiative*

In 2021, DOE announced the Carbon Negative Shot[18] initiative, an all-hands-on-deck call for innovation in CDR pathways that will capture $CO_2$ from the atmosphere and store it at gigatonne scales for less than $100/net metric tonne of $CO_2$ equivalents ($CO_2e$) within a decade.

DOE's Carbon Negative Shot is an example of how agencies and other entities could approach programs focused on CDR pathways and their development. In this draft report, DOE is outlining the following principles for this initiative for the first time. These principles may continue to evolve as Carbon Negative Shot expands.

- **Complementarity**: Ensure CDR policies complement, rather than replace, direct emissions reductions through clean energy, new materials, electrification, and energy efficiency.
- **Diversity of solutions**: Develop a range of potential solutions that are ready to scale in the coming decades. Ensure that each solution can be tailored to the unique environmental, social, and economic landscapes of communities and regions across the United States.
- **Opportunity**: Invest beyond technological innovation to enable CDR business models that create strong jobs and investment opportunities across the U.S.
- **Transparency**: Implement high quality measurement, monitoring, reporting, and verification to accurately track and measure the amount of carbon removed across different solutions.
- **Responsibility**: Ensure that CDR solutions provide the greatest benefits to communities while minimizing and mitigating any significant environmental, health, and safety risks.
- **Evidence-based investments**: Focus on innovation to steward investment and inform future policy frameworks effectively.
- **Partnerships**: Collaborate with other governments and the private sector to crowd in investment in innovation and standardize regulations.

Given these principles, DOE has developed a strategy to achieve the following strategic goals by the end of the decade:

1. **Advance CDR solutions to commercial scale**: Develop and scale a portfolio of CDR technologies by investing in pioneering science and applied innovation. Ensure that the United States has scalable, economically viable, cost-effective, safe, and environmentally-sound options ready for the large-scale deployment of CDR within the coming decades.
2. **Build infrastructure for CDR**: Establish $CO_2$ transport and storage, biomass supply chains, measuring and monitoring carbon fluxes in terrestrial and ocean ecosystems, and innovation test beds.

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[18] Carbon Negative Shot. (2021). Energy.gov. https://www.energy.gov/fecm/carbon-negative-shot

3. **Develop MMRV and carbon accounting frameworks**: Create and implement robust, transparent, and operational frameworks for MMRV through research, technology development, and computer modelling. These efforts will help measure and monitor carbon fluxes associated with CDR projects across terrestrial and ocean ecosystems at both the project and jurisdictional level.
4. **Demonstrate models for community and workforce benefits**: Ensure communities have sufficient awareness of and support for solutions, as well as regulatory safeguards so that projects can be built at pace and scale. These efforts will create high-quality jobs, investment opportunities and environmental benefits, including in those communities most affected by the deployment of projects and infrastructure.
5. **Collaborate with the private sector**: Partner with the private sector to attract private capital for CDR technology development and voluntary carbon credit investments.
6. **Mitigate environmental, health, and safety impacts**: Reduce the negative risks of large-scale CDR deployment through targeted research, robust implementation, and adherence to existing environmental regulations related to CDR projects.
7. **Support scalable regulations and incentives**: Implement clear and effective regulations and incentives to give companies and communities confidence that their investments can lead to the expected outcomes.
8. **Build international markets**: Strengthen international markets for CDR by aligning the nation's broader climate diplomacy efforts with global initiatives, encouraging other countries to fund CDR innovation and deployment. This will also help harmonize U.S. and international standards for MMRV, as well as carbon accounting.

## Policy Options for Scaling CDR

A menu of potential action items for scaling CDR in the future is described below. These options were crafted via a series of meetings of the CDR working group[19] and do not represent the Administration's policy; rather, they are intended to serve as a broad survey of options from stakeholders that can inform future policymaking.[20, 21]

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[19] DOE convened 12 virtual workshops—two workshops for each of the six workstreams corresponding to the six CDR areas examined—to collect insights from agency experts on CDR approaches, policies, and recommendations. In total, over 100 technology and policy specialists from ten agencies participated in the CDR Working Group.

[20] Further details on policy options, including specific incentives for consideration, are provided in Chapter 3.

[21] Policies to incentivize supporting infrastructure development are outside of the scope of this report. Through the Infrastructure Investment and Jobs Act, DOE will deploy approximately $10 billion in new direct carbon management funding over five years, including $2.5 billion for carbon storage validation and testing and $2.1 billion for $CO_2$ transportation infrastructure finance and innovation, The Act also provides $25 million to the U.S. Environmental Protection Agency over five years to improve Federal permitting of Class VI underground injection control wells for geologic storage and $50 million in grants for states to establish and operate their own Class VI permitting programs. This report does not focus on geologic storage and utilization, which are discussed in detail in the Council on Environmental Quality 2021 *Report to Congress on Carbon Capture, Utilization, and Sequestration*. https://www.whitehouse.gov/ceq/news-updates/2021/06/30/council-on-environmental-quality-delivers-report-to-congress-on-steps-to-advance-responsible-orderly-and-efficient-development-of-carbon-capture-utilization-and-sequestration/

**1. Establish a timeline and targets to guide the growth of the CDR industry in the U.S.**
The government can establish specific targets for how much CDR should be deployed every decade to meet emissions targets and create a thriving new industry in the U.S. Federal guidance can also inform how implementation of CDR policy can avoid competition with investments in direct emission reductions and unintended negative environmental impacts. Other jurisdictions, such as the United Kingdom and the European Union have established such CDR goals alongside their emissions reduction targets.[22]

**2. Reduce technology risk by expanding and accelerating investments in CDR research, development, and demonstrations.**
A significant increase in resources will be necessary to achieve the pace and scale of CDR research, development, and demonstration required to adequately advance a broad portfolio of CDR solutions by 2030. Funding for CDR innovation has largely focused on early-stage efforts and predominantly for direct air capture. Expanding this funding to support a broader range of CDR solutions and the full technical maturity range will be essential for enabling a robust portfolio of approaches to reach scale within the decade.

For example, one of the biggest innovation barriers that CDR companies face today is securing funding for pilot and small commercial demonstration facilities, which can range from approximately $5 million to $100 million. Given uncertainties in the private CDR market, the Federal Government has a critical role in funding these projects. However, available Federal funding is limited and insufficient to enable the rapid scaling of viable CDR technologies. Authorizations via existing legislation, including the $1 billion in the CHIPS and Science Act,[23] provide a foundation for CDR innovation if funding is appropriated in the future.

CDR approaches fit within the purview of many existing government research programs—creating opportunities to quickly and efficiently build out and scale up current activities by leveraging the authorities, networks, and infrastructure already in place. Integrating CDR with complementary Federal research and incentive programs (e.g., programs to improve air quality, wildfire management, land or water conservation, and co-generation) can lead to positive reinforcement and feedback and build a robust CDR portfolio. In particular, robust environmental impacts research is essential for CDR solutions to scale in a responsible way.

Continued emphasis on fundamental science and innovation is also important for continuous improvement of CDR approaches, and to provide a foundation for evidence-based policymaking and regulatory efforts.

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[22] European Commission - European Commission. https://ec.europa.eu/commission/presscorner/detail/en/ip_24_588 and GOV.UK. (2021, October 19). *Net Zero Strategy: Build Back Greener*. GOV.UK. https://www.gov.uk/government/publications/net-zero-strategy

[23] The CHIPS and Science act invests over $50B into domestic manufacturing of semiconductors and microchips as well as $67B into scientific research and development. As part of this, $1B of funding was authorized for DOE's carbon removal research. https://www.energy.gov/articles/statement-secretary-granholm-congressional-passage-chips-and-science-act

**3. Further enable deployment of market-ready CDR approaches.**
Additional incentives are critical for advancing the full portfolio of CDR solutions in a responsible way. Incentives can build on existing policies such as the 45Q tax credit (for carbon capture and storage, including direct air capture) to support a broader range of CDR pathways outcomes, and incentives can be tied to robust environmental safeguards and life cycle assessments (LCAs) to ensure that projects deliver net-negative emissions. Existing regulations and authorities, such as EPA's Greenhouse Gas Reporting Programs and pay-for-practice land management approaches, may be able to be expanded to encompass the broader suite of CDR technologies and codify strong MMRV approaches. Clarifying permitting processes, especially for more novel approaches in areas such as marine CDR, can provide important assurance for project developers and the general public.

The realm of possible policies to support responsible CDR innovation and deployment is far broader than what exists today. For example, CDR could be included in future regulations or taxes in a way that incentivizes direct emissions reductions while providing additional revenue to drive "learning by doing" for a portfolio of CDR options. Procurement of CDR credits and/or development of public CDR utilities (such as the Tennessee Valley Authority for power) offer additional pathways to support CDR innovation and deployment outside of emissions reductions regulatory frameworks. Federal lands also offer vast potential for CDR and leveraging the management of ecosystems and Federal pore space to scale CDR presents significant opportunities for market scale-up in the near-term. In some fields, the current U.S. permitting structure incentivizes industry and researchers to look internationally for testing and deployment, which consequently reduces the nation's competitiveness in the field.

**4. Build private sector demand and advance public-private partnerships.**
The United States has long demonstrated its capacity for leading innovation and galvanizing the private sector to accomplish monumental industry change. Crowding-in private capital will be essential for scaling CDR. New efforts to incentivize additional private purchasing of CDR credits, such as government-backed contract-for-difference frameworks, off-take guarantees, and/or tax rebates for CDR purchasing entities, can catalyze the thousands of companies with net-zero-aligned targets to start buying a small but growing amount of CDR today.

Voluntary corporate purchases of CDR credits are a major source of funding in the field today. Building that market aligns with the U.S. Government's Voluntary Carbon Markets Joint Policy Statement and Principles will position U.S. businesses to be global leaders in deploying technology and meeting emissions reduction goals.[24] Actions by the government to ensure that credits are available through capacity building, reliable through MMRV and LCA development, and internationally accepted will ensure that U.S. corporations can confidently use CDR.

24 *Voluntary Carbon Markets Joint Policy Statement and Principles.* (2024). https://home.treasury.gov/system/files/136/VCM-Joint-Policy-Statement-and-Principles.pdf

**5. Build confidence by investing in standards for MMRV and LCA of CDR projects.**

As of early 2024, over five million tons of CDR have been sold on the private market to companies wishing to encourage development of CDR technologies or to reach their own internal net-zero targets.[25] This private market has highlighted the importance of knowing exactly whether and how the various methods remove $CO_2$, and that the $CO_2$ has been verifiably removed. Companies in this market, both buyers and sellers, are clamoring for robust MMRV science and technology. This is not only necessary for sound business models, but also for building public trust in CDR solutions. As the compliance markets and other policy frameworks emerge to enable a U.S. industry for CDR, it is essential to have good controls and evaluation methods.

Expanded research, development, and demonstration can accelerate the development of improved techniques, which must then be demonstrated, field tested and validated for accuracy. Federal agencies have expertise, facilities, and capabilities required to inform independent assessment of the real long-term benefits of CDR approaches and projects. The methods, best practices, and technologies required to effectively evaluate and verify CDR vary widely by approach and will require ongoing revisions as the portfolio of approaches advances and expands. In particular, gathering the data needed to calibrate and validate models for quantifying open system CDR practices (e.g., soils, oceans, and enhanced rock weathering approaches) is a key gap that any given private sector actor is unlikely to fund alone, though such infrastructure is essential for commercial viability.

LCA methodologies and guidelines must also be developed or updated to improve cradle-to-grave greenhouse gas emission flux estimation. LCA should be supported by comprehensive guidelines for how removal estimates can be based on atmospheric drawdown rather than on displacement of emissions. Standards should be developed to accommodate robust MMRV and LCA into project-level and national-inventory level greenhouse gas accounting, as demonstrated by the recently launched IPCC process to develop national greenhouse gas inventor guidance for technological CDR.

**6. Develop and refine regional engagement guidance for Federally funded CDR projects to ensure they deliver robust community benefits, workforce development, and environmental protection.**

DOE and other Federal agencies have introduced Community Benefits Plans frameworks to guide CDR and other clean energy and industry project development. Additional guidance and resources would help enable effective community participation in project development and ensure economic and workforce benefits from projects are shared appropriately with host communities.

In addition, Federal permitting processes for pilot, demonstration, or deployment scale CDR project include procedures for assessment of impacts and provide important opportunities for public comment and engaging stakeholders in decision-making.

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25 *CDR.fyi*. https://www.cdr.fyi/

**7. Engage the international community.**

International engagement is an important aspect of a comprehensive Federal CDR strategy, and the United States has strong economic and national security incentives to be a leader in this space. The scale of CDR needed to achieve global climate goals is beyond the reach of any single country. CDR can be implemented in almost every region of the world with consideration to resource suitability, and single projects may cross international boundaries.[26] The largest private purchase of CDR to date is international, and it features Microsoft's purchase of 2.7 million tons of BiCRS removals from the Danish company Ørsted. Distributing CDR globally will enable it to scale in a more economically efficient manner in the long run. Partnerships with developing and emerging economies can be pursued to ensure an equitable approach to deploying CDR in a manner that could both protect and benefit vulnerable populations locally and globally. For example, the United States could guide capacity building and technology transfer engagement with low- and middle-income countries. International collaboration can rapidly accelerate technology advancement by distributing workloads for research, development, and demonstration among participating nations and sharing results. Supporting multilateral development finance for CDR projects will also be essential for ensuring that capital can flow to all regions with significant CDR potential, regardless of economic development status today.

The United States should continue to engage in ongoing discussions in multilateral fora to shape the international regulatory frameworks for CDR. For example, international collaboration is essential for facilitating the development and acceptance of international protocols and standards, such as greenhouse gas accounting and LCAs for CDR projects. Without harmonized standards for high-quality CDR MMRV, LCA, and domestic and cross-border carbon accounting and disclosure, project developers will face headwinds in scaling solutions across national borders. Harmonized standards will open up new opportunities for trade policy to incorporate CDR in a robust way, both incentivizing its deployment overseas to reduce the emissions intensity of export industries, as well as to fund domestic CDR implementation from potential fees paid by higher emissions intensity imported products.

[26] Specific CDR project options depend on the availability of resources. For example, reforestation storage potentials are greatest in tropical regions, soil carbon storage potentials are greatest in mid-latitudes, ultramafic rock formations are mainly located in the Middle East, Eastern Europe, and areas along the Pacific Ring of Fire, and CDR methods tied to geologic storage in sedimentary rocks are broadly distributed globally with the largest capacities in the Americas, Europe, and Australia-New Zealand (Pilorge et al, 2021).

# Table of Contents

# Preface

This report broadly assesses carbon dioxide removal (CDR) approaches and provides a portfolio of Federal policies and mechanisms that could significantly accelerate the development and deployment of CDR infrastructure to meet the net-zero emissions by 2050 target. This report considers six broad areas of CDR as delineated in the legislative mandate: direct air capture and storage, enhanced carbon mineralization, bioenergy with carbon capture and storage, forest and coastal ecosystem restoration, soil carbon management, and marine ocean capture.[27]

- **Chapter I** introduces the anticipated role for CDR in achieving net-zero emissions by 2050 and provides context for crosscutting CDR topics.
- **Chapter II** inventories the current and emerging CDR approaches and provides a high-level assessment of the advantages and disadvantages of each. Chapter II should be viewed as an overview of CDR approaches. References for further understanding of CDR topics are included throughout the chapter and are consolidated at the end of the report.
- **Chapter III** outlines DOE's strategy and grounding principles for supporting CDR innovation, along with other related activities for CDR across the Federal Government.
- **Chapter IV** identifies options for the types of legislation, incentives, partnerships, and other policy tools to advance the deployment of CDR that the Federal Government can consider.

***The report reflects existing literature, new modeling from Pacific Northwest National Laboratory, and input from the CDR Working Group. The report is not intended to be a comprehensive examination of CDR approaches nor a comprehensive analysis of benefits, impacts, or policies.***

The development of this report was led by the U.S. Department of Energy (DOE) with significant input from multiple agencies. Additionally, the U.S. Department of Agriculture (USDA), the U.S. Department of Defense (DOD), the U.S. Department of the Interior (DOI), the U.S. Environmental Protection Agency (EPA), the Global Change Research Program (USGCRP), the National Aeronautical and Space Administration (NASA), the National Institute of Standards and Technology (NIST), the National Science Foundation (NSF), and the National Oceanic and Atmospheric Administration (NOAA) contributed to the report by participating in topical workstreams and providing expert reviews of report drafts. DOE convened 12 virtual workshops—two workshops for each of the six workstreams corresponding to the six CDR areas examined—to collect insights from agency experts on CDR approaches, policies, and recommendations. In total, over 100 technology and policy specialists from ten agencies participated in the CDR Working Group.

This report is one in a series of related reports to Congress as part of the Consolidated Appropriations Act, 2021, to advance the understanding of methods and policies that the United States can employ to help address global climate change. ***While relevant to some***

[27] Chapter 1 provides a discussion of the taxonomy of CDR approaches included in this report within the six broad areas

***CDR approaches, carbon capture and storage issues are covered in other reports sought by Congress in the Consolidated Appropriations Act, 2021, and accompanying explanatory statement***, including:

- A report to Congress on recommendations to improve the Class VI permitting procedures for geologic sequestration (Division G—Department of the Interior, Environment, and Related Agencies Appropriations Act, 2021).
- A Council on Environmental Quality report to Congress on Carbon Capture, Utilization, and Sequestration (Division S, Sec. 102, Utilizing Significant Emissions with Innovative Technologies [USE IT Act]).
- A National Academies of Sciences, Engineering and Medicine study to assess the barriers and opportunities relating to the commercial application of $CO_2$ (USE IT Act).
- A Government Accountability Office report on the successes, failures, practices and improvements of DOE in carrying out commercial-scale carbon demonstrations (Division Z—Energy Act of 2020).

Furthermore, DOE has published a draft Carbon Management Strategy and commercial liftoff reports covering carbon management, which includes many CDR approaches.

# I. Introduction

> **Carbon Dioxide Removal**
>
> As defined in the Energy Act of 2020, CDR is "the capture of carbon dioxide directly from ambient air or, in dissolved form, from seawater, combined with the sequestration of that carbon dioxide" through a variety of methods.
>
> To be considered CDR, projects must also be directly caused by human activities (e.g., natural uptake of $CO_2$ from land and ocean sinks are not CDR unless enhanced by human intervention). Commercially-deployed CDR projects must result in *net negative* emissions on a life cycle basis.
>
> Therefore, CDR does not include carbon capture and storage from fossil-based facilities. Nor does it include the capture and use of $CO_2$ in short-lived products such as synthetic fuels because $CO_2$ is released when the fuel is used.

To limit the severe risks and costs of climate change, there is broad recognition that greenhouse gas emissions must rapidly decline, and atmospheric concentrations of $CO_2$ must level off then begin to decline, by the latter half of this century. Stabilizing $CO_2$ concentrations requires human-caused emissions to be net-zero, where any greenhouse gas emitted is balanced by removing an equal amount of $CO_2$-equivalents ($CO_2e$)—likely in the form of $CO_2$—from the atmosphere. In line with this science, President Biden has set a domestic climate goal to deliver an equitable, clean energy future, and put the United States on a path to achieve net-zero emissions economy-wide by 2050.[28]

To reach this ambitious goal, the United States needs to rapidly decarbonize the economy. To supplement this decarbonization effort, the nation must also develop technologies and embrace approaches to remove on the order of billions of metric tons (gigatons) of $CO_2$ directly from the atmosphere.[29] CDR at the gigatonne scale globally is essential to achieve net-zero global $CO_2$ emissions in virtually all scenarios assessed in the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.[19]

## CDR as a Critical Part of a Broader Decarbonization Strategy

The urgency and scale of the decarbonization effort required to stabilize and eventually reduce $CO_2$ concentrations necessitate multiple approaches and efforts across economic sectors. Three broad strategies for reaching net-zero emissions include:

1. Deploying *$CO_2$-avoidance* technologies and practices, such as renewable energy, energy efficiency, new materials, and land use conservation.
2. Deploying *$CO_2$-reduction* technologies and practices, such as carbon capture and storage, from facilities where it is difficult for $CO_2$ emissions to reach zero or switch to low-carbon fuels such as in shipping and aviation.

[28] On January 27, 2021, President Biden signed *Executive Order 14008 Tackling the Climate Crisis at Home and Abroad*. https://www.whitehouse.gov/briefing-room/presidential-actions/2021/01/27/executive-order-on-tackling-the-climate-crisis-at-home-and-abroad/

[29] Department of State and United States Executive Office of the President (2021). *The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050*. Washington, DC. https://www.whitehouse.gov/wp-content/uploads/2021/10/US-Long-Term-Strategy.pdf

3. Deploying *$CO_2$-removal* technologies and practices, which remove $CO_2$ from ambient air (i.e., CDR).

These three strategies are listed in order from generally the most economic, commercially ready, and efficient at reaching net-zero emissions (strategy 1) to the least efficient (in terms of cost per tonne) (strategy 3). The first and second strategies are crucial for decarbonizing most sectors of the economy, but some sources of $CO_2$ emissions are extremely difficult or costly to avoid or abate. Examples of hard-to-decarbonize industries include aviation, shipping, steel, cement, and agriculture. To reach net-zero in these sectors, CDR is needed until new zero-carbon technologies and processes can be developed and deployed in an economically, environmentally, and socially responsible manner.

**Earth Science: Carbon Cycle**[30]

The carbon cycle's response to $CO_2$ emissions and removals is asymmetric. Currently, human-caused $CO_2$ emissions are partially being taken up by land and ocean carbon stores. If $CO_2$ is removed from the atmosphere, then CDR will be partially counteracted by $CO_2$ released these stores. In other words, more than a tonne of $CO_2$ removal is required to compensate for a tonne of $CO_2$ emissions. This means that avoiding $CO_2$ emissions is more effective at lowering atmospheric $CO_2$ concentration than removing $CO_2$, from an earth science perspective.

DOE views CDR as an essential *supplemental* strategy that should not be considered a replacement for emissions avoidance or reduction where these are technically and economically feasible. DOE is working to advance a broad range of direct decarbonization approaches across all sectors of the economy to make the need for CDR as small as feasible to achieve net-zero emissions.

## Excess Atmospheric $CO_2$ to be Removed Globally by 2050

The amount of CDR that will be needed to reach net-zero emissions in 2050 depends on the speed and scale of $CO_2$ avoidance and reduction in the intervening years. The larger the overshoot, the more net negative $CO_2$ emissions needed to return to a given atmospheric concentration.[31] The magnitude of excess emissions in the atmosphere will be determined by the current and future costs of emissions reductions and avoidance technologies, as well as the near-term adoption of these technologies. These variables lead to uncertainty in predicting CDR needs, yet most models agree that billions of tons of $CO_2$ will need to be removed globally.[32, 33]

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30 K. Zickfeld *et al*., Asymmetry in the climate–carbon cycle response to positive and negative $CO_2$ emissions. Nat. Clim. Chang. 11, 613–617 (2021). https://doi.org/10.1038/s41558-021-01061-2

31 J. Rogelj et al., 2018: 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…* [V. Masson-Delmotte et al., (eds.)] https://www.ipcc.ch/sr15/chapter/chapter-2

32 Bergman, A., Rinberg, A. (2021). "The Case for Carbon Dioxide Removal: From Science to Justice" in [J. Wilcox, B. Kolosz & J. Freeman (eds.)] CDR Primer. https://cdrprimer.org/read/chapter-1

33 S. Fuss et al., (2018). "Negative emissions – Part 2: Costs, potentials and side effects". *Environ. Res. Lett*., 13, 063002. https://iopscience.iop.org/article/10.1088/1748-9326/aabf9f. The review study, Fuss et al., finds that models estimate between 1.3 and 29 GTCO2/yr will be needed by 2050, with the most likely amount being between 5 and 15 $GTCO_2$/yr.

For example, the IPCC Special Report on *Global Warming of 1.5°C* models 90 scenarios that include CDR from the combination of BECCS and direct air capture systems. These integrated assessment models show that a global range of 3.5 to 16 gigatons of $CO_2$ per year ($GTCO_2$/yr) needed to be removed in 2050 for these two technologies. By contrast, the International Energy Agency's *Net-Zero by 2050* scenario predicts a need for 1.9 $GTCO_2$/yr from BECCS and DACS in 2050.[34] The prevalence of direct air capture and BECCS in modeling scenarios is a result of limited cost and performance information on the full range of CDR pathways, such as marine CDR and enhanced rock weathering, as opposed to a judgment that these other CDR pathways will not be able to contribute meaningfully to global mitigation efforts. Obtaining that performance information on all options is a key near-term goal.

The magnitude of emissions that will likely be infeasible to mitigate directly can be used to estimate the minimum amount of CDR that will be needed to achieve global net-zero emissions.[35] One assessment of such emissions is 1.5 to 3.1 GT $CO_2$e/yr, primarily from the agriculture and transportation sectors globally.[36]

## Required $CO_2$ Removal for the United States to Reach Net-Zero by 2050

Without knowing exactly how effective and how fast overall emissions reduction strategies will be, it is necessary to create a policy and technical landscape that can deliver CDR solutions at flexible scale. If the entire U.S. electricity, building, and industrial sectors could be fully decarbonized, the remaining $CO_2$e emissions would largely be in the form of nitrous oxide from agricultural and waste and $CO_2$ from aviation and shipping,[37] which are approximately 0.6 $GTCO_2$/yr in the United States.[38] A DOE report from 2022 estimated that approximately 1.35$GTCO_2$e represented emissions that would be most challenging to eliminate directly, predominately from agriculture, aviation, shipping, and various industrial sources.[39]

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34 International Energy Agency (2021). Net-Zero by 2050. Paris, France. https://www.iea.org/reports/net-zero-by-2050

35 Bergman, A., Rinberg, A. (2021). "The Case for Carbon Dioxide Removal: From Science to Justice" in [J. Wilcox, B. Kolosz & J. Freeman (eds.)] CDR Primer. https://cdrprimer.org/read/chapter-1

36 M. Browning et al., Net-zero $CO_2$ by 2050 scenarios for the United States in the Energy Modeling Forum 37 study, Energy and Climate Change, Volume 4, 2023, 100104, ISSN 2666-2787, https://doi.org/10.1016/j.egycc.2023.100104

37 Based on analysis presented in Bergman and Rinberg (2021), which uses the IPCC 1.5 degrees Celsius report's Low Energy Demand scenario, IEA 2020 Energy Technology feasibility assessment, and other studies.

38 Based on emissions for 2019 from Agriculture Soil Management ($N_2O$), Manure Management ($N_2O$), Aquaculture ($N_2O$), Wastewater Treatment ($N_2O$), Composting ($N_2O$), Aviation ($CO_2$), and Shipping ($CO_2$). Source: U.S. Environmental Protection Agency. (2021). *Inventory of U.S. greenhouse gas emissions and sinks: 1990-2019*. Washington, DC. Office of Atmospheric Programs. 430 pp. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2019

39 Office of Fossil Energy and Carbon Management. (2022). Strategic Vision. The Role of Fossil Energy and Carbon Management in Achieving Net-Zero Greenhouse Gas Emission. Department of Energy. Washington, DC. 2022-Strategic-Vision-The-Role-of-Fossil-Energy-and-Carbon-Management-in-Achieving-Net-Zero-Greenhouse-Gas-Emissions_Updated-4.28.22.pdf

For this report, Pacific Northwest National Laboratory applied an integrated assessment model called Global Change Analysis Model[40] to assess how much CDR the United States would need to meet net-zero goals based on varying levels of CDR availability.[41] According to this analysis, the United States will need to deploy enough CDR to remove between 0.5 and 2.4 $GTCO_2$/yr to achieve net-zero emissions by 2050.[42] This finding was supported by a separate analysis, using two economy-wide models (Global Change Analysis Model and Office of Policy – National Energy Modeling System) and supplemental models for certain key sectors, which found that 1.1 to 1.9 $GTCO_2$/yr from CDR and land sinks would be required for the United States to reach net-zero by 2050.

From these analytical approaches we can identify a reasonable 2050 CDR range of 0.5 (nearly perfect other greenhouse gas control activities) to 2.4 (multiple delays in other activities) billion tons of $CO_2$/yr in 2050.

Land-based solutions are estimated to be able to provide at least 100Mt/y of new CDR in the United States, much of which can be achieved in the near-term with the appropriate incentive frameworks for land managers. Equivalent carbon prices above $100/tonne could increase this potential several fold, and innovation in biotechnology around crop varietals and soil amendments could increase this amount (but the ultimate potential for these biotech approaches is unclear). To close the gap, it will be necessary to begin deploying engineered CDR technologies in parallel.

The *Roads to Removal* Report examines existing technology applications for CDR in the United States in four areas: forests, soil, biomass utilization, and direct air capture. Other more innovative technologies have not been evaluated yet due to a lack of dependable data. The team considered the requirements and limitations for all four methods, including geologic storage, in every county in the United States, calculating a total capacity for each method. They evaluated feasibility, capacity, impacts, and costs considering removal methods that could each be expected to remove at least 10 million tonnes of $CO_2$e/yr and for which we could estimate the costs achievable by 2050. It is vital that $CO_2$ removal must not compete with urgent ongoing efforts to

40 GCAM is a global model that represents the behavior and interactions among five systems: energy, water, agriculture and land use, the economy, and climate.

41 M. Browning et al., Net-zero $CO_2$ by 2050 scenarios for the United States in the Energy Modeling Forum 37 study, Energy and Climate Change, Volume 4, 2023, 100104, ISSN 2666-2787, https://doi.org/10.1016/j.egycc.2023.100104

42 The GCAM analysis considered three fundamentally different technology suites: Land-Use Change (LUC), BECCS, and DAC. LUC approaches include forest restoration and soil carbon management, but not coastal blue carbon, direct ocean capture, or enhanced carbon mineralization. BECCS technologies include the use of bioenergy across a wide set of applications including power generation, fuel refining, and large point source energy applications. DAC includes three technology alternatives. GCAM was used to explore three different future U.S. pathways: 1) A 'LUC only scenario' where U.S. net-zero missions are achieved in 2050 without use of BECCS or DAC and is dominated by deploying technology options that induce energy conservation and the use of non-carbon-emitting energy technology options. 2) A 'Limited option scenario' where LUC and BECCS are available, which allows more residual carbon dioxide emissions to be removed to reach the 2050 net-zero goal. 3) A 'Full option scenario' where LUC, BECCS, and development of cost-competitive DAC technologies are available, resulting in the highest amount of CDR in 2050 of the three scenarios.

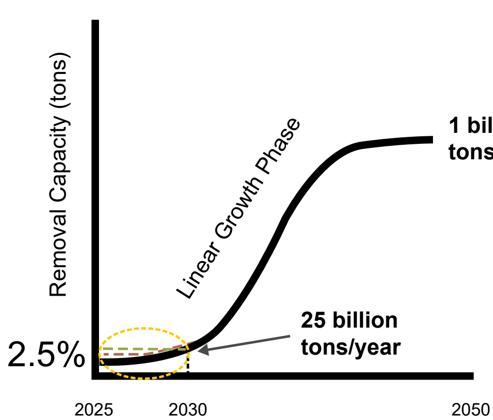
decarbonize U.S. energy, industrial, agricultural, and forestry sectors; rather, they must proceed in parallel. DOE evaluated the availability of energy that is additional to what is needed for 2035 grid-carbon neutrality. DOE also explicitly considered the amount and type of land required for each approach, as this is the primary physical constraint on the amount of $CO_2$ removal the nation can employ. Finally, DOE evaluated environmental and socioeconomic co-benefits and risks, because decarbonization and CDR must be designed to minimize risk of negative environmental, economic, and public-health impacts.

The results are best considered on a regional scale but can be summarized at the national level.

**Table 2: Applications of Carbon Dioxide Removal Summarized at National Level**

| Applications of Carbon Dioxide Removal Summarized at National Level | | |
|---|---|---|
| **Approach** | **Major Constraints and Estimated 2050 Cost** | **Estimated Maximum Additional Achievable Annual U.S. Capacity in 2050** |
| Forests | Reforestation and Afforestation, mostly in the Southeast and New England. Range $37 net revenue to $44/tonne cost. | 72 million tons |
| Soil | Mostly cover crops, also perennial borders and perennial crops @$100 carbon price. | 37 million tons |
| Biomass Utilization | Wastes and some purpose-grown crops that do not conflict with food crops. Many technologies. Cost less than $100/tonne net of valuable products. | 900 million tons |
| Direct Air Capture | Requires nearby land for renewable energy and geologic storage, cost $200-$250/ton. | 9,000 million tons |

**Figure 3: S-curve for CDR technology**[48]




By focusing on historical growth dynamics of new technologies, it is possible to *identify minimum targets* for near-term (2030) growth of CDR technologies that would enable us to achieve CDR deployment at this range of levels by 2050.

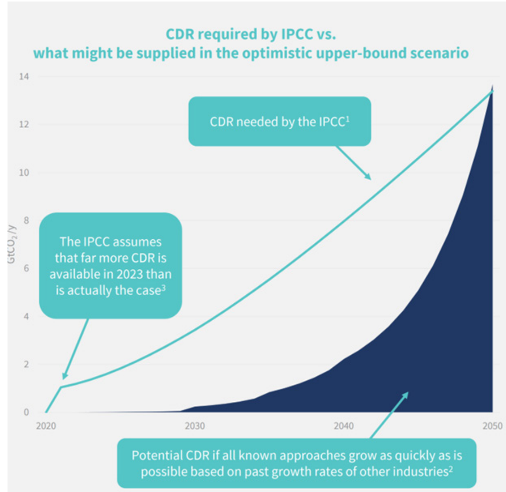
A recent analysis[43] identifies two critical phases of technology growth: a formative, early phase with exponential growth where the *performance* of the technology is the primary issue; and a later, linear phase of growth where

[43] Dataset on the adoption of historical technologies informs the scale-up of emerging carbon dioxide removal measures G Nemet, J Greene, F Müller-Hansen, JC Minx - Communications Earth & Environment, 2023 (4) p397. https://doi.org/10.1038/s43247-023-01056-1; The Applied Innovation Roadmap for CDR - RMI.

*price and market forces* are the primary issues. The combination of these two phases results in an S curve for technology development. The formative phase is typically 2.5% of the final amount. Given the range of CDR likely needed by 2050 to meet U.S. climate goals, this implies that we will need roughly 10-60 million tons of technological CDR capacity in the United States to provide the foundation for scaling the industry in coming decades.

DOE has set an interim 2030 target of 25 Mt/y of terrestrial technological CDR demand by 2030, with a minimum of 5 Mt/y for each of the solution pathways.

**Figure 4: RMI Applied Innovation Roadmap Analysis**

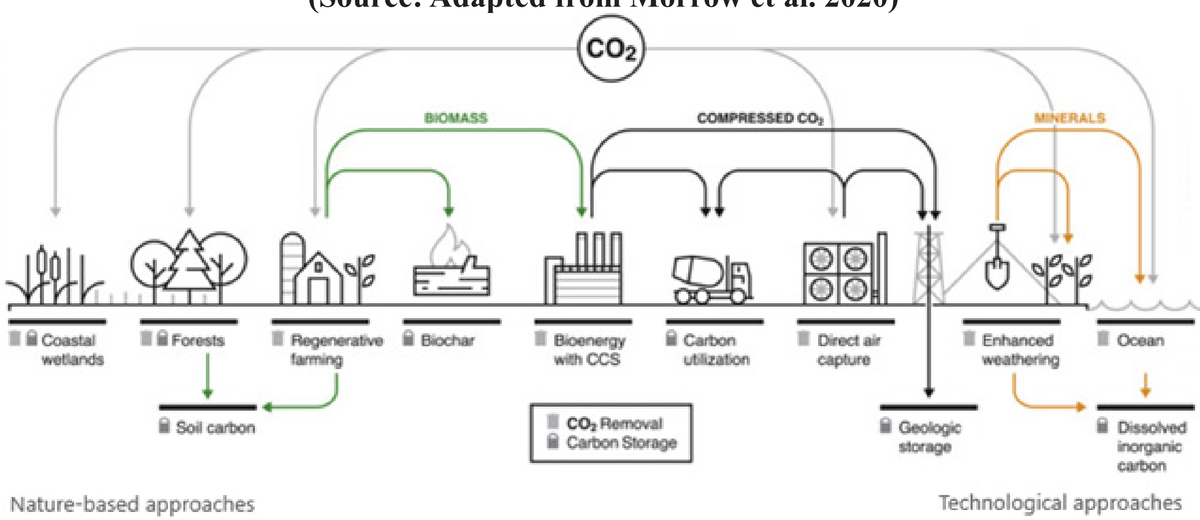



External groups have also estimated scale-up goals for CDR globally. For example, Rocky Mountain Institute's applied innovation roadmap includes the analysis in Figure 3.[44]

## Range of Approaches

One of the advantages of CDR is that it can be pursued using nature-based or technological processes, or hybrid approaches that leverage both biological and technological components (Figure 5). The wide range of methods permits multiple benefits in addition to CDR. It also creates a wide variety of ways to organize the methods (Figure 2).

**Figure 5. Examples of Potential Approaches for CDR (Source: Adapted from Morrow et al. 2020)[45]**




44 *The Applied Innovation Roadmap for CDR [Review of The Applied Innovation Roadmap for CDR*]. RMI.org; RMI. https://rmi.org/wp-content/uploads/dlm_uploads/2023/11/applied_innovation_roadmap_CDR.pdf

45 Morrow, D., Thompson, M., Anderson, A., Batres, M., Buck H., Dooley, K., Geden, O., Ghosh, A., Low, S., Njamnshi, A., Noël, J., Táíwò, O., Talati, S., Wilcox, J. (2020). "Principles for Thinking about Carbon Dioxide Removal in Just Climate Policy". One Earth, Vol, 3, Issue 2, P150-153. https://doi.org/10.1016/j.oneear.2020.07.015

A report from Rocky Mountain Institute organizes CDR approaches using the below taxonomy in Figure 4, showing that a classification of solutions has not yet converged in this newly emerging field:[46]

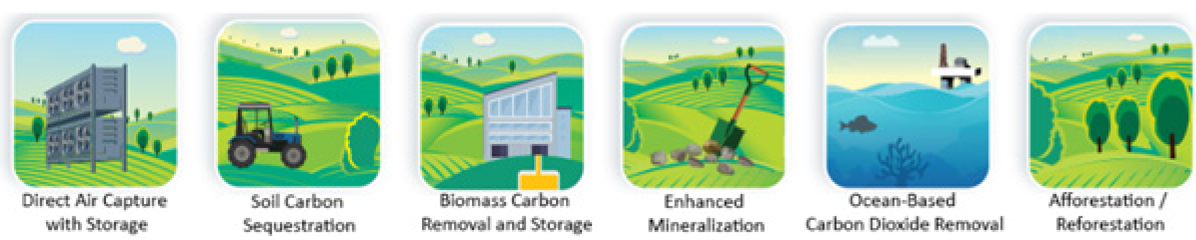
**Figure 5: Taxonomy of CDR Solutions via Rocky Mountain Institute**

| BIOGENIC (bCDR) | GEOCHEMICAL (gCDR) | SYNTHETIC (sCDR) | STORAGE |
|---|---|---|---|
| **Living biomass**<br>**1.1** Improved management<br>**1.2** Conservation/protection<br>**1.3** Restoration/creation | **Solid carbonate minerals**<br>**4.1** Surficial mineralization | **Indirect water capture[1]**<br>**6.1** $CO_2$ stripping<br>**6.2** Electrochemical alkalinity production | **Storage of $CO_2$**<br>**8.1** Conventional storage<br>**8.2** In-situ mineralization<br>**8.3** Ex-situ mineralization |
| **Stabilized biomass**<br>**2.1** Biomass direct storage<br>**2.2** Timber building products<br>**2.3** Other biomass building products<br>**2.4** Pyrolysis (biochar) and storage<br>**2.5** Pyrolysis (bioliquid) and storage<br>**2.6** Microalgae in ponds<br>**2.7** Microalgae in open water<br>**2.8** Macroalgae in open water | **Dissolved bicarbonate sequestration**<br>**5.1** Terrestrial enhanced weathering[1]<br>**5.2** Coastal enhanced weathering[1]<br>**5.3** Mineral alkalinity enhancement[1] | **Direct air capture[1]**<br>**7.1-7.3** Liquid solvent<br>**7.4-7.7** Solid sorbent<br>**7.8-7.9** Membranes<br>**7.10** Cryogenic | |
| **Sequestration of $CO_2$ from biomass**<br>**3.1** BECCS to electricity<br>**3.2** BECCS to fuels | | | |

**Note:** BiCRS encompasses "stabilized biomass" and "storage of $CO_2$ from biomass in the 'biogenic'" category above. Bioenergy with carbon capture and storage is equivalent to the "storage of $CO_2$ from biomass" category above.

The following figure depicts the six categories of CDR solutions as discussed throughout this report.

**Figure 6: CDR approaches considered in this report.**




[46] *The Applied Innovation Roadmap for CDR [Review of The Applied Innovation Roadmap for CDR*]. RMI.org; RMI. https://rmi.org/wp-content/uploads/dlm_uploads/2023/11/applied_innovation_roadmap_CDR.pdf

**Figure 6: CDR approaches considered in this report.**

| | |
|---|---|
| **Direct air capture and storage** | Chemical engineering approaches to separate $CO_2$ from ambient air and storage captured $CO_2$ in long-lived products or secure geologic formations. |
| **Soil carbon sequestration** | Agricultural management practices that increase carbon stored in the soil. |
| **Low or no-greenhouse gas emitting BiCRS** | BiCRS involves separating $CO_2$ from bioelectricity or hydrogen production and storing it securely. Non-bioenergy approaches including biomass burial, biochar, and bio-oil injection. |
| **Enhanced mineralization** | Surficial, ex-situ, and in-situ approaches for exposing $CO_2$ reactive minerals to $CO_2$ captured directly from air and/or oceans and accelerating weathering and conversion into stable carbonates. |
| **Marine CDR and blue carbon** | Methods that enhance drawdown or removal of $CO_2$ from the upper hydrosphere, directly removing it or storing it as dissolved bicarbonate or organic matter in the ocean; including ocean alkalinity enhancement, artificial upwelling or downwelling, electrochemical $CO_2$ separation from seawater, biomass sinking/aquaculture, and ocean iron fertilization. A separate discussion on coastal "blue carbon" practices to store $CO_2$ in soil and vegetation on coastal wetlands and seagrasses is also included in this section. |
| **Afforestation/reforestation** | Planting new or restoring degraded forests |

## Storage and Utilization

Any effective CDR strategy needs to not only capture $CO_2$ from the atmosphere but also store it for long periods of time. Some CDR approaches store biologically captured $CO_2$ in soils and biomass. Other CDR technologies produce a concentrated stream of $CO_2$ that can be injected into underground geological formations. Storage timeframes can vary from hundreds of years to hundreds of thousands of years, depending on the CDR approach.

Geological storage[47] methods involve pressurizing $CO_2$ into a supercritical fluid and injecting it into underground formations of porous and permeable rock including deep saline aquifers,

[47] This report uses the terms "geologic sequestration" and "geologic storage" synonymously.

depleted oil and gas reservoirs, and in basalt and other mafic and ultramafic formations.[48] While stored, depending on both the timescale and geology, the $CO_2$ remains a supercritical fluid, or reacts with underground rocks or formation fluids to form other compounds. When properly capped and sealed, this form of storage is effectively permanent. Geological storage is particularly attractive in the United States because the country has vastly more underground storage capacity than all the human-caused $CO_2$ it has emitted.[49]

$CO_2$ removed from the atmosphere can also either be mineralized into stable carbonates and stored terrestrially (e.g., mine tailings and agricultural lands) or in marine environments, or it can be converted or "recycled" into durable and useful materials, such as concrete. As part of a research and development portfolio to advance carbon capture use and storage, DOE is undertaking research and development focused on $CO_2$ conversion technologies. While some elements of carbon capture, use, and storage will be covered in this report (when relevant to approaches like direct air capture coupled to durable storage and bioenergy with carbon capture and storage [BECCS]), this report does not focus on the details of point source carbon capture, $CO_2$ transport, use, or geologic storage in saline aquifers. For more information, see the June 2021 Council on Environmental *Quality Report to Congress on Carbon Capture, Utilization, and Sequestration.*[50]

## Life Cycle Assesment and Measurement, Monitoring, Reporting, and Verification

For all CDR approaches, net emissions should be analyzed to the extent possible in a consistent, transparent manner using clearly defined life cycle assessment (LCA) methods and tools. LCA involves calculating or estimating all inputs and outputs of a product or process throughout its life cycle, from raw material extraction through use and then end-of-life (i.e., cradle to grave) and their associated environmental impacts. These inputs and outputs may include materials, energy, waste, and direct environmental pollution. A diverse set of indicators can then be calculated including greenhouse gas emissions, ozone depletion, acidification, smog formation, water depletion, ecotoxicity, and so forth.

In LCA for CDR, there is a particular emphasis on calculating net life cycle emissions inclusive not only of the capture of $CO_2$ from the air but also the emissions associated with the upstream and downstream energy and material requirements over the lifespan of the system and other associated greenhouse gas outcomes. Robust LCA for CDR ensures that the systems are verifiably removing $CO_2$ from the atmosphere on net when the entire supply chain is considered. To compare the net emissions of various CDR projects and approaches, further development and application of LCA protocols and tools is required.

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48 Additional geologic storage opportunities could include unmineable coal seams and shales, although these pose significant challenges and are thus less attractive options for $CO_2$ storage at this time.

49 U.S. Department of Energy, National Energy Technology Laboratory (2015). *DOE's Carbon Storage Atlas – Fifth Edition (Atlas V)*. Albany, United States. https://www.netl.doe.gov/sites/default/files/2018-10/ATLAS-V-2015.pdf

50 Council on Environmental Quality (2021). *Report to Congress on Carbon Capture, Utilization, and Sequestration*. Washington, D.C., United States: Executive Office of the President of the United States. https://www.whitehouse.gov/ceq/news-updates/2021/06/30/council-on-environmental-quality-delivers-report-to-congress-on-steps-to-advance-responsible-orderly-and-efficient-development-of-carbon-capture-utilization-and-sequestration/

Conducting measurement, monitoring, reporting, and verification (MMRV) of the amount of $CO_2$ removed, along with tracking its displacement and other greenhouse gas outcomes associated with the CDR process, is crucial for achieving robust net-negative outcomes needed for successful CDR projects. High-quality MMRV provides confidence to the public and to CDR purchasers that the quantity and permanence of $CO_2$ removal is accurately accounted. For a project to be successful in removing $CO_2$ from the atmosphere, the LCA must show that net emissions are negative, and the $CO_2$ removal must be verified and monitored.

MMRV protocols developed for specific CDR pathways can also be used to verify many other attributes necessary to support credible credit generation claims that increase confidence in the CDR market. One of the most important attributes is additionality, which tests whether a given CDR project goes above and beyond removal that may have occurred naturally and whether this removal would have occurred anyhow due to co-product revenues, tax incentives, or regulatory requirements. Only truly additional CDR should be used for credit generation.

## Synthesis

Available evidence shows that CDR should be a key component of the nation's clean energy and industry strategy in the coming decades, and it should complement other emissions reduction strategies and address sectors where direct decarbonization is infeasible. CDR represents the only way to remediate legacy emissions that remain in the atmosphere, so developing it today and ensuring it can reach multi-gigatonne scale is critical for addressing potential overshoots of the emissions budget associated with the Paris Agreement targets.

However, the pathway for scaling CDR remains uncertain given how nascent the CDR field is relative to other climate solutions like renewable energy, energy efficiency, and electric vehicles. The breadth of geographic opportunities further underscores the need for urgent investments across a wide range of solutions to determine which approaches work most effectively in different contexts.

Therefore, it is essential to focus on developing diverse solutions that incorporate robust and transparent MMRV systems, along with workforce benefits and environmental protections. By pairing this approach with robust analysis, the nation can ensure that investment dollars are efficiently directed toward the most impact solutions. Taking this approach over the next decade will equip the United States with the technology, policies, and markets to responsibly commercialize CDR in the following decades.

# II. Inventory of Carbon Dioxide Removal Approaches

## 1. Direct Air Capture and Carbon Storage

*Overview and Current State*

Direct air capture systems capture $CO_2$ directly from ambient air, rather than from power plant or industrial emissions. Direct air capture systems produce a $CO_2$ stream that can be injected into a geologic storage reservoir or durably incorporated into products (e.g., building materials).

Direct air capture units use chemical or physical processes to remove $CO_2$ from the air.[51] While some innovative designs exist, the typical direct air capture process involves moving air through contactors where it encounters a solvent, solid sorbent, or mineral that removes the $CO_2$ from the air. In solvent and solid sorbent systems, the $CO_2$-laden material is processed (usually by changing the temperature, pressure, or other conditions) to release the $CO_2$ from the material in a concentrated stream. The concentrated $CO_2$ can then be compressed and stored in a geological setting.[52] More dilute $CO_2$ streams are being investigated for in-situ mineralization (see Enhanced Carbon Mineralization) or use in algae farms. For direct air capture using mineral capture systems, $CO_2$ from the air is converted to a carbonate that can either be calcined to produce a concentrated $CO_2$ stream or kept as a synthetic aggregate in which the $CO_2$ is captured.

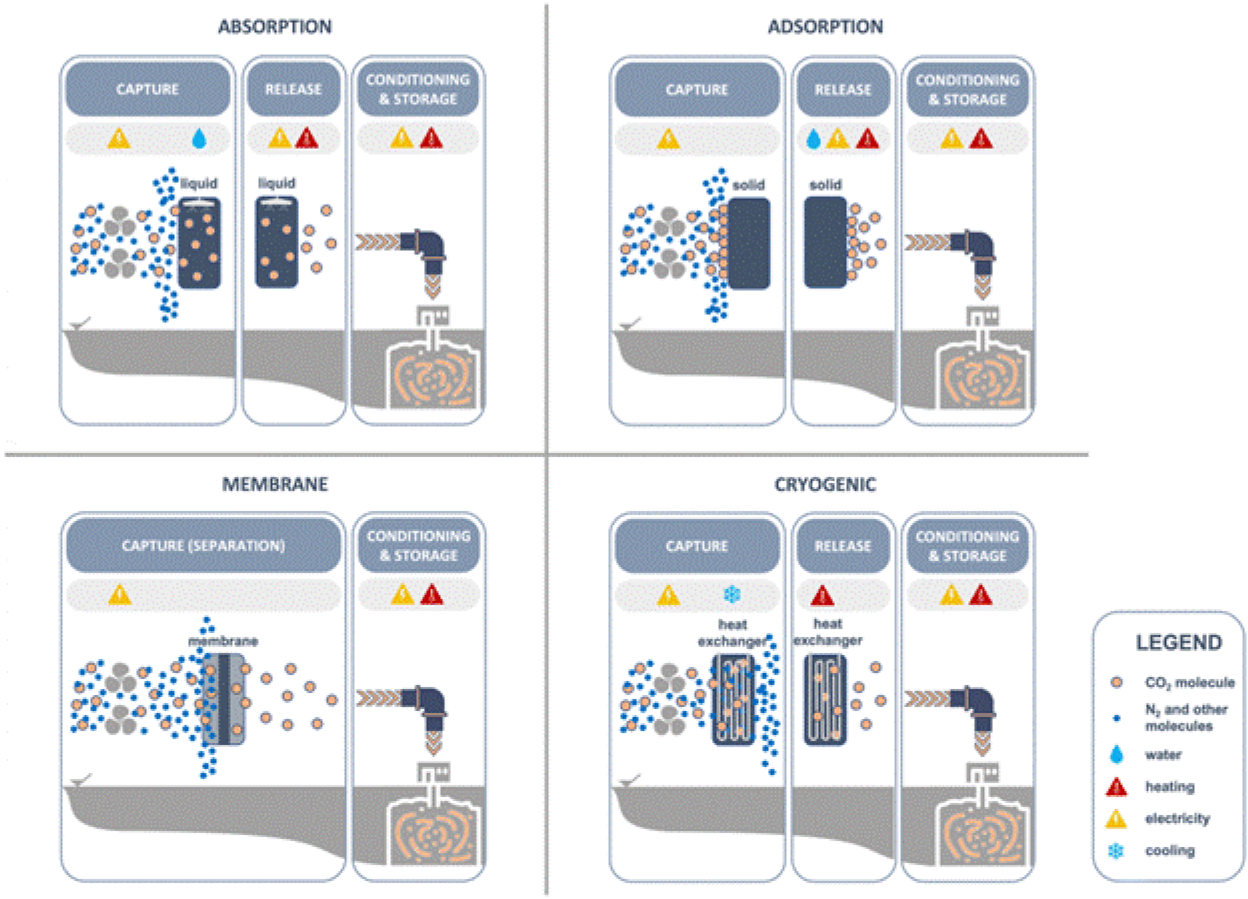
**Illustrative Examples of Direct Air Carbon Capture and Storage Projects**

- Developers began construction in 2023 of a solvent-based Direct Air Carbon Capture system in the U.S. Permian Basin able to capture 0.5 $MtCO_2$/yr when fully operational (expected in late 2025).
- A solid sorbent-based Direct Air Carbon Capture plant began operation in 2021 in Iceland with capacity to capture and geologically store 4000 $tCO_2$/yr.
- A California-based company is operating a Direct Air Carbon Capture system that uses a mineral carbonation process to capture 1000 $tCO_2$/yr from the air before storing it permanently in concrete.

51 Most direct air capture technologies use chemical separation processes because of the dilute concentration of $CO_2$ in air, although examination of physical processes for direct air capture is an active area of research. Challenges for direct air capture using physical materials, such as zeolites, activated carbons, or metal–organic frameworks, include very small $CO_2$ uptake, low $CO_2$ selectivity, and competition by water. However, physical processes require less energy for regeneration than chemical processes.

52 This report uses the terms sequestration and storage interchangeably.

**Figure 7: Roadmap for achieving scalable, safe, and low-cost direct air carbon capture and storage - Energy & Environmental Science - Royal Society of Chemistry**




First-generation Direct Air Capture systems (i.e., < 10 metric tons/day per facility) have been deployed globally at a small scale, with many different direct air capture technologies in various stages of research and development. The United States is a leader in direct air capture deployment with multiple kiloton-scale direct air capture facilities in operation and multiple megaton-scale facilities currently in development and scheduled to be operational before 2030.[53]

### *High Level Assesment of Approach*

Direct air capture offers significant potential scale and relatively straightforward MMRV potential but must overcome near-term cost challenges (**Table 3: High Level Assessment of Direct Air Capture**) while avoiding unintended environmental impacts as it scales.

53 Global DAC Deployments Map. (n.d.). Direct Air Capture Coalition. https://daccoalition.org/global-dac-deployments/

**Table 3: High Level Assessment of Direct Air Capture**

| High Level Assessment of Direct Air Capture | | |
|---|---|---|
| **Potential advantages** | **Key challenges** | **Measurement considerations** |
| • Siting flexibility, as capture unit does not need to co-locate with emissions source<br>• Modularity enables faster learning by doing, and thus greater potential for cost reductions<br>• Relatively land efficient per tonne of removal<br>• High potential for scalability | • Costs associated with capital and energy use during operations<br>• Securing clean energy as economy decarbonizes<br>• Supply chain could be water intensive, and require significant raw materials and/or chemical feedstocks that create economic and/or environmental challenges | • Measurement of $CO_2$ captured by direct air capture systems is relatively simple compared to other CDR approaches. Best practice manuals for monitoring, verification, and accounting of geologic storage projects are provided by DOE, and background on Federal permitting is summarized by the Council on Environmental Quality [54, 55] |

*Approaches and Areas of Research and Development*

Given the variability of direct air capture system performance in different local climates, in addition to the uncertainties around cost and performance potential for various approaches, it will be important to have a portfolio of direct air capture technology reach commercial scale in the next decade.

The DOE's agenda for advancing direct air capture is focused on:

- Advancing research into direct air capture-specific materials science and engineering, including materials such as metal organic frameworks, advanced solvents, air contactors and using artificial intelligence to accelerate materials discovery and testing.
- Advancing research into the chemical processes and mechanisms underlying direct air capture, including an understanding of the interfacial processes of $CO_2$ transport and reactivity across multiple length and time scales, discovery of unconventional thermodynamics and kinetics that could be exploited to drive $CO_2$ binding and release or reactivity with low energy consumption, and identification of key multiphase interfacial structures, chemistries, and phenomena that control kinetics and mechanisms of $CO_2$ transformation into minerals and materials.

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[54] U.S. Department of Energy, National Energy Technology Laboratory. (2017). *Best Practices: Monitoring, Verification, and Accounting (MVA) for Geologic Storage Projects*. Albany, United States: National Energy Technology Laboratory. https://netl.doe.gov/sites/default/files/2018-10/BPM-MVA-2012.pdf

[55] Council on Environmental Quality (2021). *Report to Congress on Carbon Capture, Utilization, and Sequestration*. Washington, D.C., United States: Executive Office of the President of the United States. https://www.whitehouse.gov/ceq/news-updates/2021/06/30/council-on-environmental-quality-delivers-report-to-congress-on-steps-to-advance-responsible-orderly-and-efficient-development-of-carbon-capture-utilization-and-sequestration/

- Piloting novel designs such as electrochemical and humidity swing. DOE anticipates that it will be necessary to fund a few dozen small pilots at the thousands of tonnes/year scale to determine which approaches merit investment at the commercial demonstration scale.
- Demonstrating successful pilots at the small commercial scale (roughly 10ks tonnes/year), to test up to a dozen units at the smallest scale in order to learn about their likely capital and operations costs at full commercial scale.
- Integrating first-of-a-kind full commercial scale direct air capture units that are successfully demonstrated at small scale into DOE's Direct Air Capture Hubs Program (at the 100ks+ tonnes/year scale) at project sites with local climate and geology best matched to the specific direct air capture technology.
- Assessing non-$CO_2$ pollution impacts and developing mitigation strategies.
- Analyzing strategies for integrating direct air capture into:
  - Power and heat systems in the most efficient and flexible way that mitigates against direct air capture competing against direct decarbonization for clean energy in the near-term.
  - $CO_2$ conversion projects that are located in optimal regions and are at appropriate scale for early direct air capture off-take.
- Developing infrastructure for rapidly prototyping and iterating on direct air capture designs of different scales, including the support for facilities at the National Energy Technology Laboratory's Direct Air Capture Center, the National Carbon Capture Center, and National Renewable Energy Laboratory's Flatiron campus.

Beyond research and development of direct air capture units, safe and secure geologic storage for direct air capture system approaches is a key component to enabling commercial scale. Projects seeking to inject $CO_2$ into subsurface formations must obtain a permit for a Class VI well, granted by the EPA or states, territories, or Tribes with primacy.[56] Key actions across the U.S. Government enabling geologic storage and commercialization of direct air capture include:

- Building "direct air capture-ready" $CO_2$ transport and storage infrastructure through DOE's Carbon Storage Assurance Facility Enterprise (CarbonSAFE) Program and the Carbon Dioxide Transportation Infrastructure Finance and Innovation (CIFIA) Program. Implementation regulations for geologic storage under EPA's Underground Injection Control Class VI program.
- Implementation of 45Q tax credits at IRS to provide $180/tonne of credit for every tonne captured and stored in a dedicated geologic formation.

## 2. Enhanced Carbon Mineralization

### *Overview and Current State*

$CO_2$ is naturally removed from the atmosphere through the formation of carbonate minerals. Carbonate minerals are formed when carbonic acid, which could be formed when $CO_2$ from the

[56] Class VI Wells. (2024) Environmental Protection Agency (EPA). https://www.epa.gov/uic/class-vi-wells-used-geologic-sequestration-carbon-dioxide

air has dissolved in water, react with positively charged metals (e.g., calcium and magnesium) such as those that leach from silicate rocks. Mineralization of $CO_2$ takes place at the surface of the Earth where silicate rocks are exposed, in the subsurface through the percolation of $CO_2$ rich water into reactive rock formations, and in the ocean through formation of dissolved bicarbonates that have the potential to precipitate as solid carbonates. Naturally, mineralization occurs on the scale of millennia.

Enhanced carbon mineralization is a CDR approach intended to accelerate this natural process of atmospheric $CO_2$ removal. Enhanced carbon mineralization approaches can be classified as (1) land methods, including *ex situ*, surficial, and *in-situ* (i.e., subsurface) mineralization, or (2) ocean methods, including direct addition of reactive minerals to the ocean that react with dissolved $CO_2$. This latter topic is also addressed in the section on marine CDR.

The rocks that are most susceptible to rapid carbon mineralization are silicate-containing mafic and ultramafic rocks. While these are most common deep below the surface, major deposits can also be found at or near the surface in some regions. Such deposits are broadly distributed in the United States and are found throughout the Pacific Coastal region, the Appalachian Mountains, and in other regions.[57]

DOE has sponsored significant amounts of basic research in enhanced carbon mineralization. There has been a large increase in research and development and financial interest by academic institutions, national laboratories, private companies, and others within the last one to two decades, including an extensive summary of enhanced carbon mineralization in the 2005 IPCC *Special Report on Carbon Dioxide Capture and Storage*.[58]

### *High Level Assessment of Approach*

Enhanced mineralization offers significant scale potential, and open systems such as spreading rock on agricultural soils (i.e., enhanced rock weathering) could offer dramatically lower costs than other approaches if scientific uncertainties and measurement challenges can be adequately addressed (Table 4).[59]

[57] USGS Data Series 414 Mapping the Mineral Resource Base for Mineral Carbon Dioxide Sequestration in the Conterminous United States. https://pubs.usgs.gov/publication/ds414

[58] Intergovernmental Panel on Climate Change (2005). Special Report on Carbon Dioxide Capture and Storage. [Metz,B., Davidson, O., de Coninck, H., Loos, M., and Meyer, L. (Eds.)]. Cambridge University Press, UK. https://www.ipcc.ch/report/carbon-dioxide-capture-and-storage/

[59] Beerling, D.J., Leake, J.R., Long, S.P. et al. Farming with crops and rocks to address global climate, food and soil security. *Nature Plants* 4, 138–147 (2018). https://doi.org/10.1038/s41477-018-0108-y

**Table 4: High Level Assessment of Enhanced Mineralization**

| High Level Assessment of Direct Air Capture | | |
|---|---|---|
| **Potential advantages** | **Key challenges** | **Measurement considerations** |
| • Potential for very low costs, in some cases enabled by leveraging byproducts from mining and manufacturing industries.<br>• Opportunities for shorter MMRV timeframes for some approaches.<br>• Required human capital aligned with existing expertise in fossil fuel-intensive mining and heavy industries.<br>• Co-benefits can include local soil and ocean deacidification. | • Potentially high capital costs associated with dedicated mining/drilling efforts.<br>• Potential for land and resource intensity depending on location and type of process.<br>• Dedicated mining efforts face environmental and public acceptance challenges.<br>• Fundamental scientific research to address outstanding questions on the multiphase interfacial structure, chemistry, and phenomena controlling kinetics and mechanisms of $CO_2$ transformation into minerals and materials that limit scalable and durable storage. | • At present, no government standards exist for quantifying $CO_2$ mineralization. While in-situ approaches are potentially possible to integrate into existing underground $CO_2$ storage regulations, new frameworks will be needed for ex situ approaches. For ex situ, it may be necessary to rely on models (instead of direct measurements) to implement at scale. For all approaches, technical challenges remain for measuring $CO_2$ precisely and cheaply, with the greatest uncertainties around ex situ approaches. |

*Approaches and Areas of Research and Development*

The U.S. Government's strategy to enable innovation is focused on the following goals:

- Enable in-situ mineralization to have the same regulatory robustness as $CO_2$ storage in saline aquifers. To do this, DOE is focusing on advancing science and monitoring associated with basalt and other mafic formations to address key uncertainties regulators must address to issue permits.
- Develop confident estimates of carbon storage outcomes from various ex-situ approaches. To do this, longitudinal field trials coupled with advances in monitoring techniques will need to be integrated into computer models that can accurately estimate full carbon cycle impacts of various approaches at the landscape level, as well as likely techno-economic baselines for leading approaches.

- Provide resources to developers about where the best potential opportunities for $CO_2$ mineralization are likely to be found via national-level mapping of key feedstocks for $CO_2$ mineralization and estimating resource potential.
- Protect the environment from any negative unintended consequences of the entire value chain for $CO_2$ mineralization approaches, via funding for environmental impact research and analyses.
- Unlock co-benefits of $CO_2$ mineralization approaches via dedicated analyses on how different approaches could optimize around these co-benefits, and how policy design can unlock these benefits alongside the potential for CDR.
- Understanding fundamental science processes such as those controlling $CO_2$ transfer between phases, the resulting chemical species that form, the factors that determine the mineral formation rates at the interface, and the evolution of the subsurface over time in response to $CO_2$ mineralization.[60]

## 3. Biomass Carbon Removal and Storage

*Overview and Current State*

Biomass produced with low or zero greenhouse gas emissions plus carbon removal and storage is a suite of a CDR strategies in which plants capture $CO_2$ via photosynthesis, and then the carbon in those plants is stored directly underground or in long-lived bioproducts (e.g., biomass burial, bio-oil injection, biochar); or via carbon capture, use, and storage of the $CO_2$ associated with bioenergy production, known as bioenergy with carbon capture and storage (BECCS). This broader definition of biomass carbon removal was first introduced in a 2020 Innovation for Cool Earth Forum report.[61]

**Illustrative Biomass Carbon Removal and Storage Examples**

- A plant in Arkansas is converting wood waste and sawdust into sealed bricks that can be permanently stored in dedicated underground facilities.
- The Orsted Kalundborg Hub in Denmark will capture and store 430,000 tons of $CO_2$ from power plants burning waste wood and straw. The $CO_2$ will be stored in local geologic storage projects.
- BeccsStockholm will capture 700,000 tons of $CO_2$ per year from the heat and power plant in central Stockholm fired by wood waste from logging. The $CO_2$ will be shipped to Norway for storage.
- The ARCHES coalition in California's Central Valley is designing two plants to convert agricultural waste into hydrogen and $CO_2$ which will be permanently stored in the valley.
- Quebec is constructing a biochar plant in Port-Cartier that will create 75,000 tons per year from wood waste, for storage in agricultural soils.
- Charm Industrial is burying ktons of bio-oil at sites in the United States.

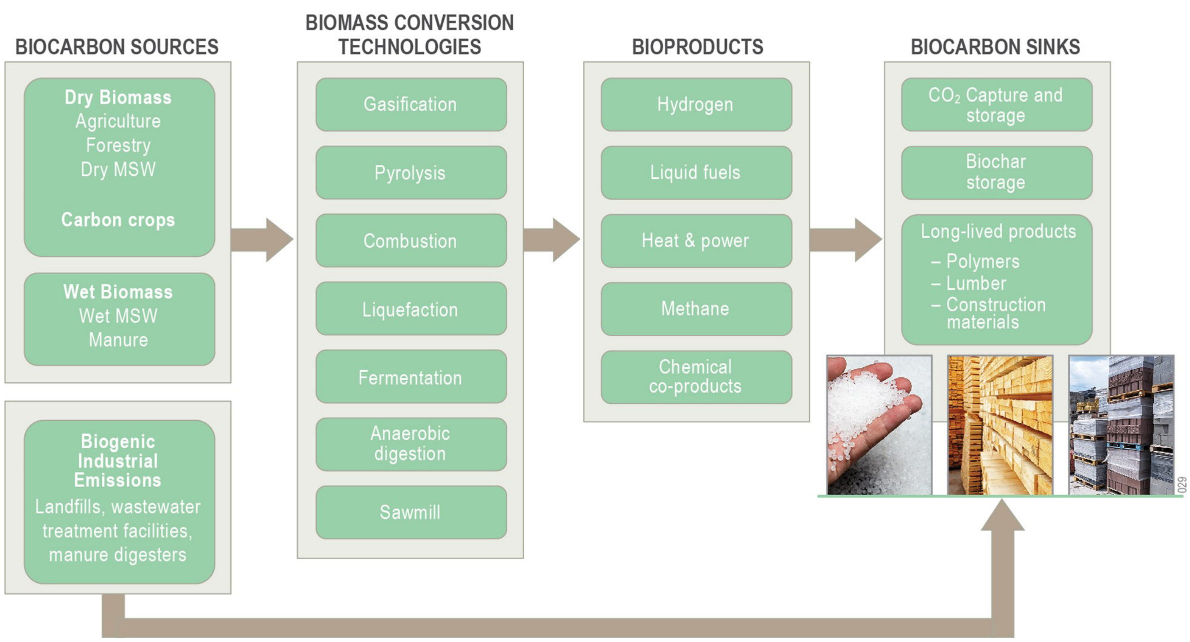
60 Basic Energy Sciences Roundtable: Foundational Science for Carbon Dioxide Removal Technologies. US DOE Office of Science, Washington, DC (United States). https://science.osti.gov/-/media/bes/pdf/reports/2024/CDR-full-report_0607224_2.pdf

61 Innovation for Cool Earth Forum (ICEF). (2023). Innovation for Cool Earth Forum (ICEF). icef.go.jp/wp-content/uploads/2024/02/icef2020_roadmap.pdf

All the Intergovernmental Panel on Climate Change integrated assessment models that reach well below 2°C rely heavily on biomass-based removal methods. These models primarily rely on the combustion of biomass to produce electricity paired with the subsequent capture of produced $CO_2$ and injection into porous rocks underground for secure geological storage (i.e., BECCS).[62, 63] The best estimate[64] of current biomass carbon removal and storage (BiCRS) deployment globally is about 2.3 million tons per year, of which 0.5 million tons is biochar. Several biomass carbon removal facilities are at the commercial pilot phase.

The concept of BiCRS acknowledges a future in which biomass could be more valuable for its carbon content than for its energy content[65] due to the potential to remove and store large quantities of atmospheric $CO_2$. We broadly use the term BiCRS to encompass all approaches that (a) use biomass to remove $CO_2$ from the atmosphere and (b) store biomass carbon as $CO_2$ deep underground, as soil carbon, or in long-lived products. However, careful systems analysis is necessary to direct limited supplies of biomass to the highest uses as the economy accelerates decarbonization.

**Figure 7: Overview of possible BiCRS pathways. In the U.S., these pathways have the aggregate potential to remove more than 800 million tonnes of $CO_2$ per year at a cost less than $100/tonne $CO_2$, with no impact on cropland or commodity prices.[70]**




[62] P. Smith et al., (2015). "Biophysical and economic limits to negative $CO_2$ emissions". Nature Climate Change, 6. pp. 42-50. https://doi.org/10.1038/nclimate2870

[63] Intergovernmental Panel on Climate Change (2018). Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C [V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, & R. Pidcock, (eds.)]. 1. https://www.ipcc.ch/sr15/

[64] S. Smith et al., (2023). The State of Carbon Dioxide Removal - 1st Edition. The State of Carbon Dioxide Removal. https://www.doi.org/10.17605/OSF.IO/W3B4Z

[65] Analysis in Pett-Ridge et. al. shows that under 45Q $CO_2$ values, the $CO_2$ is always worth more than a fuel product including hydrogen or jet fuel.

### *High Level Assessment of Approach*

A group of national laboratories and universities has completed a study[66] of the capacity for BiCRS in the United States. They found that over 800 million tons of annual $CO_2$ removal could be obtained with net benefits (products and fuels) that offset much of the cost. Some of the most important issues for advancement of BiCRS in the United States include identifying biomass that can be used without impacting crop production, food prices, and GHG emissions fluxes, and retrofitting existing bioenergy, biofuel, and pulp and paper facilities to capture and store $CO_2$ that today is vented to the air (Table 5). There is a limited total amount of feedstock material, even though it is very large.

[66] Pett-Ridge et al. Op. Cit.

**Table 5: High Level Assessment of Biomass Carbon Removal and Storage**

| High Level Assessment of Biomass Carbon Removal and Storage | | |
|---|---|---|
| **Potential advantages** | **Key challenges** | **Measurement considerations** |
| • Relatively high technology readiness level (TRL) ranging from TRL 4–7 and generates marketable energy products (electricity/ fuels/hydrogen).[67, 68, 69]<br>• Can provide markets for low-value plant products and by-products, such as organic material in trash, crop residue, and forest waste which can help reduce wildfire risk.<br>• Can aid rural economic development.<br>• Biofuel and pulp/paper are large-scale industries that have large stakeholder and investor bases that can aid rapid growth.<br>• Because BiCRS creates valuable products besides $CO_2$ removal, net costs are potentially low.<br>• Using above-ground biomass for BiCRS can encourage healthy ecosystems and storage of carbon in soils. | • Long-distance transport of biomass can be a major cost and emissions challenge. Facilities must be sited near sources and $CO_2$ storage.[70]<br>• Producing electricity is not cost-competitive with other renewable energy.[71]<br>• Expanding beyond 500 MT of available waste may create direct and indirect land-use change greenhouse gas and other environmental issues.<br>• Air quality is a primary community concern because of previous biomass burning.<br>• The greenhouse gas benefits associated with using biomass in the context of energy production and/or other BECCS applications are uncertain.<br>• MMRV for greenhouse gas outcomes from land-based processes underlying BiCRS processes. | • The carbon capture component is relatively easy to measure at the capture and storage sites.<br>• Benefits and problems accrue across engineered and natural systems, requiring comprehensive measurement.<br>• USDA's Agricultural Research Service measures cropland soil organic carbon storage. The Forest Service conducts on-the-ground management of carbon stocks and land use change modeling.<br>• USDA's Forest Service Forest Inventory and Analysis (FIA) is a nationwide statistical survey of forests and land use changes, with measurements used for all forest carbon pools and soil carbon sampled. |

67 A. Bhave, (2017). "Screening and techno-economic assessment of biomass-based power generation with CCS technologies to meet 2050 $CO_2$ targets". *Applied Energy*, 190, pp. 481-489. ISSN 0306-2619. https://doi.org/10.1016/j.apenergy.2016.12.120

68 U.S. Department of Energy, National Energy Technology Laboratory. (2015). DOE's Carbon Storage Atlas – Fifth Edition (Atlas V). Albany, United States: National Energy Technology Laboratory. https://www.netl.doe.gov/sites/default/files/2018-10/ATLAS-V-2015.pdf

69 Fuss, S. & Johnsson, F. (2021). "The BECCS Implementation Gap – A Swedish Case Study". Frontiers in Energy Research, 11 February 2021. https://doi.org/10.3389/fenrg.2020.553400

70 Pett-Ridge Op.Cit.

71 Consoli, C. (2019). *Bioenergy and Carbon Capture and Storage*. Melbourne, Australia: Global CCS Institute. https://www.globalccsinstitute.com/wp-content/uploads/2019/03/BECCS-Perspective_FINAL_18-March.pdf

*Approaches and Areas of Research and Development*

The U.S. Government's innovation strategy is focused on the following goals:

- Advancing technology for converting biomass to energy with carbon storage, including to produce electricity, hydrogen, and fuels/chemicals from benchtop through early commercial demonstration scale.
- Assessing supply chains to understand scale of available biomass that is optimized for CDR compared to other uses of biomass.
- Developing advanced plant genetics to optimize for conversion to products and/or carbon storage.
- Supporting the development of biomass supply chains and $CO_2$ transportation and storage infrastructure.

## 4. Forests

*Overview and Current State*

Forest management practices for CDR include reforestation, afforestation, and other forest management strategies needed to restore desired forest structure and function within the appropriate sociopolitical, ecological, and historical contexts.[72] Forest restoration includes activities intended to return ecological function and productivity to forests disturbed by planned (e.g., tending and harvesting) or unplanned (e.g., fire and insects) disturbances. Reforestation is the act of planting or naturally regenerating a forest or woodland with trees following a disturbance. Afforestation is the process of establishing a forest or woodland on land previously used for other purposes.[73] The concept of sustainable forest management includes managing forests for carbon storage and storage as well as other essential goods and services provided by healthy and resilient forests. This includes limiting carbon losses due to wildfires and other major disturbances that are outside the range of variability typically associated with each forest type.

**Illustrative Examples of Forest Projects**

- A project in Hawaii is re-establishing native forests on private lands, storing about 6 metric tons of $CO_2$ per hectare per year.
- A project in Oregon is increasing carbon stocks on 634,000 acres by extending timber harvest rotation ages and using silviculture to maximize long-term growth as part of a contract that includes long term monitoring.
- A private sector carbon market in the U.S. Southeast provides landowners with payments in exchange for deferring their timber harvest compared to business-as-usual, which is verified using remote sensing technology at one-acre resolution.

Importantly, to be considered CDR, the forest carbon activity must be an intentional act leading to additional net $CO_2$ captured from the atmosphere and stored for a long duration and appropriately measured and monitored. CDR includes human-caused enhancement of $CO_2$ sinks

[72] Stanturf, J. (2005). "What is Forest Restoration?". *Restoration of Boreal and Temperate Forests*. Boca Raton, United States: CRC Press, pp. 3-11. https://www.fs.usda.gov/treesearch/pubs/22209

[73] For the purposes of this report, previously unforested is defined as before European settlement.

but excludes natural $CO_2$ uptake not directly caused by human activities, which includes most of the stored 774.6 MMT $CO_2e$ of ongoing U.S. forestry sink.[74]

Over the past ten years, forest land acreage has increased at a constant rate by a net average three million acres per year, which can be considered CDR. EPA estimated that these newly forested lands were responsible for storing 99 MMT $CO_2e$ each year.[75]

### *High Level Assessment of Approach*

Forestry approaches are a central aspect of CDR in the United States. Ongoing reforestation provides immediate and substantial CDR and is associated with strong environmental improvements and can be very cost-effective. A significant limitation to these approaches is the land limitation—much of the United States that was deforested in early years has been reforested today (such as the forests of Maine) and does not count explicitly as CDR today, although the ongoing forestry sink is an important part of the U.S. emissions inventory (Table). The amount of land on which new reforestation activities are available is the primary long-term limitation in their impact in the United States.[76]

74 EPA (2024). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2022 U.S. Environmental Protection Agency, EPA 430R-24004. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2022.

75 The 99 MMT of $CO_2e$ is the gross amount of carbon stored over approximately 30 million acres of land that has been converted from other land uses to forest over the past 10 years.

76 Pett-Ridge et al. Roads to Removal op cit.

**Table 6: High Level Assessment of Forest Management Practices**

| High Level Assessment of Forest Management Practices | | |
|---|---|---|
| **Potential advantages** | **Key challenges** | **Measurement considerations** |
| • Cost-effective methods and infrastructure already exist for most forest restoration approaches.<br>• Ecosystem services and increased biodiversity are created alongside jobs for rural economies.<br>• Reforestation/ afforestation can be a cost-effective CDR approach.[77] | • Reversibility of the $CO_2$ capture mechanism is a major risk to success.<br>• Reforestation/ afforestation methodologies are dependent upon available land, rate of tree growth, and vulnerable to loss from disturbance events (e.g., wildfire, drought, storms, and insect or disease outbreaks) which are becoming more frequent and intense due to climate change. | • Forest increases are generally trackable by well-established methods.<br>• The Forest Inventory and Analysis Program of the USDA Forest Service is the nation's forest census.<br>• Additionality is a key issue which can be hard to confirm.<br>• Long-term land management is required and can impact the payment methods for credits.<br>• The National Aeronautics and Space Administration uses satellite data to assess changes in forest area and biomass<br>• DOE maintains AmeriFlux datasets that provide linkages between terrestrial ecosystem processes and responses at landscape, regional, and continental scales. |

The key goals of ongoing innovation in forest restoration are to increase nursery capacity and associated supply chains, identify and prioritize sites, and optimize labor and transport logistics and costs, maintenance, and related funding.[78, 79] This includes the following approaches and areas of research and development:

- Landscape-scale conservation and management to protect and restore carbon storage in existing forests.
- Development of long-term forest products as substitutes for non-wood building materials.
- Implementation of afforestation projects in non-traditional areas such as open urban environments, frequently flooded areas, travel corridors, and mine and brown field reclamation.
- Exploring opportunities of aligning forest and coastal carbon activities with economic development in rural and coastal communities.

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77 B. Griscom et al., (2017). "Natural climate solutions". *Proceedings of the National Academy of Sciences of the USA*, 114(44): 11645–11650. https://doi.org/10.1073/pnas.1710465114

78 J. Fargione et al., (2021). "Challenges to the reforestation pipeline in the United States". *Frontiers in Forests and Global Change*, 4: 629198, 8 pp. https://doi.org/10.3389/ffgc.2021.629198

79 National Association of State Foresters. (2016). National Survey of State Operated Tree Seedling Nurseries and Tree Improvement Programs. Washington, D.C., United States: *National Association of State Foresters*. https://www.stateforesters.org/wp-content/uploads/2018/08/NASF-Report-National-Survey-of-State-Operated-Tree-Seedling-and-Tree-Improvement-Programs.pdf

## 5. Soil Carbon Managment

*Overview and Current State*

Soil carbon management aims to increase the storage rates and permanence of atmosphere-derived carbon in soils. The total organic carbon content in soils represents the difference between inputs and losses of soil organic carbon. Inputs from plants are driven by photosynthesis, which stores a net three gigatons of carbon per year.[95] Losses are primarily caused by lower amounts of plant roots and residues returned to the soil, increased decomposition from land cultivation or forest harvesting, and wind- and water-caused soil erosion. Organic carbon content can be affected by factors such as land cover, land management practices, climate, and soil type. Over the last 12,000 years, land cultivation has resulted in an estimated loss of 133 GT of elemental carbon (equivalent to 487 GT of $CO_2$) from the surface of the top two meters of soil.[80] One third of the increase in atmospheric $CO_2$ concentrations since 1850 can be attributed to soil organic carbon loss from land use change, particularly deforestation and land cultivation.[94]

Estimates of agricultural soil-based CDR and emissions reduction capacity in the United States range from 0.24 to 0.80 gigatons of $CO_2$ per year, based on widespread adoption of current best practices to adoption of new technologies.[81] Not only can land use significantly affect both the quality and quantity of plant residues delivered to soils and their processing, it also can affect erosional losses and deposition. Climate change, especially in northern latitudes, may cause significant losses of soil carbon.[82] Proper grazing management, retaining forest residues and surface organic horizons, selecting appropriate species, and reducing wildfires can reduce soil carbon losses. Management options for actively storing carbon into soil can be influenced by topographical and mineralogical characteristics and disturbance histories (e.g., fire-return interval and land-use change history).[104]

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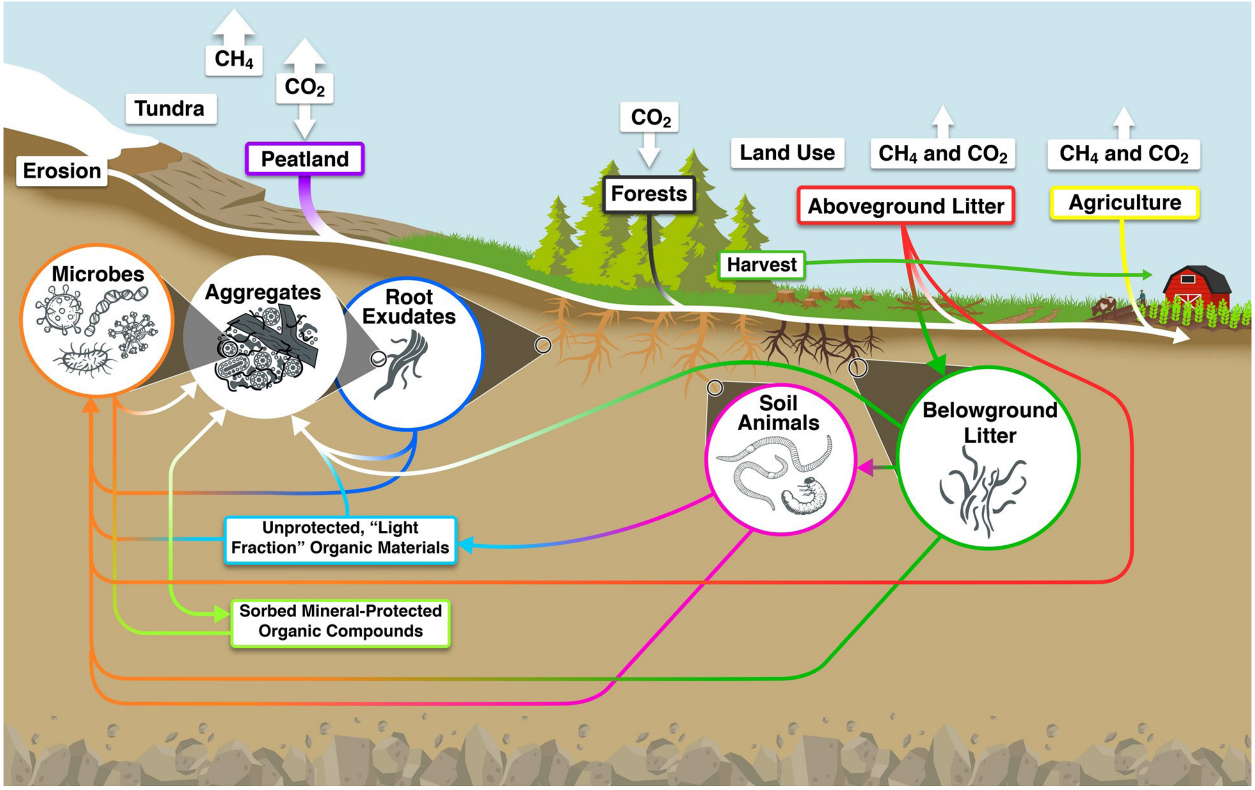
80 Sanderman, J., Hengl, T. & Fiske, G. (2017). "Soil carbon debt of 12,000 years of human land use". *Proc. Natl. Acad. Sci*., 114, 9575 LP – 9580. https://doi.org/10.1073/pnas.1706103114

81 G. Dipple et al., (2021). "The Building Blocks of CDR Systems" [J. Wilcox, B. Kolosz & J. Freeman (eds.)]. CDR Primer. https://cdrprimer.org/read/chapter-2

82 U.S. Global Change Research Program (2018a). K. Lajtha *et al.*, (2018). "Chapter 12: Soils." In Second State of the Carbon Cycle Report (SOCCR2): A Sustained Assessment Report. [N. Cavallaro et al., (eds.)]. Washington, D.C., United States: U.S. Global Change Research Program, pp. 469-506, https://doi.org/10.7930/SOCCR2.2018.Ch12

**Figure 8: Processes Involved in Controlling Fluxes and Stabilization of Soil Carbon (Source: U.S. Global Change Research Program, 2018a)**



*High Level Assessment of Approach*

**Table 7: High Level Assessment of Soil Carbon Management**

| High Level Assessment of Soil Carbon Management | | |
|---|---|---|
| **Potential advantages** | **Key challenges** | **Measurement considerations** |
| • Soil carbon approaches are readily applied in existing agricultural practice.<br>• Soil carbon management has many co-benefits, including increasing water holding capacity, improving groundwater quality, improving soil fertility and increasing crop productivity through improved soil health, microbial activity, and nutrient cycling, and biodiversity, and improving human health by reducing smog and airborne dust.<br>• There is large-scale potential for global soil carbon storage.<br>• There are a variety of practices that can promote soil carbon storage or reduce soil carbon loss, making it flexible for various land management scenarios and soil ecologies.<br>• Soil carbon management can improve long-term profitability for farmers, natural resource managers, rural communities, and landowners.<br>• Perennial grasses can rapidly store soil carbon, with significant increases in soil carbon less than five years after seeding. | • Reversibility is a major risk to success due to natural factors, wildfire, wind and water erosion, or if farmers and landowners disrupt soil as part of farm or land management.<br>• Carbon storage rates and permanence vary by climate, soil type, and land use and management practices.<br>• Uncertainties associated with carbon storage estimates.<br>• Carbon and nitrogen fluxes in and from soils are difficult to measure, quantify, and attribute to specific practices (i.e., additionality).<br>• Fertilizer additions benefit soil carbon but cause other emissions that can offset the benefit.<br>• Practices that take land out of production to establish vegetative cover/ biomass (e.g., buffers, strip cropping, etc.) may displace production (and therefore emissions) to another place.<br>• Costs of MMRV may be prohibitive when implementing some of these practices. | • Demonstrating additionality of gains to soil carbon stocks accurately and affordably presents a formidable measurement challenge for soil management approaches.<br>• Several carbon measurement systems and networks at various scales, funded and coordinated by multiple agencies, include soil carbon, as inventoried in the State of the *Carbon Cycle Report.*[83]<br>• Carbon must be measured to significant depths to fully account carbon gains and losses.<br>• Needs include remote sensing for below ground soil carbon stocks, rapid, non-destructive, in-field soil carbon measurement, soil sensor networks, including direct measurement of organic and inorganic carbon infrared sensing and satellite imagery to measure biomass density. |

83 State of the Carbon Cycle Report. https://carbon2018.globalchange.gov/chapter/preface/

*Approaches and Areas of Research and Development*

Many of the land management practices that can increase soil carbon storage and/or decrease loss of soil carbon are not widely implemented. These practices, as well as emerging approaches that are being improved by research and development, present opportunities for greater soil carbon storage and climate-smart land management.

**Illustrative Examples of Soil Carbon Restoration Projects**

- One contract in a private sector carbon market, which requires soil management best practice methodologies and third-party verification, entails storing 0.1 $MtCO_2$/y with contracted 20-year durability via reduced tillage and adding cover crops at participating farms across 19 U.S. States.
- Several large cattle ranches in Australia are implementing rotational and prescribed grazing practices to increase soil carbon storage by a combined 0.1 $MtCO_2$/y with 25-year contracted durability.

Led by USDA, multiple agencies are facilitating development and implementation of technologies for measurement and verification of soil carbon storage, including coordination on best available data and collaboration through the Greenhouse Gas Monitoring and Measurement Interagency Working Group.[84]

USDA is investing $300 million through Inflation Reduction Act funding to establish a National Soil Carbon Monitoring Network, conduct field trials, collect data, improve models, and apply findings through the USDA Greenhouse Gas Inventory and Assessment Program.

At DOE, programs such as the ARPA-E SMARTFARM fund research to develop tools and databases to rapidly and accurately measure both above ground greenhouse gas fluxes and below ground soil carbon dynamics. This is just one part of the broader DOE research portfolio addressing fundamental science to enhance soil carbon sequestration and storage. The USDA Forest Inventory and Analysis program surveys forest soil carbon and forest floor carbon on a subsample of their nationwide statistically designed survey of ground plots. The USDA Agricultural Research Service Long-Term Agroecosystem Research Network establishes a statistically paired comparison of long-term aspirational vs. business-as-usual agricultural practices at both plot and field scales across the continental United States, allowing direct assessment of management impacts on soil organic carbon storage in cropland, rangeland, and integrated crop-livestock systems.

## 6. Marine Carbon Dioxide Removal and Coastal Blue Carbon

*Overview and Current State*

The ocean naturally takes up approximately one-third of the anthropogenically emitted $CO_2$ in the atmosphere and has the potential to absorb more. Marine CDR is any method that accelerates biological or non-biological processes to move carbon dioxide from the atmosphere into the ocean carbon sink. Marine CDR approaches may have potential to be highly scalable and

[84] *Fact Sheet: Biden Administration Tackles Super-Polluting Methane Emissions.*(2022, January 31). The White House. https://www.whitehouse.gov/briefing-room/statements-releases/2022/01/31/fact-sheet-biden-administration-tackles-super-polluting-methane-emissions/

effective at removing $CO_2$ from the atmosphere but need continued foundational research to inform societal and scientific decision making.

No marine CDR approach is ready for large-scale commercial deployment because significant questions remain about their efficacy and potential impacts. Scaled and iterative testing of approaches that involves modeling, laboratory studies, and controlled permitted field trials is needed to resolve these questions in a scientifically-sound manner. Various categories of marine CDR methods have been reviewed in several reports, including a report by the National Academies of Science, Engineering, and Medicine.[85] Examples of marine CDR categories include ocean fertilization; artificial upwelling and downwelling; cultivation and sinking of marine or terrestrial biomass; ocean alkalinity enhancement; and direct ocean capture (e.g., engineered approaches to directly remove $CO_2$ from ocean waters).

These marine CDR approaches, which transfer more CO2 from the air into the ocean, are still in early stages of technological development. Research is needed to assess the technology cost, effectiveness, and potential environmental impacts, including co-benefits and risks.

In September 2023, the MCDR-FTAC[86] was established by action of the National Science and Technology Council (NSTC). The objectives of the MCDR-FTAC were to develop a plan to advance work in three areas: 1) establish a comprehensive Federal research plan, 2) clarify permitting, regulations, and guidelines, and 3) improve coordination among government agencies and other sectors. This action responds to a recommendation of the Ocean Climate Action Plan[87] to facilitate and accelerate relevant policy and research on marine CDR and storage. The FTAC has developed a report summarizing a national mCDR strategy[88] .

### Illustrative Examples of Marine CDR Projects

- An ocean alkalinity project in Halifax, Nova Scotia added 280 tons of brucite ($Mg(OH)_2$) into the harbor, estimated to consume more than 200 tons of extra $CO_2$ from the atmosphere.
- The U.S. Naval Research Laboratory has operated an electrochemical system in Key West, Florida to electrochemically remove $CO_2$ from seawater.
- Ebb Carbon is testing a 100T ocean alkalinity enhancement system in the laboratory at Sequim Pacific Northwest National Laboratory facility.
- Vesta began conducting an ocean alkalinity enhancement field test offshore of Duck, North Carolina.
- Equatic, a company based out of the University of California, Los Angeles, is in the planning stages to build a plant that could be capable of removing 109,500 tons $CO_2$/year 2026-2027.

85 A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration (2022) https://nap.nationalacademies.org/read/26278

86 Marine Carbon Dioxide Removal Fast Track Action Committee of the Subcommittee on Ocean Science and Technology National Science and Technology Council. https://www.noaa.gov/sites/default/files/2023-10/mCDR_FTAC_charter_2023_09_19_approved.pdf

87 Opportunities to Accelerate Nature-Based Solutions. (2023). https://www.whitehouse.gov/wp-content/uploads/2022/11/Nature-Based-Solutions-Roadmap.pdf

88 https://www.whitehouse.gov/wp-content/uploads/2024/11/U.S.-Marine-Carbon-Dioxide-Removal-Research-Strategy.pdf

Several Federally funded mCDR research programs have also been established. NOAA and the National Oceanographic Partnership Program (NOPP) announced marine CDR research awards totaling $24 million in fiscal year 2023. The research resulting from this program will support the assessment of risks, co-benefits, and science needs to build regulatory frameworks for testing and scaling various marine CDR pathways. ARPA-E has begun a program, Sensing Exports of Anthropogenic Carbon through Ocean Observation (SEA-$CO_2$), that will use new sensor technology to measure and track marine $CO_2$ removal. DOE also released a funding opportunity for small marine CDR pilots,[89] which will move beyond fundamental research to demonstrate the feasibility and cost of scaling up marine CDR approaches from lab-scale trials to larger demonstration projects.

While frequently considered outside the traditional umbrella of marine CDR approaches, coastal blue carbon approaches, including plant growth and accumulation and burial of organic matter in the soil of tidal wetlands and in seagrass systems, has the potential for carbon removal on the order of 30-80Mt/y in the coming decades, while also providing significant ecosystem co-benefits.[90] In general, blue carbon approaches are associated with strong environmental improvements and are very cost-effective. As for forestry, for blue carbon to be considered CDR the activity must be an intentional, well-monitored act leading to additional net $CO_2$ captured from the atmosphere and stored for a long duration and appropriately measured and monitored. A primary limitation to scale-up in the United States is the amount of land on which new blue carbon activities can be carried out.[91]

89 *FECM Carbon Dioxide Removal Announcements*. Energy.gov/FECM. https://www.energy.gov/sites/default/files/2023-10/FECM%20CDR%20Announcements_August%202023.pdf

90 Chapter Two of the 2019 NAS Study on Negative Emissions Technologies covers coastal blue carbon approaches and estimates that by 2030 and 2060, coastal blue carbon approaches have the potential to remove 37Mt/y and 77Mt/y, respectively. https://nap.nationalacademies.org/read/25259/chapter/4

91 *Ibid. 2019 NAS Negative Emissions Technologies, Chapter 2.*

**Table 8: High Level Assessment of Marine Carbon Dioxide Removal and Coastal Blue Carbon**

| High Level Assessment of Marine Carbon Dioxide Removal and Coastal Blue Carbon | | |
|---|---|---|
| **Potential advantages** | **Key challenges** | **Measurement considerations** |
| • There are many proposed approaches to marine CDR.<br>• Some approaches have shown promise at smaller scales, and this early success has stoked increasing interest in marine CDR from multiple sectors.<br>• Some marine CDR approaches may have potential co-benefits, including reducing localized ocean acidification.<br>• *Coastal blue carbon*: Coastal blue carbon provides many co-benefits beyond removals, such as methane emission reductions, resilience of fisheries, water quality, coastal protection (wave and flood attenuation), and connectivity with different ecosystems. | • Exploration of these solutions must be informed by science and underpinned by community values.<br>• Marine CDR approaches are in the early stages of technological readiness; further research and development, potentially including permitted field trials, is needed to determine the efficacy of various marine CDR approaches and to better understand potential impacts to communities, the environment, and other ocean uses.<br>• Verifiability of carbon removal for marine CDR approaches is a major challenge. New sensing technology and approaches, such as novel remote sensing assessments, and state of the art modeling will be needed.<br>• The autonomous sensors needed to constrain the carbon system at desired test sites (coastal systems) and relevant water depths do not yet exist and require additional research investments.<br>• *Coastal Blue carbon*: Restoration and promotion of wetland transgression requires significant tradeoffs in land uses. | • Measurements of the carbon system will underpin accountable and verifiable carbon credits.<br>• Regional ocean models are highly developed, but local models must be developed that can validated with direct measurements.<br>• The marine environment presents unique measurement challenges, due to considerations like spatial and temporal variability in physical, chemical, and biological conditions in the ocean and various biogeochemical controls and feedback.<br>• The National Ocean and Atmospheric Administration (NOAA), in addition to other Federal agencies, has substantial experience in measurement and modeling of these phenomena at regional scale that must be expanded to the local scale on which projects will be operated.<br>• Remote sensing measurements (airborne, satellites) will be critical to monitor environmental changes and inform diagnostic and regional modeling<br>• Coastal blue carbon: Uptake of $CO_2$ by Blue carbon ecosystems can be measured, monitored, and verified by a variety of methods, including remote sensing. However, improved and novel approaches are required for some ecosystems, including seagrasses. |

Most of the world's ocean $CO_2$ measurement technologies and methods are conducted by NOAA, which is responsible for measurements of surface ocean $CO_2$ and ocean carbon chemistry. EPA also contributes by publishing trends in pH and related properties of ocean water, based on a combination of direct observations, calculations, and modeling. In addition, DOE's National Renewable Energy Laboratory and Pacific Northwest National Laboratory also study ocean $CO_2$ measurement and processes. The National Aeronautics and Space Administration's (NASA) Plankton, Aerosol, Cloud ocean Ecosystem (PACE) mission offers opportunities to monitor phytoplankton and surface ocean biogeochemistry (including dissolved and particulate carbon) in the ocean. Agencies like the National Aeronautics and Space Administration, NOAA, and NSF have funded several research programs aimed at measuring $CO_2$ uptake, transformation, and transport in the ocean.

*Approaches and Areas of Research and Development*

Given the early stage of development in the field of marine CDR, it is important for the U.S. Government to have a cohesive strategy to support researchers on the path to investigating the potential of marine CDR as a viable, environmentally safe, and effective CDR solution. To this end, the White House-organized the Fast Track Action Committee on Marine CDR, a multi-Agency effort, that released a Marine CDR Research Strategy report.[92] This plan helps clarify the U.S. Government's view and strategy for the future of marine CDR research to inform potential scaling of marine CDR by 2030. To date, the U.S. Government involvement in marine CDR has been in support of the following goals, which are also highlighted in the 2024 FTAC mCDR Strategy report:

- Support robust research into potential marine CDR pathways, through modeling, lab, and field trial stages. NASA has invested in foundational field campaigns and modeling (e.g. Export Processes in the Ocean from Remote Sensing) to assess the pathways for the fate of biogenic carbon, proving mechanistic insights into the different pathways of carbon sequestration and potential future change. NOAA's Ocean Acidification Program is at the forefront of these mCDR efforts, with pathway-agnostic Federal funding support in the form of the National Oceanographic Partnership Program mentioned above, complemented by funds from the Inflation Reduction Act, DOE, Office of Naval Research, ClimateWorks Foundation, and NOAA's Global Ocean Monitoring and Observing Program.
- Maintain and expand global networks for both oceanic carbon observations, and atmospheric greenhouse gas observations to establish a strong baseline of global carbon fluxes. This current observing work is carried out largely by NOAA and is critical to the MMRV that will underpin a responsible and accountable CDR economy. ARPA-E is funding a $36 million portfolio of projects with their Sensing Exports of Anthropogenic Carbon through Ocean Observation program mentioned above, aiming to accelerate the development of novel efforts to measure, report, and validate marine CDR. NASA's remote sensing observations remain critical for local, regional and global carbon monitoring and flux calculations, and enable the expansion of MMRV activities. The US GHG Center will facilitate coordination across Federal and non-federal, domestic and international entities to integrate data and capabilities towards monitoring and measurement of GHG that can inform the efficacy of CDR efforts.

[92] National Marine Carbon Dioxide Removal Research Strategy, A Report by the Fast Track Action Committee on Marine Carbon Dioxide Removal. https://www.whitehouse.gov/wp-content/uploads/2024/11/U.S.-Marine-Carbon-Dioxide-Removal-Research-Strategy.pdf

- Provide clarity and guidance on permitting of marine CDR field research and pilot projects. In general, marine CDR projects that take place in coastal, or ocean waters are permitted by the EPA, USACE, or an authorized state agency under the Clean Water Act discharge permitting program under Section 401, Clean Water Act dredged and fill material permitting program under Section 404, or the Marine Protection, Research, and Sanctuaries Act for disposition of materials in ocean waters. Depending on the nature and location of proposed activities, other Federal, state, Tribal, or local requirements would apply[93].
- Engage[94] with and build social license in communities that may be impacted by, or invested in, marine CDR research. Community co-design and education is imperative for effective research and possible scale-up of marine CDR. This fact is recognized by the U.S. Government in efforts like the MCDR-FTAC, and within agencies like NOAA and their Sea Grant Office.

*Coastal Blue Carbon*

The key goals of ongoing innovation in coastal blue carbon are to develop tools to monitor wetland condition, improve wetland protection, and better identify restoration opportunities.

- Including explicit and regulated consideration of current and future wetland condition and CDR during infrastructure and coastal resilience decisions. Lack of coordination will drive progressive wetland loss, methane emissions, and emission of existing carbon stocks.
- Protecting and restoring blue carbon habitats, such as salt marshes, mangroves, seagrass beds, and kelp forests, to increase $CO_2$ storage, protect coasts from flooding, storm and wave erosion, and habitat loss.
- Improving remote observations to quantify blue carbon changes and resilience to perturbations across scales.
- Improving wetland hydrology by modifying hardened coastal infrastructure.
- Development of maps and remote sensing products to indicate wetland management and hydrologic condition, as a primary predictor of CDR and methane emissions, and gauge greenhouse gas management potential.
- Adjustments to wetlands protection policies that prohibit wetland filling activities as they relate to beneficial sediment or other additions intended to raise wetland soil elevation relative to sea level and promote persistence of the ecosystem.

## 7. Synthesis

All the solutions discussed above have significant potential to contribute to large-scale CDR. At the same time, each of the solutions above faces significant barriers that must be overcome through testing and smaller scale demonstration to inform decision making on deployment, coupled with the buildout of supporting infrastructure needed for large scale in the long run. Some CDR approaches are more developed while others will require significant research to

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93 https://www.whitehouse.gov/wp-content/uploads/2024/11/U.S.-Marine-Carbon-Dioxide-Removal-Research-Strategy.pdf

94 https://www.epa.gov/ocean-dumping/marine-carbon-dioxide-removal-and-solar-radiation-management-permitting

understand their potential to contribute to large-scale CDR, including careful consideration of how adverse impacts to communities, the environment, and other land or ocean activities can be avoided or mitigated. Furthermore, significant uncertainties remain as to which of the solutions will be able to overcome the barriers they face most swiftly and begin scaling.

The strategy that DOE is pursuing on CDR is rooted in the significant potential, and uncertainties, facing all CDR solutions. An innovation portfolio is designed to support a diversity of technology to move as fast as practical to commercial scale. This approach enables learning about key challenges that can only be revealed through actual projects at the smallest, and thus most cost-effective, scale. This CDR strategy is designed to support effective carbon removal outcomes—not specific technologies—wherever practical, and to avoid locking in certain pathways or technology approaches within each pathway prematurely.

# III. Current DOE CDR Strategy and Related Activities Across the U.S. Federal Government

## Summary of DOE'S CDR Strategy

CDR is just one component of DOE's broader climate strategy. Most of DOE's climate action efforts are focused on reducing emissions via the adoption of energy efficiency, clean energy, electrification, other fuel switching, and point source carbon capture and storage. The Inflation Reduction Act and Bipartisan Infrastructure Law funding provide at most a single-digit percentage of their overall climate support for CDR. At DOE, CDR receives around $100 million in annual innovation funding out of a roughly $10 billion annual science and applied energy budget.

DOE's strategy for developing CDR solutions is grounded in the following principles:

- **Implementing CDR policy as a complement, not substitute to direct emissions reductions:** Support for CDR will be counterproductive if it comes at the expense of direct emissions reduction. However, CDR policy need not be zero-sum with direct emissions reductions, and in many cases can help accelerate the pace of emissions reductions. CDR policy can help subsidize infrastructure for broader biomass, carbon management, and nature-based climate activities. Coupled with significantly more support and mandates for direct emissions reductions across all sectors of the economy, CDR will not enable business-as-usual emissions indefinitely. Even if we manage the improbable task of directly eliminating all emissions by midcentury globally, CDR is the only option for accelerating the reduction in atmospheric $CO_2$ concentrations from past industrial activity that will be needed to rebalance carbon stocks towards pre-industrial levels.
- **Supporting solution diversity:** While many CDR pathways show promise, all face significant uncertainties as to their ultimate efficacy, risks, and scale potential. Furthermore, the potential for various CDR pathways varies significantly by region. As a result, it is important to support a portfolio of solutions today to ensure that we don't lock into suboptimal long-term pathways or fail to develop the CDR pathways that might hold promise in specific geographic regions.
- **Creating economic opportunity:** In addition to investing in the technological innovation that will scale CDR solutions, it is important to enable the economic viability of the market, including economies of scale and CDR business models that create strong jobs and investment opportunities across the United States.
- **Advancing high quality MMRV:** Any CDR industry of the future will require transparent, robust, and workable standards for MMRV that compare solutions in an apples-to-apples manner. Monitoring of environmental changes associated with CDR approaches is critical to responsible implementation of long-term, large-scale CDR operations.
- **Providing community benefits and protecting the environment:** CDR solutions must be developed in ways that provide meaningful benefits such as high-quality jobs to host communities, and they must only be deployed in places that want them. CDR solutions should also not have unacceptable adverse impacts to communities, the environment, biodiversity, or other land or ocean uses.

- **Informing innovation with robust analysis:** Given uncertainties facing solutions today, technology development must be coupled with robust and transparent evaluation of solutions and associated standards and regulatory frameworks to enable taxpayer, and private funding is stewarded to the highest impact efforts in the future.
- **Partnering with other governments and the private sector:** CDR must be a global enterprise to have a meaningful climate impact, making it imperative to work with other governments and private organizations to crowd in innovation funding and harmonize standards for projects to scale across borders in the future.

Given these principles, DOE is pursuing a strategy to achieve the following strategic goals by the end of the decade:

1. **Advance CDR solutions to commercial scale:** Develop and scale a portfolio of CDR technologies by investing in pioneering science and applied innovation. Ensure that the United States has scalable, economically viable, cost-effective, safe, and environmentally-sound options ready for the large-scale deployment of CDR within the coming decades.
2. **Build infrastructure for CDR:** Establish $CO_2$ transport and storage, biomass supply chains, measuring and monitoring carbon fluxes in terrestrial and ocean ecosystems, and innovation test beds.
3. **Develop MMRV and carbon accounting frameworks:** Create and implement robust, transparent, and operational frameworks for MMRV through research, technology development, and computer modelling. These efforts will help measure and monitor carbon fluxes associated with CDR projects across terrestrial and ocean ecosystems at both the project and jurisdictional level.
4. **Demonstrate models for community and workforce benefits:** Ensure communities have sufficient awareness of and support for solutions, as well as awareness of regulatory safeguards so that projects can be built at pace and scale. These efforts will create high-quality jobs and investment opportunities, including in those communities most affected by climate change and the transition to a net-zero economy.
5. **Collaborate with the private sector:** Partner with the private sector to attract private capital for CDR technology development and voluntary carbon credit markets investments.
6. **Mitigate environmental, health, and safety impacts:** Reduce the negative risks of large-scale CDR deployment through targeted research, robust implementation, and adherence to existing environmental regulations related to CDR projects.
7. **Support scalable regulations and incentives:** Ensure projects funded or contracted by DOE adhere to applicable regulations and implement incentives to give companies and communities confidence that their investments can lead to the expected climate and economic impacts. Ensure that negative societal and environmental impacts are minimized.
8. **Build international markets:** Strengthen international markets for CDR by aligning the nation's broader climate diplomacy efforts with global initiatives, encouraging other countries to fund CDR innovation and deployment. This will also help harmonize U.S. standards for MMRV, as well as carbon accounting.

This strategy was designed to mitigate against several risk factors:

- **Setting overly constraining near-term deployment targets:** Setting deployment targets too high too soon risks deployment of solutions before appropriate technology de-risking has occurred, or regulatory frameworks and standards are in place to protect against unintended community and environmental impacts. This could lead to an unnecessary backlash against CDR which would hinder its ability to attract political support in the future. Setting deployment targets too low would risk locking in only the solutions that are nearest commercial readiness, even if these solutions are suboptimal in the long run. Solution diversity also hedges against technical, economic, and/or social risks of any pathway failing to scale as expected.
- **Underdelivering on CDR project outcomes given MMRV uncertainties:** Given the experience of other carbon credit markets, having robust, workable, and transparent MMRV frameworks are critical for market acceptance and demand growth. Without such frameworks, potential CDR credit purchasers face the risk of paying for something that ultimately fails to deliver, jeopardizing their regulatory and marketing efforts around the credits.
- **Over emphasizing technology development and standards creation at the expense of social, economic, and environmental impact of solutions:** Failing to engage with communities in places where CDR holds the greatest promise is likely to lead to significant backlash against solutions which are seen as novel and complex to the public today. Without investing in communities today, project developers will likely face unnecessary headwinds when attempting to scale solutions in the future.
- **Scaling policy and regulation design and implementation too quickly:** By focusing on regulatory and demand side policy creation today, the Administration can develop the human capital and institutional structures to be able to scale regulatory and demand incentive implementation in the future.
- **Fiscal headwinds in the public sector:** Macroeconomic and political conditions could jeopardize near-term funding for CDR, making collaboration with the private sector and other governments for solution investment and demand generation an essential near-term priority.
- **International heterogeneity in markets:** Without harmonization of standards for MMRV and carbon accounting, CDR developers will face barriers when attempting to scale their solutions across national borders.

DOE's implementation of its CDR strategy consists of the following tactics:

1. **Research and technology innovation funding:** The United States is investing in a funnel of pioneering science and applied innovation across the portfolio of CDR solutions. In the remainder of the decade, the United States will need to fund thousands more research projects. Those projects will inform the funding of parallel investments in hundreds of small pilots at the 1kt/y scale. In turn, these small pilots will inform parallel investments in the dozens of larger demonstrations at the 10kt/y scale, and ultimately in a handful of commercial scale projects at the 100kt/y scale needed to adequately assess technoeconomic potential and access debt and equity markets. The United States is also leveraging its research apparatus to explore how any unintended environmental impacts of CDR project deployments at successively larger scales can be mitigated proactively.

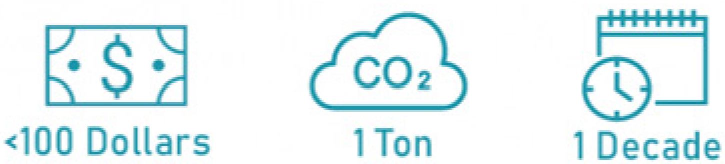
2. **MMRV and carbon accounting tool and framework development:** Supporting research, technology development, and computer modelling for measuring and monitoring carbon fluxes associated with CDR projects across terrestrial and ocean ecosystems, as well as developing and implementing frameworks for reporting CDR outcomes and accounting for them at a government and national level.
3. **CDR regulatory and incentives development:** Pioneering “demand pull” initiatives such as DOE’s CDR Purchase Pilot, implementing frameworks for safe and equitable infrastructure construction, administering tax incentives, and accounting for CDR in government and national emissions accounting.
4. **Community engagement**: Developing community benefits frameworks and communications materials to support project development across the nascent CDR industry.
5. **Public-private partnerships:** Working with industry to provide cost-share for grant funding and through initiatives like DOE’s Voluntary CDR Purchasing Challenge.
6. **International diplomacy:** Working with partner countries via the Carbon Management Challenge and the Mission Innovation CDR Launchpad to catalyze global effort on CDR development and to harmonize standards for MMRV and carbon accounting.

Federal programs, policies, and regulations in place today are supporting CDR approaches at different levels of technological maturity, spanning from basic research to technologies and practices currently in use. If properly funded and well-coordinated, these activities, spanning multiple agencies, can be essential components of larger efforts to achieve large scale CDR deployment.

## Cross-Cutting Activities

Several cross agency efforts are underway to support the development of CDR. For example, the U.S. Global Change Research Program (USGCRP) is supporting research on CDR through its carbon cycle science working group. Their 2022-2031 Strategic Plan lists priorities for carbon cycle research, including the feasibility, risks, and scalability of CDR strategies. To inform Federal decision-making, the program is preparing a report that will place Federal CDR research in context of individual agency capabilities, highlight synergies, and identify areas for potential collaboration. USGCRP agencies are already planning CDR research activities that span geologic, terrestrial, ocean/marine, coastal, and engineered systems. As a Federal program under the Office of Science and Technology Policy, USGCRP is well-positioned to coordinate with other interagency initiatives such as the U.S. Greenhouse Gas Center, the MCDR-FTAC, and the U.S. Greenhouse Gas Measurement, Monitoring, and Information System.

DOE is pursuing several activities that span multiple CDR pathways across the Federal Government. In particular, the Carbon Negative Shot is DOE’s framing principle to accelerate CDR to achieve the goal of net-zero emissions by 2050. It is an all-hands-on-deck call for innovation in CDR pathways that will capture $CO_2$ from the atmosphere and store it at gigatonne scales for less than $100/net metric tonne of $CO_2e$.




The Carbon Negative Shot requires the investment of funding and resources to enable the scale-up of multiple CDR approaches. It defines four criteria that describe goals for a portfolio of CDR pathways: 1) less than $100/net metric tonne $CO_2$e for both removal and storage; 2) robust accounting of full lifecycle emissions (i.e., ensures emissions created when running and building the removal technology are accounted for); 3) high-quality, durable storage with costs demonstrated for MMR for at least 100 years; and 4) enable necessary gigatonne scale removal.

The diverse suite of technologies and approaches in CDR requires integrated investment across the full research, development, demonstration, and deployment (RDD&D) spectrum such that breakthroughs are rapidly transferred and scaled, and so deployment of first-of-its-kind technologies quickly informs the next generation of innovation. These investments are described in DOE's recent budget requests[95]. CDR approaches include, but are not limited to, biomass with carbon removal and storage, direct air capture with durable storage, biological methods to stored products, enhanced mineralization, soil carbon storage, and marine CDR such as direct ocean capture with durable storage. Within these approaches, the mechanisms for $CO_2$ removal are variable, leading to challenges in how to quantify reductions via LCA and how to accurately define the economics and costs.

Appendix A has more information on these cross-cutting programs, on topics such as:

- **Carbon Negative Shot:** Under this initiative, DOE has announced $100 million in funding for small scale pilots across a range of CDR approaches, along with Energy Earthshot research centers.
- **CDR Purchasing Pilot Prize:** DOE is pioneering a $35 million program to purchase CDR credits and has $20 million in fiscal year 2024 funding from Congress to run a second round of the purchase effort. In parallel, DOE has launched a Voluntary CDR Purchasing Challenge to encourage private CDR credit purchases.
- **MMRV and carbon accounting:** DOE is supporting four projects at its national laboratories to advance MMRV technologies and develop standards across a wide range of CDR activities.
- **Infrastructure for $CO_2$ transport and storage:** DOE is funding a number of activities related to $CO_2$ transportation and storage, including the CarbonSAFE, CIFIA, and Regional Initiative programs, which are all relevant for transporting $CO_2$ from

95 The U.S. Department of Energy's Budget Requests to Congress, including the Carbon Dioxide Removal cross-cutting activity: https://www.energy.gov/budget-performance

atmospheric as well as point sources.

Going forward, DOE has developed a strategic framework for achieving the Carbon Negative Shot, that aligns with the goals put forward in this report. To establish a mix of CDR pathways that will comprise the gigatonne portfolio of CDR solutions, DOE, subject to available funding, will:

1. Strategically assess the evolution of CDR pathways and model post-2028 CDR deployment.
2. Carry out targeted research, development, and demonstration activities after identifying and prioritizing critical cost drivers.
3. Define and critically evaluate resources necessary for each CDR pathway—including infrastructure, energy, water, and materials—and will prepare for these changes and mitigate impacts for both short-term and post-2035 growth scenarios.
4. Support the development of robust carbon markets.
5. Strive for a short-term deployment target of 25-million-tonne capacity by 2030 for terrestrial technological solutions, while consistently refining the likely make-up of post-2035 deployment scenarios.

**Examples of Federal Agency Activities Related to Direct Air Capture (see Appendix B for more details)**

**DOE** – Funding research and development in early-stage direct air capture approaches, including fundamental science concepts, as well as late-stage technologies; conducting technoeconomic analyses of direct air capture options; developing LCAs for direct air capture; ARPA-E research on direct air capture technologies.

**EPA** – Protecting underground sources of drinking water through the Underground Injection Control program; collecting facility-level greenhouse gas data through the Greenhouse Gas Reporting Program.

**BLM** – Coordinating land use proposals and site coordination.

**USGS** – Assessing geologic reservoirs for carbon storage or for use in energy storage applications such as compressed air.

**NSF** – Supporting basic research to support direct air capture technology development.

**BSEE/BOEM** – Examining saline aquifers, physical traps, and off-shore depleted oil and gas fields as potential geologic storage sites.

*Direct Air Capture and Carbon Storage*

At the Federal level, the following illustrative policies and legislation currently support direct air capture:

- Section 45Q of the U.S. tax code provides a tax credit for $CO_2$ storage, including direct air carbon capture and storage, offering varying tax credits based on specific end uses of $CO_2$. Projects that geologically store $CO_2$ will receive \$180 per metric tonne while geologically store $CO_2$ used for other qualified uses of $CO_2$ will receive \$130 per metric ton.
- DOE has selected approximately \$1.2 billion of the \$3.5 billion of direct air capture bubs programs in the Bipartisan Infrastructure Law. In addition, DOE has issued over \$60 million in funding opportunity announcements (FOAs) for direct air capture under its base appropriations program, that will provide funding for preliminary front-end engineering and design

(pre-FEED) and front-end engineering and design (FEED) studies, as well as small pilots.

- The USE IT Act (part of the Consolidated Appropriations Act, 2021) authorizes EPA to develop a Direct Air Capture Technology Advisory board and a prize program.[96] Several other requirements for EPA and DOE exist in the USE IT Act, however, they were not appropriated at the time of this report.
- The National Defense Authorization Act for Fiscal Year 2020 authorizes DOE, in cooperation with the U.S. Department of Defense (DOD) and the U.S. Department of Homeland Security (DHS), to carry out a research and development program on direct air capture.[97]

At the state level, the California Low Carbon Fuel Standard (LCFS) is a market-based program that focuses specifically on reducing carbon intensity of fuels used within the state.[98] Although it was originally founded to promote the use of low-carbon fuel, the California LCFS was recently expanded to include direct air capture as an eligible methodology for credits, which have traded between $50-200/metric tonne over the past few years.

### *Enhanced Carbon Mineralization*

Currently, government policy encouraging enhanced carbon mineralization is sparse. Policies broadly supporting carbon capture and storage may apply to carbon mineralization in some instances. For example, Section 1703 of Title XVII of the Energy Policy Act of 2005 authorizes DOE to support innovative projects that are typically unable to obtain conventional financing due to perceived high technology risk and that avoid, reduce, or store greenhouse gas emissions. By this authority, DOE's Advanced Fossil Energy Projects Solicitation can support carbon

**Examples of Federal Agency Activities Related to Enhanced Carbon Mineralization (see Appendix A for more details)**

**USGS** – Developing resource assessments for mineralization potential with mafic and ultramafic rocks in the subsurface; studying reactions of $CO_2$ with alkaline industrial waste and mine waste.

**BLM** – Managing Federal land for mining (among other uses) of silicate rocks and rocks rich in Ca and Mg; Developing GHG task force.

**DOE** – Researching in-situ mineralization as part of geologic storage programs and basic science research; investigating surficial mineralization opportunities including surface mine tailing and alkaline industrial wastes.

**EPA** – Protecting underground sources of drinking water through the Underground Injection Control program.

**NOAA** – Maintaining and improving broad observing system for changes in global carbon system due to mineralization or other CDR activities; conducting predictive modeling of mineralization impacts to atmosphere and oceans.

**BOEM** – Conducting studies on long term effects of $CO_2$ storage; implementing statutory authority to manage offshore $CO_2$ storage.

**NSF** – Supporting basic research in accelerated carbon mineralization processes

96 Division S, Section 102 of Consolidated Appropriations Act, 2021. https://www.congress.gov/116/bills/hr133/BILLS-116hr133enr.pdf

97 Division A, Title II, Sec. 223 of National Defense Authorization Act for Fiscal Year 2020. https://www.congress.gov/116/bills/s1790/BILLS-116s1790enr.pdf

98 https://ww2.arb.ca.gov/our-work/programs/low-carbon-fuel-standard/about

mineralization projects through loan guarantees.

DOE's CarbonSAFE Initiative[99] has funded some projects related to *in-situ*, subsurface carbon mineralization in basalts, however many of the sites for injection of carbon into the subsurface are in sandstones and other unreactive rock, where the $CO_2$ is generally intended to remain in the formation near the injection borehole, unreacted. Injection wells used for long-term $CO_2$ storage deep underground, known as Class VI wells, are regulated by EPA as implemented by the Underground Injection Control program to protect underground sources of drinking water. As noted earlier, the Class VI permitting program is discussed in a separate report to Congress required under Division G of the Energy Act of 2020.

Enhanced carbon mineralization is subject to various international, Federal, and U.S. state laws and regulations, depending on the source of cations (e.g., crushed rock and waste), the size of the material (e.g., PM2.5 or PM10 or larger), and the site of application (e.g., agricultural land, other terrestrial environments, and ocean), as well as any secondary benefits of the application (e.g., the fertilization of crops).

### *Biomass Carbon Removal and Storage*

For the past several decades Federal policies and incentives have focused on production of ethanol and biodiesel fuels primarily from corn, soy, and more recently cellulosic feedstocks and algae. Examples include the Bioenergy Program for Advanced Biofuels and the Rural Energy for America Program (REAP) Grants, reauthorized in the 2018 Farm Bill.[100] Federal investment in carbon capture and storage has emphasized reducing the cost of carbon capture technologies, developing bioenergy with carbon capture and storage technologies and performing life cycle assessment, supported by grant programs such as DOE's research, development, and demonstration funding opportunities. DOE's Bioenergy Technologies Office (BETO) leads efforts for improving life cycle assessment of bioenergy with carbon

**Examples of Federal Agency Activities Related to BECCS (see Appendix A for more details)**

**DOE** – Managing fundamental and applied RD&D programs in bioenergy and carbon capture, use, and storage.

**EPA** – Implementing the renewable fuels standard program; collecting facility-level GHG data through the GHG Reporting Program; protecting underground sources of drinking water through the Underground Injection Control program.

**USDA-FS** – Inventorying carbon storage and flux across forested ecosystems; administer programs for bioenergy, bioproducts, and timber; development of biochar technologies; conducting forest planning and management.

**NSF** – Supporting basic research that support bioenergy and carbon capture.

**NOAA** – Implementing R&D and community programs for aquaculture development.

**BOEM/BSEE** – Assessing offshore storage capacity and well integrity; regulating the alternative use of an existing offshore continental shelf facility for energy- or marine-related purposes.

**USGS** – Conducting research and assessments on geological carbon storage and carbon cycling through the ecosystem, including land, water, minerals, and energy.

99 The Carbon Storage Assurance Facility Enterprise (CarbonSAFE) is an initiative within the CCUS and Power Systems program of the DOE Office of Fossil Energy and Carbon Management. https://netl.doe.gov/carbon-storage/carbonsafe

100 Title IX, Section 9005 and Section 9007 of the Agriculture Improvement Act of 2018. https://www.congress.gov/115/plaws/publ334/PLAW-115publ334.pdf

capture and storage and funds research on bioenergy with carbon capture and storage technologies, alongside FECM. While several Federal programs broadly support the technologies and approaches associated with bioenergy with carbon capture and storage (see sidebar), few policies are currently in place to encourage deployment specifically for bioenergy with carbon capture and storage.

Section 45Q of the U.S. tax code provides a tax credit for certain $CO_2$ storage projects, which can include carbon capture and storage applied to combustion of biomass. Biomass carbon capture and storage projects are eligible for the $85/tonne 45Q credit for dedicated storage, or the $60/tonne credit for storage with utilization.

DOE is funding research and development associated with biomass conversion for hydrogen and energy production, including co-firing biomass with coal as part of its point source carbon capture and storage applied energy program. Furthermore, biomass burial and other carbon negative conversion approaches are eligible under DOE's Carbon Negative Shot pilot funding opportunity announcement.

The Renewable Fuel Standard allows for the generation of credits for renewable fuels that meet certain requirements, including meeting greenhouse gas emission reduction thresholds.[101] In 2016, EPA proposed regulatory requirements that would allow for the inclusion of carbon capture and storage as an emission reduction technology when calculating the life cycle greenhouse gas emission of fuels.[102] However, that rulemaking has not yet been finalized and the program is not currently structured to reward the implementation of carbon capture and storage.

State policies such as the California Low Carbon Fuel Standards could also apply to bioenergy with carbon capture and storage projects.[103]

### *Forest Restoration*

Federal policies and measures supporting reforestation/afforestation focus on national forests, wildlife conservation, and land use, as well as providing assistance for lands managed by Tribal, state, and local governments. USDA and the DOI Bureau of Land Management implement most Federal reforestation/afforestation efforts on Federal land. Other agencies engaged in reforestation/afforestation include EPA, the U.S. Geological Survey (USGS), the Office of Surface Mining Reclamation and Enforcement (OSMRE). A sample of key legislation and other policies in place today include the following:

- The Knutson-Vandenberg Act of 1930 authorizes the USDA to establish forest tree nurseries and prepare planting on national forests. The Act requires the purchaser of national forest timber to make deposits of money to cover the cost of planting, sowing tree seeds, cutting, destroying, or otherwise removing undesirable trees or other growth, and protect-

101 Authorized under Title XV of the Energy Policy Act of 2005 (https://www.congress.gov/109/plaws/publ58/PLAW-109publ58.pdf) and expanded under Title II, Subtitle A of the Energy Independence and Security Act of 2007. https://www.congress.gov/110/plaws/publ140/PLAW-110publ140.pdf

102 Department of Agriculture (2021). *Climate-Smart Agriculture and Forestry Strategy: 90-Day Progress Report*. Washington, D.C., United States: U.S. Department of Agriculture. https://www.usda.gov/sites/default/files/documents/climate-smart-ag-forestry-strategy-90-day-progress-report.pdf.

103 https://ww2.arb.ca.gov/resources/documents/carbon-capture-and-sequestration-protocol-under-low-carbon-fuel-standard

ing and improving the forests' future productivity.[104]

- The Bankhead-Jones Farm Tenant Act of 1937 directs the USDA to develop a program of land conservation and land utilization assisting in controlling soil erosion, reforestation, and preserving natural resources.[105]
- The Anderson-Mansfield Reforestation and Revegetation Act of 1949 provides for the reforestation and revegetation lands under the administration or control of the USDA Forest Service.[106]
- The Granger-Thye Act of 1950 authorizes the USDA to cooperate or assist public and private agencies in performing work to be done for the protection, improvement, and reforestation of U.S. lands.[107]
- The Supplemental National Forest Reforestation Fund Act of 1972 directs the USDA to establish a Supplemental National Forest Reforestation Fund; Reforestation, Recreation Boating Safety and Facilities Improvement Act of 1980 establishes the Reforestation Trust Fund at the U.S. Treasury.[108]
- The National Forest Management Act of 1976 states that all forested lands in the National Forest System be maintained in appropriate forest cover with species of trees, degree of stocking, rate of growth, and conditions of stand designed to secure the maximum benefits of multiple use sustained yield management in accordance with land management plans.[109]

**Examples of Federal Agency Activities Related to Reforestation/ Afforestation (see Appendix A for more details)**

**USDA-FS** – Prepares estimates of forest and land use GHG emissions and sinks for the annual U.S. Greenhouse Gas Inventory; developing reforestation GIS mapping programs; assisting with local decision-making through regional climate hubs; researching improvements to silvicultural practices; partnering with Tribal, state, and private landowners for improved forest management.

**BLM** – Reforesting severely burned areas; managing and assessing forests for carbon storage and resilience.

**USGS** – Developing tools to monitor aboveground carbon and land cover changes.

**EPA** – Maintains the official annual greenhouse gas inventory that includes forest carbon emissions and sinks and land use emissions and sinks.

**OSMRE** – Encouraging the restoration of high-quality forests on reclaimed coal mined lands by planting native trees and using techniques that increase the survival rates and growth rates of planted trees while also expediting the establishment of forest habitat through natural succession.

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104 Section 2 and Section 3 of the Knutson-Vandenberg Act of 1930. https://www.agriculture.senate.gov/imo/media/doc/Act%20Of%20June%209,%201930-(Knutson-vandenberg%20Act).pdf

105 Title 3, Section 31 of the Bankhead-Jones Farm Tenant Act. https://www.fs.usda.gov/grasslands/documents/primer/App_G_Bankhead-Jones_Act.pdf

106 Section 2 of the Anderson-Mansfield Reforestation and Revegetation Act. United States Code 16 USC 581j

107 Section 20 of the Granger-Thye Act of 1950. https://www.fs.fed.us/specialuses/commsites/documents/Granger-Thye-Act-of-April%2024-1950.pdf

108 Section 1 of the Supplemental National Forest Reforestation Fund Act of 1972. https://www.congress.gov/92/statute/STATUTE-86/STATUTE-86-Pg678.pdf

109 Section 4 of the National Forest Management Act of 1976. https://www.fs.fed.us/emc/nfma/includes/NFMA1976.pdf

- The Healthy Forests Restoration Act of 2018 directs the USDA Forest Service to restore old-growth tree habitats damaged by wildfires and reduce fire risk on Federal lands.[110]
- The Farm Bill of 2018, Good Neighbor Authority authorizes the USDA Forest Service to collaborate with states, counties, and Tribes in forest restoration activities.[111]
- The Renewable Resources Extension Act of 1978 supports state cooperative extension services in education and technology transfer regarding the management and utilization of "renewable resources" including timber, rangeland, and urban environments.[112]
- The Appalachian Regional Reforestation Initiative (ARRI) is a cooperative effort between a branch of OSMRE; state agencies in Alabama, Kentucky, Maryland, Ohio, Pennsylvania, Tennessee, Virginia, and West Virginia; industry partners; environmental organizations; academia; and private landowners to encourage restoration of forests on reclaimed coal mined lands in the eastern United States.[113]
- Private Landowner Assistance Programs are a class of government assistance for landowners interested in maintaining, developing, improving, and protecting wildlife on their property, usually administered through provisions of the Farm Bill. Each state provides various programs that assist landowners in agriculture, forestry, and conserving wildlife habitat. Some states offer technical assistance which includes:
    - The Environmental Quality Improvement Program provides technical assistance and cost sharing to eligible landowners for forestry practices, such as site preparation and planting of hardwood and pine trees, fencing to keep livestock out of the forest, forest road stabilization, timber stand improvement, and invasive species control.[114]
    - The Wildlife Habitat Incentives Program is a landowner program for the improvement of upland wildlife habitat, including forests.[115] While WHIP is no longer available for new enrollment, existing contracts remain active. It enrolled nearly 11,000 landowners totaling 1,600,000 acres since 1998.
    - The Forest Land Enhancement Program provides financial and educational assistance to landowners to maintain the long-term sustainability of non-industrial private forest.[116]

In addition to Federal policies and incentives, some state programs use tax incentives to persuade private landowners to conserve their land. For example, Louisiana has a tax exemption program providing tax relief for landowner that commit to specific management plans.[117]

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[110] Authorized under Title I of the Healthy Forests Restoration Act of 2003 (https://www.congress.gov/108/plaws/publ148/PLAW-108publ148.pdf) and amended in 2018. https://www.congress.gov/115/bills/s1033/BILLS-115s1033is.pdf

[111] Title VIII, Section 8624 of the Agriculture Improvement Act of 2018. https://www.congress.gov/115/plaws/publ334/PLAW-115publ334.pdf

[112] https://nifa.usda.gov/sites/default/files/Renewable%20Resources%20Extension%20Act%20Of%201978.pdf

[113] https://www.osmre.gov/programs/arri

[114] https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/programs/financial/eqip/

[115] https://www.nrcs.usda.gov/wps/portal/nrcs/detail/null/?cid=nrcs141p2_024540

[116] https://www.Federalregister.gov/documents/2015/01/06/2014-30806/forest-land-enhancement-program-flep

[117] Title 56, Section 24, Louisiana State Law. http://www.legis.la.gov/legis/Law.aspx?d=105078

**Additional Forest Carbon Measurement Activities and Key Resources**

- EPA Inventory of U.S. greenhouse gas emissions and sinks: 1990–2019. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks
- USDA Forest Service, Forest Inventory and Analysis data https://www.fia.fs.fed.us/tools-data/index.php/
- US Global Change Research Program, USGCRP State of the Carbon Cycle Report – Carbon Cycle Observations and Measurement Programs - https://carbon2018.globalchange.gov/chapter/appendix-c/
- Global Forest Watch Open Data https://data.globalforestwatch.org/
- NASA EarthData and Oak Ridge National Laboratory dataset of global distribution, biomass, and other attributes of terrestrial ecosystems https://modis.ornl.gov/globalsubset/

*Soil Carbon Management*

Given the promising potential of soil carbon management for gigatonne-scale removal opportunities, it has long been recognized as a key pathway for the United States to meet its climate goals. As a result, this CDR area has benefited from development of numerous policy roadmaps (such as the Land Carbon Policy Roadmap Initiative, 2016) and USDA programs (primarily through the Natural Resources Conservation Service), partnerships, and authorities, as part of its Climate-Smart Agriculture and Forestry Strategy.[118, 119]

Due to the significant potential for carbon storage and numerous environmental and social co-benefits, several policy mechanisms exist to incentivize or otherwise promote and accelerate soil carbon management, such as the following:

- Voluntary conservation programs (e.g., USDA NRCS's EQIP, Regional Conservation Partnership Program, Conservation Stewardship Program, Soil Health Demonstration Trials, Climate Smart Partnerships Program) tax credits or other financial incentives to landowners and farmers provide financial and technical assistance to implement a range of practices that increase soil health and reduce soil erosion and sedimentation, including cover crops, conservation tillage, and certain agroforestry practices.
- Information sharing, workforce development, and education strategies that promote carbon soil management strategies, such as open-source databases (including publicly available sensors and tools for quantifying carbon intensity in agricultural and forestry landscapes); technical assistance programs for groups of farmers and land owners with carbon-draw-down landscape design and practices; regional testing centers; and public-private partner-

[118] McGlynn, E., Galik, C., Tepper, D., Myers, J. & DeMeester, J. (2016). *Building Carbon in America's Farms, Forests, and Grasslands: Foundations for a Policy Roadmap*. Washington, D.C., United States: Forest Trends Association. https://www.forest-trends.org/wp-content/uploads/imported/carbon-sinks-report-022416-final-pdf.pdf

[119] U.S. Department of Agriculture (2021). *Climate-Smart Agriculture and Forestry Strategy: 90-Day Progress Report*. Washington, D.C., United States: U.S. Department of Agriculture. https://www.usda.gov/sites/default/files/documents/climate-smart-ag-forestry-strategy-90-day-progress-report.pdf

ships that may enable cost sharing mechanisms outside of what the government is able to provide.

- Grants supporting applied research and demonstration projects associated with the various aspects of the carbon soil management chain, including measurement and monitoring systems, integrated modeling and analysis, techniques for soil carbon storage, fundamental and applied research on carbon-relevant soil properties, and externality pricing methodologies.
- State level initiatives to incentivize farming practices that store carbon in the soil, such as California's Healthy Soils Initiative.[120]
- Related but distinct from public policy are private sector actors and public-private partnerships that support particular strategies, such as carbon crediting programs (e.g., Nori, AgOutcomes and ReHarvest Partners' Soil and Water Outcome Fund, Ecosystem Services Market Consortium, IndigoAg, Agoro Carbon Alliance).

**Examples of Federal Agency Activities Related to Soil Carbon Management (see Appendix A for more details)**

**DOE**- Conducting basic research to understand carbon cycling, sequestration and storage in soils as part of the Carbon Negative Shot within the Office of Science Earthshot efforts.

**USDA** – Incentivizing soil carbon storage through agricultural and forestry conservation programs; monitoring carbon storage and fluxes in forest, rangeland, and agricultural soils.; researching carbon dioxide emissions and storage due to emerging biomass and biochar markets, fires, and best management practices.

**BLM** – Assessing and monitoring carbon in soil; administering leases and permits for grazing and other land use; implementing programs on native seeds and post-fire rehabilitation.

**EPA** – Inventorying greenhouse emissions including soil carbon measurement; assessing soil health.

**NSF** – Supporting basic research on carbon cycle, including carbon in soils.

U.S. Carbon Cycle Science Program/USGCRP – Coordinating terrestrial, oceanic, and atmospheric carbon cycle research, including societal dimensions across the Federal Government.

### *Marine Carbon Dioxide Removal*

Few Federal policies are currently in place that are specifically designed to increase the deployment of engineered marine CDR solutions, although there are a number that authorize monitoring and research which may help in accelerating marine CDR technology development. The publication of the White House's Ocean Climate Action Plan in 2023 calls for building and providing clarity for the applicable regulatory framework for marine CDR by 2030, with the goal of substantial ramp up of marine CDR deployment. To that end, the White House National Science and Technology Council convened a MCDR-FTAC, which released a Research Strategy to help inform decisions about potential marine CDR scaling by 2030.

There are currently a few funded programs focused specifically on marine CDR-related research. NOAA via the NOPP announced marine CDR research awards totaling $24 million in 2023 as a

120 For an overview of the largest state cover crop programs, see https://www.ers.usda.gov/publications/pub-details/?pubid=100550

first-of-its-kind research program specifically for marine CDR. In addition to leveraged interagency funds from DOE, the Office of Naval Research, and NSF, some funding for this program comes from the Inflation Reduction Act, as well as a philanthropic partner ClimateWorks Foundation. DOE has also awarded funding for small marine CDR pilots and ARPA-E has funded MMRV technology development for marine CDR.

There are no known state-level incentives for marine CDR. There are several Federal statutes, regulations, policies, research programs, and monitoring programs that are applicable to marine CDR systems, including, but not limited to, the following:

- The Federal Ocean Acidification Research and Monitoring (FOARAM) Act of 2009 requires that NOAA and NSF carry out monitoring and research on the impact and mitigation of ocean acidification.[121] The FOARAM Act is relevant since certain marine CDR technologies like ocean alkalinity enhancement has the potential to locally mitigate ocean acidification in the process of removing $CO_2$.
- The Integrated Coastal and Ocean Observing Act grants authorities for research and monitoring. It authorizes activities to promote basic and applied research for improvements in coastal and ocean observation technologies, as well as conserving health and restoring degraded coastal ecosystems.
- The Coastal Zone Management Act of 1972, amended in 1990, requires understanding and predicting long-term climate change. Under this Act, NOAA has authority to research climate change, which pertains to marine CDR.

**Examples of Federal Agency Activities Related to mCDR (see Appendix A for more details)**

**NOAA** – Developed a strategy document on CDR regarding specific agency roles in marine CDR and other approaches; quantifying carbon fluxes through earth system modeling; co-chairing the MCDR-FTAC; launched and currently overseeing the first U.S. research program specifically focused on marine CDR pathways research

**EPA** – Administers Federal permitting programs that regulate marine CDR projects under the Marine Protection, Research, and Sanctuaries Act and Clean Water Act Section 402. Administer national programs that protect human health and the environment.

**BSEE/BOEM** – Providing permitting authority for $CO_2$ storage in sub-seabed geologic formations on the Outer Continental Shelf (OCS); authority to reuse existing OCS facilities for marine-related purposes; examining repurposing of existing OCS facilities for CDR activities.

**USACE** – Overseeing authority over ocean infrastructure, including marine CDR through the Clean Water Act, in U.S. navigable waters.

**DOD Naval Research Laboratory** – Studying use of marine carbon for production of fuels and materials.

**DOE** – Partnering with NOAA, through a Memorandum of Agreement (MOA), to increase collaboration and leverage NOAA's leading oceanographic expertise to advance marine CDR research and development.

[121] Section 6 and Section 7 of the Federal Ocean Acidification Research and Monitoring Act of 2009. https://coast.noaa.gov/data/czm/media/CZMA_10_11_06.pdf

- Mandates under the Oceans Act of 2000 led to the development of the U.S. Ocean Action Plan of 2005, which requires Federal agencies to participate in building a Global Earth Observation Network that includes integrated oceans observations.[122, 123]
- The EPA and U.S. Army Corps of Engineers (USACE) administer permitting programs applicable to mCDR projects, under the Marine Protection, Research, and Sanctuaries Act, the Clean Water Act Section 402 (National Pollutant Discharge Elimination System), and Clean Water Act Section 404.[124] Projects that may obstruct navigability may require a permit from USACE under the Rivers and Harbors Act (RHA).[125, 126]
- The Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972 (London Convention) and the London Protocol are the principal global regimes for the protection of the marine environment from pollution caused by wastes and other matter dumped in the ocean. The London Convention and London Protocol parties are considering measures for assessment and control of marine geoengineering activities, including some mCDR approaches, especially where potential deleterious effects may be widespread, long lasting, and severe[127]. The United States is a Party to the London Convention and has signed but is not a Party to (i.e., has not ratified) the 1996 London Protocol. As a signatory, the United States has an obligation to refrain, in good faith, from acts that would defeat the object and purpose of the Protocol.

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[122] Section 4 of the Oceans Act of 2000. https://www.congress.gov/106/plaws/publ256/PLAW-106publ256.pdf

[123] https://cdn.ioos.noaa.gov/media/2017/12/US_ocean_action_plan.pdf

[124] EPA. Permitting for mCDR. https://www.epa.gov/ocean-dumping/permitting-mcdr-and-msrm; NPDES Permit Basics | US EPA; USACE. Regulatory Program and Permits. https://www.usace.army.mil/Missions/Civil-Works/Regulatory-Program-and-Permits/.

[125] USACE. Regulatory Program and Permits. https://www.usace.army.mil/Missions/Civil-Works/Regulatory-Program-and-Permits/

[126] https://www.whitehouse.gov/wp-content/uploads/2024/11/U.S.-Marine-Carbon-Dioxide-Removal-Research-Strategy.pdf

[127] https://www.imo.org/en/OurWork/Environment/Pages/geoengineering-Default.aspx

# IV. Options for Policies to Advance the Deployment of Carbon Dioxide Removal Projects

Below follows a series of options that were developed with input from the CDR Working Group participants, but do not necessarily reflect DOE or the Administration's current policy. These policy options reflect a mixture of actions that the Administration can take with existing authority from Congress, and those that will require additional Congressional action. They are intended to serve as a broad survey of options that can inform future policymaking.[128, 129]

**1. Establish a timeline and targets to guide the growth of the CDR industry in the US.**
The government can establish specific targets for how much CDR should be deployed every decade to meet climate targets and create a thriving new industry in the U.S. Federal guidance can also inform how implementation of CDR policy can avoid competition with investments in direct emission reductions and unintended negative environmental impacts. Establishing 25 million tons of capacity by 2030 is an evidence-based near-term goal, with 1 GT/yr by 2050 as a reasonable long-term goal.

Two key policy steps would help guide CDR development:

- Set minimum goals for CDR development through 2030 and 2050. These targets will help ensure that we have the minimum required to meet climate targets, and that we can scale further as needed. These targets would be most valuable if structured to ensure that policy can appropriately support the development of a diversity of CDR solutions as is needed.

**2. Reduce technology risk by expanding and accelerating investments in CDR research, development, and demonstrations.**
A significant increase in resources will be necessary to achieve the pace and scale of CDR research, development, and demonstration required to adequately demonstrate and deploy a broad portfolio of CDR solutions by 2030. Funding for CDR innovation has largely focused on early-stage efforts and predominantly for direct air capture. Expanding this funding to support a broader basket of CDR solutions and the full technical maturity range will be essential for enabling a robust portfolio of approaches to reach scale within the decade. Furthermore, additional research and development funding to understand environmental impacts can help proactively identify and mitigate any unintended environmental risks. Several outside groups

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[128] Further details on policy recommendations, including specific incentives for consideration, are provided in Chapter 3.

[129] Policies to incentivize supporting infrastructure development are outside of the scope of this report. Through the Infrastructure Investment and Jobs Act, DOE will deploy approximately $10 billion in new direct carbon management funding over five years, including $2.5 billion for carbon storage validation and testing and $2.1 billion for $CO_2$ transportation infrastructure finance and innovation, The Act also provides $25 million to EPA over five years to improve Federal permitting of Class VI underground injection control wells for geologic storage and $50 million in grants for states to establish and operate their own Class VI permitting programs. This report does not focus on geologic storage and utilization, which are discussed in detail in the Council on Environmental Quality 2021 Report to Congress on Carbon Capture, Utilization, and Sequestration. https://www.whitehouse.gov/ceq/news-updates/2021/06/30/council-on-environmental-quality-delivers-report-to-congress-on-steps-to-advance-responsible-orderly-and-efficient-development-of-carbon-capture-utilization-and-sequestration/

have estimated the scale of innovation funding required to meet Carbon Negative Shot goals. The National Academies 2018 report identified an approximate need for $10-25 billion in investment to achieve the goals over a 10-year period, and the Ocean-Based Carbon Dioxide Removal National Academies 2021 report suggests an additional $2 billion in funding, including funding for foundational research on the potential for environmental and social impacts and efficacy of marine CDR approaches. The Rocky Mountain Institute identified a similar need for funding in their 2023 The Applied Innovation Roadmap for CDR. The uncertainty in this investment need is based on the fact that it is unclear which technologies will fail to meet early technical milestones and not merit large-scale follow-on investment.

One of the biggest innovation barriers that CDR companies face today is securing funding for pilot and small commercial demonstration facilities, which can range from $5 million to $100 million. Such facilities can be too expensive to reasonably finance with venture capital but are too risky to fund with traditional project or corporate finance funding. Given uncertainties in the private CDR market, the Federal Government has a critical role in funding these projects, but available Federal funding is limited and insufficient to enable the rapid scaling of viable CDR technologies. In particular, funding for pilot and small commercial demonstration facilities ($5 million - $100 million) are critical, alongside the early innovation funding in existing legislation. Authorizations via existing legislation, including the $1 billion in funding in the bipartisan CHIPS Act, provide a foundation for future appropriations for Federal funding of CDR innovation.

CDR approaches fit within the purview of many existing government research programs (see: Appendix A. Summary of Federal Agency Activities Relevant to Carbon Dioxide Removal), creating opportunities to quickly and efficiently build out and scale up current activities by leveraging the authorities, networks, and infrastructure already in place. Integrating CDR with complementary Federal research and incentive programs (e.g., programs to improve air quality, wildfire management, land or water conservation, and co-generation) can lead to positive reinforcement and feedback and build a robust CDR portfolio.

It will also be helpful to include CDR innovation funding in the supply chains of agriculture, mining, and other industries where CDR can occur as a complement. Leveraging existing industries to fund CDR innovation will help defray initial investment levels.

Finally, dedicated CDR innovation test beds will enable rapid iteration of technologies. It will be important to create innovation test beds that can support the full range of CDR options, across the entire TRL spectrum. Furthermore, diversity of geographies for CDR innovation facilities will enable innovators to learn from a range of real-world weather and atmospheric conditions.

**3. Further enable deployment of market-ready CDR approaches.**

Additional incentives are critical for advancing the full portfolio of CDR solutions in a responsible way. Incentives can build on existing policies such as the 45Q tax credit (for carbon capture and storage, including direct air capture) to support a broader range of CDR pathways outcomes, and incentives can be tied to robust environmental safeguards and LCAs to ensure that projects deliver net-negative emissions. Existing regulations and authorities, such as EPA's Greenhouse Gas Reporting Programs and pay-for-practice land management approaches can be expanded to encompass the broader suite of CDR technologies and codify strong MMRV approaches. Providing clear information about permitting process for CDR approaches, especially for more novel approaches in areas such as marine CDR[130] can provide important assurance for project developers and the general public.

The realm of possible policies to support responsible CDR innovation and deployment is far broader than what exists today. For example, CDR can be included in any future regulations or taxes in a way that incentivizes direct emissions reductions while providing additional revenue to drive "learning by doing" for a portfolio of CDR options. Procurement of CDR credits and/or development of public CDR utilities (such as the Tennessee Valley Authority for power) offer additional pathways to support CDR innovation and deployment outside of emissions reductions regulatory frameworks. Federal lands also offer vast potential for CDR with the potential for leveraging the management of ecosystems and Federal pore space to scale CDR, presenting significant opportunities for market scale-up in the near-term.

Coupling CDR to trade policy such as carbon border adjustment mechanism can help defray investment costs in CDR credit purchases and stimulate private demand for CDR to avoid potential carbon intensity penalties. Finally, incorporating CDR in international compliance markets such as the Carbon Offsetting and Reduction Scheme for International Aviation and future Article 6 markets associated with the Paris Agreement could help provide demand for CDR projects. This suite of policies can pave the way for CDR to be incorporated into emissions trading systems that develop in the United States in the future at the state, regional, and/or Federal level.

There is also significant opportunity for CDR to be included outside of project-level crediting systems. For example, pay-for-practice incentives in the Farm Bill can encourage adoption of forestry, soil carbon, and enhanced weathering. Furthermore, piloting CDR on Federal lands can provide opportunities for demonstrating approaches at scale and for gathering the data needed to improve the cost and performance of different CDR solutions.

On the regulatory front, it is essential to define what practices count as CDR and what MMRV standards must be met to claim CDR outcomes. Additionally, coordinated and expedited review and permitting processes for CDR projects should address maintaining efficacy, protection of the environment, and consideration of unintended consequences. Additional regulatory policy options for advancing CDR development are to:

- Examine whether the scope of projects covered under FAST-41 should be expanded to include new carbon mineralization operations and other CDR approaches not already covered by the Act. Such projects would be eligible for streamlined environmental review and authorization processes involving a coordinated Federal response.
- Examine opportunities to place enhanced carbon mineralization, direct ocean capture (DOC), bioenergy with carbon capture and storage, and other CDR projects that fall under multiple jurisdictions under coordinated permitting processes on land and coastal waters among the various jurisdictions. For example, expanding bioenergy to new practices like aquaculture may require new regulations and engagement from relevant agencies.

[130] EPA (2023). Permitting for mCDR and mSRM. https://www.epa.gov/ocean-dumping/permitting-mcdr-and-msrm

- Continue to create guidance documents and best practice resources where needed as related to permitting processes, regulatory requirements, and environmental reviews to assist with developing projects efficiently and responsibly.
- Leverage lessons learned from existing regulatory frameworks such as EPA's Underground Injection Control Class VI requirements and Greenhouse Gas Reporting Program requirements for geologic storage of $CO_2$ to identify similarly robust approaches for all CDR methods. Clarify and improve the existing Federal Government regulatory framework to ensure that carbon capture, use, and storage is responsibly scaled in a timely manner that is aligned with climate goals and ensures protection of communities and the environment.[131] Existing onshore and offshore infrastructure could be evaluated for geologic storage coupled with various CDR approaches, including DACS, BECCS, enhanced carbon mineralization, and DOC.
- Investigate and consider developing arbitration models for forest management to reduce administrative appeals and litigation and to increase the pace and scale of sustainable, fair, and equitable forest management projects. Arbitration models could help settle disputes among companies, organizations, communities, governments, and other parties involved in forest management that prevent progress.
- Improve clarity on approaches to crediting blue carbon CDR on Federal, state, and private lands, and process for using Federal land for blue carbon CDR. Adjust wetlands protection policies that prohibit wetland-filling activities as they relate to beneficial sediment or other additions intended to raise wetland soil elevation relative to sea level and promote persistence of the ecosystem. Institute policies and methodologies that simultaneously encourage natural climate solutions without undermining reductions in fossil emissions.

**4. Build private sector demand and advance public-private partnerships.**

The United States has long demonstrated its capacity for leading innovation and galvanizing the private sector to accomplish monumental industry change. Crowding-in private capital will be essential for scaling CDR. New efforts to incentivize additional private purchasing of CDR credits, such as government-backed contract-for-difference frameworks, off-take guarantees, and/or tax rebates for CDR purchasing entities, can catalyze the thousands of companies with net-zero and Paris Agreement-aligned climate targets to start buying a small but growing amount of CDR today.

Voluntary corporate purchases of CDR credits are a major source of funding in the field today. Building that market aligned with the U.S. Government's Voluntary Carbon Markets Joint Policy Statement and Principles will strengthen U.S. climate achievement and position U.S. businesses to be global leaders in the net-zero world.[132] Actions by the government to ensure that credits are available through capacity building, reliable through MMRV and LCA development, and

[131] For more details, see: Council on Environmental Quality (2021). *Report to Congress on Carbon Capture, Utilization, and Sequestration*. Washington, D.C., United States: Executive Office of the President of the United States. https://www.whitehouse.gov/ceq/news-updates/2021/06/30/council-on-environmental-quality-delivers-report-to-congress-on-steps-to-advance-responsible-orderly-and-efficient-development-of-carbon-capture-utilization-and-sequestration/

[132] Voluntary Carbon Markets Joint Policy Statement and Principles. (2024). https://home.treasury.gov/system/files/136/VCM-Joint-Policy-Statement-and-Principles.pdf

internationally accepted will ensure that U.S. corporations can confidently use CDR to build a net-zero future.

- Corporate purchases of CDR credits are the major source of funding in the field today. Building that market will strengthen U.S. climate achievement and position U.S. businesses to be global leaders in the net-zero world. Actions by the government to ensure that credits are available through capacity building; reliable and consistent through MMRV and LCA development; and internationally accepted will ensure that U.S. corporations can confidently use CDR to build a net-zero future.
- Private sector capital and voluntary action is essential for scaling CDR in the future, and today crowding-in private capital will be essential for scaling CDR. Efforts to incentivize additional private purchasing of CDR credits, such as contract-for-difference frameworks, tax rebates for CDR purchasing entities, and project evaluation assistance from National Labs, can catalyze the thousands of companies with net-zero and Paris Agreement-aligned climate targets to start buying a small but growing amount of CDR today. Private partnerships can provide near-term capital that is flexible and nimble, filling gaps in public funding.
- There are several potential regulatory efforts that would help advance more public-private partnerships. For example, clear guidance for buyers, sellers, and intermediaries around CDR credits will help remove friction in that market. Furthermore, providing cross value-chain risk insurance for associated $CO_2$ transport and storage projects will enable greater investments in direct air capture and bioenergy with carbon capture projects. Efforts to make this transport and storage infrastructure open access would enable greater innovation.

**5. Build confidence by investing in standards for MMRV and life cycle assessment (LCA) of CDR projects.**

As of early 2024, over five million tons of CDR have been sold on the private market to companies wishing to encourage development of CDR technologies or to reach their own internal net-zero targets. This private market has highlighted the extraordinary importance of knowing exactly how the various methods work, and that the $CO_2$ has truly been removed so that removal claims can be robustly substantiated. Companies in this market, both buyers and sellers, are clamoring for robust measurement, reporting, and verification science and technology. As the compliance markets and other policy frameworks emerge to enable the 1 billion tonne/year-scale U.S. industry for CDR, the importance of good controls and evaluation methods is essential.

Expanded research, development, and demonstration can accelerate development of improved techniques, which must then be demonstrated, field tested and validated for accuracy. Federal agencies have unparalleled expertise, facilities, and capabilities required to inform independent and unbiased assessment of the real long-term benefits and risks of CDR approaches and projects. Reliable quantification and validation of the carbon that is removed are key enablers for widespread CDR deployment for both technological and nature-based approaches. The methods, best practices, and technologies required to effectively evaluate and verify CDR vary widely by approach and will require ongoing revisions as the portfolio of approaches advances and expands. Gathering the data needed to calibrate and validate models for quantifying open system

CDR practices—such as soils, oceans, and enhanced rock weathering approaches—is a key gap that is unlikely to be profitable from any given private sector actor. Development and deployment of systems to monitor changes in environmental conditions due to large-scale CDR deployment is also crucial to effective evaluation and management of CDR approaches.

LCA methodologies and guidelines must also be implemented in a clear way focused on cradle-to-grave, full greenhouse gas emission fluxes. LCA should be supported by comprehensive and consistent baselines and guidelines for how removal estimates can be based on atmospheric drawdown rather than on displacement of emissions relative to a nonstationary baseline. Standards should be developed to accommodate robust MMRV and LCA into project-level and national-inventory level greenhouse gas accounting.

Significant additional investment is needed to enable robust MMRV across CDR solutions in an apples-to-apples manner. This investment will involve:

- **Science**: to better understand the precise impacts of CDR projects on net carbon storage and ecosystems over time. The biggest scientific gaps remain around open system approaches such as marine CDR, enhanced $CO_2$ mineralization, and soil carbon storage.
- **Technology development**: for tools to measure net carbon storage directly and/or estimate it accurately based on software models.
- **Standards**: for the MMRV requirements, including details such as lifecycle carbon accounting boundaries, for making CDR claims at both the project (i.e., carbon credits in emission trading systems) and jurisdictional level (i.e., in national greenhouse gas inventories).

There is also an opportunity to launch cross-agency grand challenges related to MMRV.

| Topic | Potential Actions for Key Agencies |
|---|---|
| $CO_2$ mineralization | • DOI USGS mapping and characterization of mineral types; database of abandoned mines that could be suitable for enhanced carbon mineralization; methodology to assess $CO_2$ capture potential in U.S. rock formations; and coordination with state agency geologic offices.<br>• DOI Bureau of Ocean Energy Management (BOEM) mapping and characterization of offshore Outer Continental Shelf (OCS) in-situ mineralization and related leasing activities.<br>• DOI Bureau of Safety and Environmental Enforcement (BSEE) permitting offshore injection wells and related relevant operations, advising on seabed siting of mineralized $CO_2$ relative to existing critical seabed infrastructure, and enforcing avoidance of mineralized $CO_2$ during other authorized seabed activities.<br>• U.S. Department of Commerce National Institute of Standards and Technology (NIST) developing measurement techniques and coordination of standards for $CO_2$ mineralization.<br>• DOE national laboratories developing measurement technologies suitable for upscaling from the lab to the field, including fundamental research on the chemistry and materials involved in $CO_2$ capture and durable storage of $CO_2$, particularly processes occurring in subsurface geologic systems.<br>• NASA, the U.S. Department of Commerce, and NOAA refining methods for observation, monitoring, and verification of $CO_2$ in atmosphere and ocean.<br>• EPA developing methodologies for greenhouse gas measurement and reporting. |
| Marine CDR | The National Marine CDR Research Strategy developed by the mCDR FTAC outlines several potential actions for key agencies, including actions to advance responsible and interdisciplinary research and develop MMRV.[133]<br>• Scale up DOE funding via ARPA-E, FECM, and WPTO pilots, and National Laboratory funding.<br>• Increase NOAA funding to set monitoring protocols, in conjunction with DOE and NIST, and serve as a verifier for pilot studies.<br>• Leverage and increase NOAA, NASA, and NSF ocean science funding to develop a global ocean monitoring and modeling network, and to specifically fund foundational marine CDR research programs<br>• Develop and Coordinate standards for mCDR credits through NIST. |

133 https://www.whitehouse.gov/wp-content/uploads/2024/11/U.S.-Marine-Carbon-Dioxide-Removal-Research-Strategy.pdf

| Topic | Potential Actions for Key Agencies |
|---|---|
| Marine CDR | • Collaborate with U.S. Department of Defense research and monitoring facilities.<br>• Increase cross-agency coordination, led by NOAA and DOE, to establish marine CDR test beds, with the goal of accelerating research and minimizing financial burden<br>• Through NOAA and NIST, develop market-relevant marine CDR data reporting best practices and marine CDR-specific databases |
| Soil Carbon | • USDA funds pay-for-practice adoption of soil carbon storage practices with associated funding for longitudinal measurement of carbon cycles<br>• NSF coordinating with other agencies to launch moonshot on advanced agricultural plants and microbial engineering designed for optimal soil carbon storage<br>• Department of Interior supporting practice adoption and associated science on Federally owned lands<br>• NIST for developing and coordinating standards for soil carbon storage credits |

Additional relevant elements of policies recommended for consideration are to:

- Develop international guidance for reporting carbon removals as part of national greenhouse gas emissions inventories.
- Develop international guidance for which standards can be used for project-level CDR credits across solution types.
- Conduct research and development on technologies to measure CDR and permanence of storage; conduct scale up monitoring, observations, and information exchange; and provide funding opportunities to develop and demonstrate methods or technologies that reliably measure the amount of CDR.
- Model greenhouse gas fluxes in agricultural, forested, wetland, and oceanic ecosystems to reduce the costs of project implementation and monitoring; expand implementation of greenhouse gas flux monitoring and verification technologies and approaches.
- Advance and deploy environmental monitoring, ocean observing systems, and the remote energy systems that power monitoring and removal tools.
- Create methodologies, guidelines, standards, and protocols for measuring, monitoring, and verifying the efficacy, efficiency, and impact of CDR deployments. Coordinate across Government and partner with academia, companies, and standards development organizations to evaluate existing verification protocols and develop new measurement and verification protocols, as needed, for all CDR approaches. Provide targeted support for MMRV protocols regarding quantification of eligible carbon credits, particularly in agricultural and forest systems.

- Define a government-wide standard for evaluating the cost of CDR approaches based on net $CO_2e$ removed and have costs be inclusive of MMRV for ensuring storage for timescales significant for addressing climate change.
- Design CDR accounting methodologies that consider the full life cycle of a CDR system as well as all locations, inputs, outputs, and other variables. Where applicable, consider monitoring protocols that include a combination of *in-situ* and spaceborne satellite monitoring to detect $CO_2$ leakage. Work with standards development organizations to incorporate LCA results into accounting protocols to make it easier to compare approaches, standardize guidance, and understand net effects of options.
- Facilitate interagency knowledge sharing on LCA and measurement, monitoring, and verification through structured working groups and open data portals. For example, relevant agencies could consider publishing a repository for LCA methodology, results, and information related to CDR, building on existing collaboration through the Federal LCA Commons.[134]
- Encourage forest certification bodies (e.g., Sustainable Forestry Initiative, Programme for the Endorsement of Forest Certification, and the Forest Stewardship Council) to incorporate $CO_2$ storage from reforestation/afforestation into performance indicators.

**6. Develop and refine regional engagement guidance for Federally funded projects to ensure robust project development for CDR projects.**

The Biden Administration has committed to advancing CDR responsibly, as explained in the CEQ guidance on carbon management.

The engagement framework should refine how best to work with local communities and stakeholders early in the decision-making process, including involvement in the development of projects, and requesting and incorporating feedback throughout the project. Other improvements could include areas such as: developing and publicly disseminating accurate and timely information about CDR, including the effects, costs, and benefits; and identifying workforce development opportunities to help communities make the most of the economic co-benefits of CDR. Expanding incentives for CDR deployment to directly fund state/local governments and/or community organizations dedicated to supporting equitable and safe CDR project development would help improve public support for CDR.

The CDR Working Group also recommended considering the following relevant policies:

- Provide grants and technical assistance to evaluate benefits and concerns related to deploying a CDR approach with specific communities.
- Organize workshops and listening sessions that are independent of existing or future financial assistance opportunities.
- Provide cities, states, and Tribal nations with technical assistance for developing valuation taxation policies to benefit CDR.

[134] Council on Environmental Quality (2022). Notice of availability, request for comments on interim guidance document "Carbon Capture, Utilization, and Sequestration Guidance". Page 53. https://www.Federalregister.gov/documents/2022/02/16/2022-03205/carbon-capture-utilization-and-sequestration-guidance#p-53

- Create a website with clear information about Government programs, RD&D opportunities and results, technoeconomic information, and other technical and policy analysis.

**7. Engage the international community.**

International engagement is an important aspect of a comprehensive Federal CDR strategy. The scale of CDR needed to achieve global climate goals is beyond the reach of any single country. CDR can be implemented in almost every region of the world with consideration to resource suitability, and single projects may cross international boundaries.[135] The largest private purchase of CDR to date is international: Microsoft's purchase of 2.7 million tons of BiCRS removals from the Danish company Ørsted. Distributing CDR globally will enable CDR to scale in a more economically efficient manner in the long run. For example, the United States could guide capacity building and technology transfer engagement with low- and middle-income countries. International collaboration can rapidly accelerate technology advancement by distributing workloads for research, development, and demonstration among participating nations and sharing results. Supporting multilateral development finance for CDR projects will also be essential for ensuring that capital can flow to all regions with significant CDR potential, regardless of economic development status today.

International collaboration is also essential for facilitating the development and acceptance of international protocols and standards, such as greenhouse gas accounting and life cycle assessment. Without harmonized standards for CDR MMRV, LCA, and domestic and cross-border carbon accounting and disclosure, project developers will face unnecessary headwinds in scaling solutions across national borders. Doing so will open up new opportunities for trade policy to incorporate CDR in a robust way, both incentivizing its deployment overseas to reduce emissions intensity of export industries as well as to funding domestic CDR implementation from potential fees paid by higher emissions intensity imported products.

To accelerate adoption of a global market, CDR can be integrated into existing multilateral collaboration efforts such as the Carbon Management Challenge and the Mission Innovation CDR Launchpad. These efforts can be scaled to set global CDR innovation and deployment targets, and provide forums for harmonizing standards for CDR.

In addition to existing multilateral efforts, there are opportunities to build international coalition for CDR purchasing. Such "clubs" of CDR purchasers could harmonize financial commitments, standards for MMRV, and methods for raising revenue for CDR purchases based on carbon intensity-based tariffs. Such clubs could also help finance CDR projects in the global south via efforts like dedicated trust funds at the World Bank or similar multilateral financial institutions.

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[135] Specific CDR project options depend on the availability of resources. For example, reforestation storage potentials are greatest in tropical regions, soil carbon storage potentials are greatest in mid-latitudes, ultramafic rock formations are mainly located in the Middle East, Eastern Europe, and areas along the Pacific Ring of Fire, and CDR methods tied to geologic storage in sedimentary rocks are broadly distributed globally with the largest capacities in the Americas, Europe, and Australia-New Zealand (Pilorge et al, 2021).

Additional opportunities for international engagement include:

- Incorporating CDR into bilateral and multilateral research, development, and demonstration initiatives for exchanging technical information, expertise, best practices, and lessons learned through government and private-sector involvement.
- Supporting development of robust international policies and standards to enable verifiable, durable, and environmentally safe CDR projects (e.g., develop international protocols for LCAs and platforms for exchange).
- Providing capacity building and technology transfer support for developing and emerging economies (e.g., build stronger partnerships for socially responsible methods of CDR deployment).

# Appendix A. Summary of Federal Agency Activities Relevant to Carbon Dioxide Removal

## Department of Agriculture

Programs promoting soil carbon management and forest restoration practices are integrated across the USDA and include a wide range of initiatives that provide cost share and financial assistance for on-farm and forest conservation. In May 2021, USDA published a climate-smart agriculture and forestry (CSAF) strategy, a multi-pronged plan that includes enhancing nature-based carbon sinks such as farms and forests. These strategies include the quantification, tracking, and reporting of benefits of CSAF, development of CSAF strategies that work for all stakeholders (e.g., farmers, ranchers, foresters, communities), integration of CSAF into current USDA programs, increase in outreach and technical assistance for CSAF practices, development of a forest and wildfire resilience strategy, support for new and better markets for agricultural and forestry products that were generated through CSAF practices, and enhanced research on CSAF. The CSAF strategy integrates conservation actions that provide measurable carbon reductions and storage.

In 2022, the USDA launched the Partnerships for Climate-Smart Commodities initiative, which is comprised of more than $3.1 billion in investments for more than 141 projects intended to expand markets for climate-smart commodities generating greenhouse gas mitigation benefits from climate-smart production. Projects may provide technical and financial assistance to producers to implement CSAF practices on a voluntary basis on working lands. The implementation of these practices will lead to an estimated 60 million metric tons of $CO_2e$ stored over the lives of the projects.

Additionally, the Inflation Reduction Act authorized $19.5 billion in new funding over nine years for a variety of existing conservation programs supporting the implementation of CSAF practices. These programs include the Environmental Quality Incentives Program, which provides agricultural producers and forest landowners with financial resources and one-on-one assistance to plan and implement conservation practices; the Conservation Stewardship Program, which incentivizes enhanced environmental stewardship; the Agricultural Conservation Easement Program, which helps landowners, land trusts, and other entities protect, restore, and enhance wetlands, grasslands, and working farms and ranches through conservation easements; the Regional Conservation Partnership Program, which provides funding to producers and landowners to support conservation activities;[136] and Conservation Technical Assistance through NRCS. Additional USDA conservation programs supporting the CSAF strategy include the Conservation Reserve Program, which provides annual rental payments to farmers enrolled in the program who agree to remove environmentally sensitive land from agricultural production while planting species that improve environmental health and quality; the Conservation Innovation

[136] Natural Resources Conservation Service. https://www.nrcs.usda.gov/programs-initiatives/rcpp-regional-conservation-partnership-program

Grants, which spurs on-the-ground innovation and learning; and the Forest Legacy Program, which encourages the protection of privately owned forest lands through conservation easements or land purchases. Other forest conservation programs include the Community Forest Program, Forest Stewardship Program, Sustainable Forestry African American Land Retention Program, and Urban and Community Forestry Program.

Addressing the need to quantify, track, and report on greenhouse gas benefits, USDA is also investing $300 million to improve MMRV of greenhouse gas emissions and carbon sequestration across the agriculture and forestry sectors.[137] These investments will help advance priorities set by the broader Federal Strategy to Advance Greenhouse Gas Measurement and Monitoring for the Agriculture and Forestry Sectors, released in November 2023.

In 2024, USDA announced that it is establishing a new Greenhouse Gas Technical Assistance Provider and Third-Party Verifier Program. The program is authorized under the Growing Climate Solutions Act, part of the Consolidated Appropriations Act of 2023. The new program will facilitate better technical assistance by providing a list of qualified technical assistance providers and third-party verifiers who work with producers to generate credible carbon credits, enabling USDA to share trusted information and reduce market confusion. USDA will also list widely accepted voluntary carbon credit protocols designed to ensure consistency, reliability, effectiveness, efficiency, and transparency.

The USDA Forest Service (USDA-FS) manages 193 million acres of forest and grassland, including 96 million acres of actively managed timber lands. The agency's top priority is to maintain and improve the health, diversity, and productivity of the nation's forests and grasslands to meet the needs of current and future generations. Healthy, resilient, and productive forests provide carbon storage from decades to centuries and avoid large carbon loses due to insects and disease, wildfire, and other disturbances. The USDA-FS Research and Development Forest Inventory and Analysis (FIA) program conducts national statistical surveys of U.S. Forest lands of all ownerships, public and private, and from these data as well as remotely sensed information provides national reporting on soil and biomass carbon storage and flux, forest area extent, and other indicators of forest health. Many entities rely on the FIA data and information for carbon reporting. The USDA-FS Research and Development Forest Products Laboratory and USDA-FS State & Private Forestry find new ways to expand forest products markets and integrate mass timber, biofuels, and other agricultural products into the economy, making carbon storage more economically viable. In collaboration with the Northern Institute of Applied Climate Science and the nonprofit group American Forests, the USDA-FS developed a forest carbon management menu which offers natural resource managers options to increase carbon storage on their lands.

[137] Biden-Harris Administration Announces New Investments to Improve Measurement, Monitoring, Reporting and Verification of Greenhouse Gas Emissions through President Biden's Investing in America Agenda. (2023). Usda.gov. https://www.usda.gov/media/press-releases/2023/07/12/biden-harris-administration-announces-new-investmentsimprove#:~:text=WASHINGTON%2C%20July%2012%2C%202023%20%E2%80%93%20Agriculture%20Secretary%20Tom

The USDA Agricultural Research Service (ARS) is the USDA's research arm and runs 15 national research programs, several of which are dedicated to resources and sustainability. The ARS conducts multiple national research programs on climate change in partnership with universities, nonprofits, industry, and other stakeholders. The USDA-ARS utilizes a genetics, environment, and management (Genetics x Environment x Management x Social interactions) approach to understand and overcome constraints to productivity and improve agroecosystem resilience to climate change. Research topics include soil organic carbon storage, agroecosystem greenhouse gas emissions, climate-adaptive agriculture, sustainable intensification, and the development of improved germplasm, agronomic management, and conversion chemistry for renewable bio-based energy and low-carbon products. The USDA-ARS also maintains long-term research in cropland, rangeland, and integrated crop-livestock systems, providing valuable empirical and meta-data in a publicly available database for the research and development community.[138] Finally, the USDA-ARS in partnership with the USDA-FS lead the 10 regional USDA Climate Hubs which are designed to develop and deliver science-based, region-specific information and technologies that enable climate-informed decision-making and provide access to assistance to implement those decisions.

The National Institute of Food and Agriculture, the National Resources Conservation Service, the National Agricultural Statistics Service, and the Economic Research Service are also engaged in research into soil carbon management and reforestation, with the goal of making these approaches not only workable but economical. The USDA has also established 10 regional climate hubs, which coordinate research between different USDA agencies, partner with universities and industry, and provide outreach and education to farmers, ranchers, and landowners on science-based risk management and agricultural carbon storage practices.

A summary of USDA programs, initiatives, and announcements can be found here: https://www.usda.gov/climate-solutions

## Department of Commerce

The U.S. Department of Commerce includes the National Oceanic and Atmospheric Administration (NOAA) and the National Institute of Standards and Technology (NIST), each with central roles in research and measurement of carbon inventories and fluxes to inform earth system and climate science, assess ecosystem response and feedback, and manage and protect marine resources. Such research is executed across numerous laboratories and programs with missions relevant to CDR.

NOAA is the lead Federal agency for determining the changing concentrations, sources, sinks and fate of greenhouse gas emissions including $CO_2$ in the atmosphere, oceans, and terrestrial biosphere to better understand changes in weather, climate, and ocean and coastal ecosystems. As such, it has the primary responsibility for maintaining the internally accepted standards, global observing networks and earth system models to determine the long-term changes and fate

[138] ArcGIS Hub. (2018). Arcgis.com. https://agcros-usdaars.opendata.arcgis.com/

of the carbon system, including changes resulting from CDR. Through these calibrations, and sustaining and expanding observing and modeling systems, NOAA has the potential means to measure and evaluate the effectiveness of CDR methods considered here. NOAA has an active internal CDR Task Force, which collaborates on several current contributions that the agency makes to CDR efforts and examines potential future contributions.

NOAA has several Congressional mandates that allows it to carry out research relevant to marine CDR. Specifically, NOAA's Ocean Acidification Program (OAP) within OAR is mandated to study ocean acidification, which relates to marine CDR, and therefore is the program taking the lead on NOAA's marine CDR efforts. Currently, OAP manages a $24 million portfolio via a NOPP partnership that specifically focuses on marine CDR research. NOAA's leadership is recognized in the Federal space, as it was named as a lead Agency on approximately 75% of Ocean Climate Action Plan action items, including marine CDR-related work. Additionally, NOAA served as a co-chair on the White House NCST marine CDR Fast Track Action Committee.

NOAA's National Marine Fisheries Service (NMFS) and National Ocean Service (NOS) monitor and manage U.S. coastal ecosystems and fisheries under several statutes.[139] NMFS and NOS also oversee and supports the aquaculture industry, which has the potential to store carbon in marine plants. NMFS contributes to research and development of microalgae and macroalgae strains, and recently began designating Aquaculture Opportunity Areas for potential use in blue carbon. NOAA also funds work to restore coastal blue carbon habitats. Blue carbon and coastal wetlands research is supported by NOAA's National Ocean Service, OAR, and university-affiliated Sea Grant programs in order to integrate coastal wetlands in the annual Inventory of the U.S. Greenhouse Gas Emissions and Sinks and blue carbon in National Greenhouse Gas Inventories in the United States and in developing countries.

NOAA also has expertise in other topics relevant to CDR across multiple programs, such as marine policy and siting infrastructure in marine locations.

NIST is responsible for maintaining internationally accepted measurement standards, including those which pertain to carbon flux observations. NIST also provides calibrations and special tests to improve the accuracy of a wide range of instruments and techniques used in climate research and monitoring. Because of its prominence in the field of scientific measurement, NIST could play a central role in the development of CDR monitoring and verification methods.

## Department of Energy

DOE engages in a wide range of CDR technologies and approaches. Overall, the Department's strategy focuses on innovation funding and supports a funnel of breakthrough science, to small protype applied research, through pilots and demonstrations of technology to reach commercial

139 See, e.g., Endangered Species Act (ESA), NOAA Fisheries. Understanding Permits and Authorizations for Protected Species. https://www.fisheries.noaa.gov/insight/understanding-permits-and-authorizations-protected-species; Marine Mammal Protection Act (MMPA), ibid; Magnuson-Stevens Fishery Conservation and Management Act (MSA), NOAA Fisheries. Consultations for Essential Fish Habitats. https://www.fisheries.noaa.gov/national/habitat-conservation/consultations-essential-fish-habitat

scale. There are additional tools in the DOE toolkit that support CDR including:

- Financing support for early commercial facilities, primarily through the Loan Programs Office
- Analysis, including lifecycle assessment, technoeconomic modeling, and energy systems analysis.
- Support for measurement, reporting, and verification (including support for measurement tool innovation and development of protocols and standards for CDR).
- Demand-side innovation support tools, especially for CDR credit purchases

Furthermore, while DOE is does not have regulatory authority over CDR, the Department sees interagency collaboration with regulators as a key role for DOE. DOE provides technical assistance to support with robust environmental permitting as well as lifecycle carbon accounting associated with tax credits.

Specifically, DOE plays a leading role in advancing innovation around engineered solutions, such as direct air capture and storage. While DOE supports the full range of CDR solutions, DOE work on land- and ocean-based solutions is focused on advancing technology innovation through small pilots and MMRV tools and systems development, as well as through a Memorandum of Agreement with NOAA on advancing marine CDR research and development. DOE plays a supporting technology innovation role in marine CDR to NOAA, and to land-based CDR to USDA.

DOE's coordinated CDR RDD&D activities span its foundational science, applied energy, and infrastructure and demonstration program offices. These are funded through annual appropriations in addition to supplemental funding from the Bipartisan Infrastructure Law. The table below summarizes the range of DOE technology offices funding CDR through annual appropriations and their most recent funding level and budget requests.[140]

In addition to CDR technologies, DOE has also funded the development of supporting carbon management infrastructure necessary for large-scale CDR deployment. This includes carbon transport and storage systems, point source capture technologies FEED studies for direct air capture combined with storage and coupled with low-carbon energy, and other pilots, demonstrations, and loan guarantees to enable the creation of carbon hubs. DOE also funds the development of MMRV technologies for CDR.

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[140] From the Department of Energy's FY2025 Budget Request for Crosscutting Activities, https://www.energy.gov/sites/default/files/2024-03/doe-fy-2025-budget-vol-2-v3.pdf

**Table v2 FY2024* values are not yet updated to reflect the final appropriations.**

| Appropriation and Program Control | FY 2020 | FY 2021 | FY2022 | FY2023 | FY2024* | FY2025 |
|---|---|---|---|---|---|---|
| | Enacted | Enacted | Enacted | Enacted | Annualized CR | Request |
| **Advanced Research Projects Agency - Energy** | **3,895** | **1,944** | **45,500** | **0** | **0** | **0** |
| ARPA-E Projects | 3,895 | 1,944 | 45,500 | - | - | - |
| **Energy Efficiency and Renewable Energy** | **20,325** | **20,350** | **16,000** | **23,300** | **20,850** | **13,300** |
| Advanced Manufacturing Office | 10,000 | 10,000 | - | 9,300 | 9,300 | - |
| Bioenergy Technologies Office | 10,000 | 10,000 | 13,000 | 11,000 | 11,000 | 3,000 |
| Industrial Energy and Decarbonization Office | - | - | - | - | - | 9,300 |
| Water Power Technologies Office | 325 | 350 | 3000 | 3000 | 550 | 1,000 |
| **Fossil Energy and Carbon Management** | **20,000** | **40,000** | **49,000** | **74,500** | **74,500** | **130,200** |
| Carbon Dioxide Removal | 20,000 | 40,000 | 49,000 | 70,000 | 70,000 | 90,200 |
| Carbon Transport and Storage | - | - | - | 4,500 | 4,500 | 40,000 |
| **Science** | **27,500** | **35,500** | **46,700** | **70,628** | **87,512** | **94,035** |
| Advanced Scientific Computing Research | - | - | - | - | 20,000 | 30,000 |
| Basic Energy Sciences | 4,500 | 12,500 | 23,700 | 28,878 | 25,762 | 20,235 |
| Biological and Environmental Research | 23,000 | 23,000 | 23,000 | 41,750 | 41,750 | 43,800 |
| **Carbon Dioxide Removal Total** | **71,720** | **97,794** | **157,200** | **168,428** | **182,862** | **237,535** |

FECM has been working on carbon capture, utilization, and storage projects for over 20 years and has invested heavily in the development of technologies to capture $CO_2$ from power plants and industrial sources. More recently, FECM has been applying research, development, and demonstration technologies to various CDR approaches, including bioenergy with carbon capture and storage, enhanced mineralization through mineral carbonation, and DACS. FECM partners with the national laboratories, industry, academia, and other organizations to conduct research and development on a range of promising CDR technologies, demonstrate CDR and carbon storage at scale, and help bring technologies to a market-ready state. FECM funds mostly TRL 2-6 projects, focused on chemical and mineral-based CDR approaches under its Carbon Capture Program. FECM also funds FEED studies, analysis for CDR in energy systems models, MMRV development, and technoeconomic analyses of CDR approaches.

More recently, FECM announced a $35 million CDR Purchase Pilot Prize that will enable companies to compete for the opportunity to sell CDR credits directly to DOE, and a parallel Voluntary CDR Purchase Challenge. This will help build standards for successful CDR programs and create a market to encourage technology innovation and the growth of the industry.

The Bioenergy Technologies Office (BETO) within DOE's Office of Energy Efficiency and Renewable Energy (EERE) participates in RDD&D regarding the production, conversion, and use of bioenergy applicable to bioenergy with carbon capture and storage. BETO is working with FECM to investigate opportunities for generating energy from biomass waste coupled with carbon capture, use, and storage to achieve negative emissions in an economical manner. BETO is coordinating concerted bio-based fuels and power RDD&D to reduce costs and the energy penalty, and improve scalability, siting, and operations. Related efforts focus on conducting materials and components RDD&D, pilot-scale testing, front-end engineering and design studies, and large-scale extended tests.

DOE's Office of Clean Energy Demonstrations (OCED) is a multi-technology office with funding for demonstrations that include advanced nuclear, clean hydrogen, carbon management, long-duration energy storage, industrial decarbonization, and more. OCED contributes to the advancement of DOE's CDR goals through its oversight of the 3.5 billion Regional Direct Air Capture Hubs program, which it manages in partnership with FECM. The Direct Air Capture Hubs program will develop four regional direct air capture hubs, as directed by the Bipartisan Infrastructure Law. Each will demonstrate a direct air capture technology or suite of technologies at a commercial scale with the potential for capturing at least 1 million metric tons of $CO_2$ annually from the atmosphere. In August of 2023, OCED selected two pre-construction projects for award negotiation—the South Texas Direct Air Capture Hub and Project Cypress in Louisiana while FECM simultaneously announced the selection of 19 earlier-stage direct air capture Hub projects. Future funding opportunities will be designed to advance projects that can help deliver on the program's legislative goals.

EERE's Advanced Manufacturing Office (AMO) and its successor Industrial Energy Decarbonization Office has a long history of improving manufacturing systems, processes, and components to increase energy efficiency across the industrial sector. More recently, AMO expertise in industrial systems and manufacturing has been used for more efficient and cost-effective carbon capture technology. It is also helping design more productive capture systems through integration with industrial processes. AMO is responding to a separate Congressional request on developing an industrial decarbonization roadmap.

WPTO, also within EERE, supports a National Laboratory early-stage seed funding program where activities include co-locating marine energy and macroalgae aquaculture, marine energy-powered electrolytic limestone precipitation, $CO_2$ capture for de-acidification of aquaculture feedwaters, and wave-powered autonomous underwater vehicles for kelp forest restoration monitoring. WPTO is exploring marine energy (e.g., wave, tidal, current, salinity and pressure gradient, and ocean thermal energy conversion) research and development to support macroalgae aquaculture activities and is interested in advancing ocean observing systems to assess marine CDR and coastal restoration.

ARPA-E partners with third party organizations to develop and commercialize next-generation energy and climate change technologies. The Sensing Exports of Anthropogenic Carbon through Ocean Observation program seeks to accelerate the development of the marine CDR carbon capture industry through the advancement of scalable MMRV technologies. The Rhizosphere Observations Optimizing Terrestrial Sequestration program seeks to develop new technologies and crop cultivars that increase soil carbon accumulation by 50%, reduce N2O emissions by 50%, and increase water productivity by 25%. ARPA-E's SMARTFARM program supports this effort by funding research into new technologies and low-cost methods for monitoring agricultural CDR. Regarding enhanced carbon mineralization, DOE has funded experimental and modeling studies of $CO_2$ injection into mafic and ultramafic rocks. ARPA-E has funded projects to reduce the cost of direct air carbon capture and storage via approaches such as alternative solvent regeneration methods, advanced air contactors, and integration with point source carbon capture and storage systems. ARPA-E has also funded projects in the area of DOC.

DOE's Office of Science (SC) provides foundational knowledge and state-of-the-art capabilities in support of CDR research and has supported theoretical and experimental science related to understanding chemical and biological processes, separations, materials, and geochemistry related to carbon capture for many years. Further, SC operates major X-ray, neutron, nanoscience, genome sequencing, and high-performance computing user facilities that provide advanced synthesis, fabrication, characterization, and computational capabilities that supports CDR efforts across the spectrum of basic and applied research. SC's Office of Basic Energy Sciences (BES) has a wide range of fundamental and basic research programs that advance the scientific foundations to enable the development of new CDR technologies. BES research emphasizes the discovery, design, and understanding of new materials and new chemical, biochemical, and geological processes at atomic through macroscopic levels, as a basis for new approaches to harness energy resources and mitigate impacts of energy use. Projects span a range of fundamental materials and chemical science efforts aimed at discovering novel materials, chemistries, and processes for removal of $CO_2$ from the air and other dilute sources such as surface waters. Fundamental separation science, materials chemistry, and catalysis science research in BES core programs provides new insights into mechanisms underlying the capture, conversion and storage of $CO_2$. The BES core program in geosciences furthers the fundamental mechanistic understanding of processes important for mineralization and geologic storage of $CO_2$. In addition to the BES core programs, BES invests in CDR research through Energy Frontier Research Centers (EFRCs) and topical funding opportunities. For instance, the EFRC "Center for Interacting Geo-processes in Mineral Carbon Storage" focuses on a mechanistic understanding of mineral carbonation in the subsurface by studying the reaction, flow, and fracture processes; the fundamental knowledge from this effort can provide a foundation for the evaluation of the rate and amount of carbon that can be stored in a reservoir. SC's Office of Biological and Environmental Research (BER) uses insights obtained from sequenced genomes of plants, microorganisms, and microbiomes to understand natural processes of carbon capture, conversion to biomass, and deposition of carbon in soils. This research enables the development of new tools to manipulate these pathways and helps to identify key biogeochemical processes that govern the long-term stability of soil carbon. BER research also addresses key uncertainties in regional to global-scale Earth system change arising from the interactions and interdependencies of the atmospheric, terrestrial, cryospheric, oceanic, and human-energy components of the Earth system. DOE supports long-term field experiments to advance process and systems level understanding; scale-aware parameterizations that can be incorporated into multi-scale models; and advanced software tailored to models that can be ported to DOE's fastest supercomputers, stewarded by SC's Office of Advanced Scientific Computing Research. DOE also invests in novel machine learning and uncertainty quantification methodologies that allow model products to be more useful.

## Department of the Interior

Agencies within DOI that implement programs and measures relevant to CDR include USGS, the Bureau of Land Management (BLM), the U.S. Fish and Wildlife Service, the National Park Service, the Office of Surface Mining Reclamation and Enforcement (OSMRE), the Bureau of Safety and Environmental Enforcement, and the Bureau of Ocean Energy Management.

USGS applies earth science expertise to climate change and carbon storage research and plays a major role in the monitoring, verification, and modeling of carbon stocks and emissions. USGS oversees the National Land Imaging Program, which provides multi-decadal records of land cover, vegetation type, and vegetation condition. Using this data, USGS is able to track past and present trends in climate change, $CO_2$ emissions, and storage; build models of future climate change scenarios; and support conservation and carbon storage efforts in local communities nationwide. USGS uses National Land Imaging Program data to produce an annual estimate of greenhouse gas emissions from fossil fuel extraction and use on Federal lands. USGS also runs the Land Change Science and Climate research and development programs, which use National Land Imaging Program data to document past and current changes in climate and model future climate change scenarios.

The USGS LandCarbon program performs research on ecosystem carbon cycles, identifying methods to monitor and increase the amount of carbon stored in soils, coastal waters, and plants. USGS engages in several programs to monitor land use changes, droughts, fires, snow cover, and other phenomena that might impact biological carbon storage, and simulate how these phenomena might change in future climate scenarios.

USGS programs are engaged in robust and integrated coastal blue carbon field research, modeling, mapping, and remote sensing to support assessments, land management strategies, and policy at local, state, and national scales. Programs include Coastal & Marine Hazards and Resources within the Hazards Mission Area, National Land Imaging and Land Change Science within the Core Science Systems Mission Area, Climate Research and Development and Climate Adaptation Science Centers within the Ecosystems Mission Area, and the Water Mission Area.

The USGS Energy Resources Program conducts research and assessments of the geological carbon storage and mineralization resources of the United States and coordinates with other USGS programs to produce an annual estimate of greenhouse gas emissions from fossil fuel extraction and use on Federal lands.

The BLM is the largest Federal land manager with 245 million acres (12% of total U.S. land area) under its jurisdiction, including 50 million acres of forest land. BLM's Assessment, Inventory, and Monitoring Strategy collects environmental and resource data on BLM lands, including soil carbon data, to guide management decisions. BLM has formed a greenhouse gas task force to analyze and utilize information pertinent to the carbon cycle and climate change, but it does not yet have an explicit policy on CDR.

BLM manages its land to benefit both the economy and the environment. BLM issues leases and permits for a wide variety of climate-relevant activities on its land, including grazing, fossil fuel extraction, timber production, and mining. BLM also conducts a wide variety of programs to maintain the land under its jurisdiction, including native plant cultivation, restoration and damage assessment, and post-fire stabilization and rehabilitation. As part of these efforts, BLM plants approximately 2 million trees across 7,000 acres each year. BLM also manages its land for long-term resilience in order to reduce the risk of fire and prevent carbon stored in forests and soils from being released into the atmosphere.

OSMRE works with states and Tribes to ensure that citizens and the environment are protected during coal mining and that the land is restored to beneficial use when mining is finished. OSMRE and its partners are also responsible for reclaiming and restoring lands degraded by mining operations before 1977. OSMRE has been a leader within the Appalachian Regional Reforestation Initiative (ARRI), which is a cooperative effort between OSMRE, state agencies in eight Appalachian states, industry partners, environmental organizations, academia, and private landowners to encourage the restoration of forests on reclaimed coal mine lands in the eastern United States. ARRI advocates using a technique known as the Forestry Reclamation Approach (FRA). Before ARRI, mine land reclamation practices focused extensively on achieving stability through soil compaction. The recognition that these overly compacted soils did not promote good vegetation resulted in the development of the FRA. ARRI's goals are to communicate and encourage mine reforestation practices that 1) plant more high-value hardwood trees on reclaimed coal mined lands in Appalachia; 2) increase the survival rates and growth rates of planted trees; and 3) expedite the establishment of forest habitat through natural succession. ARRI and partners have planted more than 162 million trees on about 240,000 acres since ARRI's inception in 2004.

FWS manages over 560 units of the National Wildlife Refuge System (Refuges) across the United States, including its territories, for their habitat values and importance to wildlife. It is the only agency solely dedicated to the conservation of wildlife and their habitat. These units represent habitat types from mangrove forests to tundra. While management actions are guided by species needs, these habitats store carbon and provide significant societal and environmental co-benefits. Refuges is developing a new program working with the USGS to identify units where habitat restoration projects can maximize the biological storage of carbon. This will help prioritize restoration projects.

Pursuant to the Outer Continental Shelf Lands Act (OCSLA), BOEM and BSEE are responsible for managing the development of the Outer Continental Shelf (OCS) energy, mineral, and geological resources in a safe and environmentally and economically responsible way. The Infrastructure Investment and Jobs Act (i.e., Bipartisan Infrastructure Law) of 2021 amended OCSLA's leasing provisions to authorize DOI to grant leases, easements, and rights-of-way on the OCS for the purpose of sub-seabed sequestration of $CO_2$. BOEM and BSEE are currently developing regulations to implement this new authority. BSEE also has authority to approve plans for $CO_2$ enhanced oil recovery operations on existing oil and gas leases on the OCS. BOEM and BSEE may also authorize and regulate alternative uses of an existing OCS facility for energy- or marine-related purposes. BOEM is conducting an assessment on potential locations for storing $CO_2$ in saline aquifers, physical traps, and in depleted sub-seabed hydrocarbon reservoirs. BOEM will also be conducting studies on potential environmental impacts to the marine and coastal environment from carbon sequestration activities. BSEE would be responsible for permitting $CO_2$ injection wells and overseeing safe operations during sequestration of $CO_2$ in sub-seabed geologic structures on the OCS, among other responsibilities.

## Environmental Protection Agency

EPA is guided by a clear and vital mission: to protect human health and the environment. Although the Agency has made progress in advancing this mission over the last fifty years, much work remains to guarantee that all Americans share in the benefits of clean air, clean water, and safe communities and are protected from the urgent threats posed by climate change.

EPA evaluates the potential impacts of climate change on human health and the environment, as well as potential economic and environmental outcomes of different mitigation and adaptation activities, including CDR.

Among other things, EPA, in cooperation with other U.S. Government agencies, prepares the Inventory of U.S. Greenhouse Gas Emissions and Sinks. This annual report provides a comprehensive inventory of total greenhouse gas emissions for all man-made sources in the United States. The Inventory also includes estimates of CDR from the atmosphere by "sinks," e.g., through the uptake of carbon and storage in forests, vegetation, and soils. EPA's Greenhouse Gas Reporting Program (codified at 40 CFR Part 98) requires reporting of greenhouse gas data and other relevant information from large greenhouse gas emission sources, fuel and industrial gas suppliers, and $CO_2$ injection sites in the United States.

EPA implements the Renewable Fuel Standard (RFS) program, which requires certain volumes of renewable fuel to replace or reduce the quantity of petroleum-based transportation fuel, heating oil, or jet fuel sold or introduced into commerce in the United States. Under the RFS program, renewable fuel producers may generate credits for fuels that meet the requirements of the Clean Air Act, including reducing life cycle greenhouse gas emissions by specified amounts when compared to the 2005 petroleum baseline. In 2016, EPA proposed regulations for including carbon capture and storage as an emissions reduction technology for calculating the life cycle greenhouse gas emissions from renewable fuels; however, that rulemaking has not yet been finalized.

EPA's Underground Injection Control Program regulates the construction, operation, permitting, and closure of injection wells used to emplace fluids underground for storage or disposal, including wells used for geologic storage of $CO_2$. The definitions of an underground injection control well and well classes are codified at 40 CFR 144.6.

EPA administers a permitting program under the Marine Protection, Research, and Sanctuaries Act (MPRSA),[141] for the transportation and disposition of material in the ocean which is applicable to certain marine CDR activities. The MPRSA implements the United States' obligations under the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972. The London Convention was revised in 1996 by the London Protocol. The London Protocol was designed to clarify and strengthen the London Convention. The United States has signed but is not a Party to (i.e., has not ratified) the 1996 London Protocol. As a signatory, the United States has an obligation to refrain, in good faith, from acts that would defeat the object and purpose of the Protocol. The two treaties comprise the principal global regimes for the protection of the marine environment from pollution caused by wastes and other matter dumped in the ocean. London Convention and London Protocol Contracting Parties have adopted several resolutions regarding the assessment and regulation of ocean fertilization and have issued statements regarding the need for a science-based approach when evaluating marine CDR techniques for permitting. The London Protocol was amended in 2013 (not yet in force) to provide for a science-based, global, transparent, and effective control and regulatory mechanism applicable to deliberate interventions in the marine environment, especially where potential deleterious effects may be widespread, long lasting, and severe. Refer to EPA's webpages on permitting of marine CDR and the London Convention and London Protocol for additional information.

EPA and authorized states administer the National Pollutant Discharge Elimination System (NPDES) permitting program under the Clean Water Act Section 402. In general, discharges of pollutants from point sources (from land-based sources and outfalls from fixed structures at sea) into waters of the United States are regulated under the Clean Water Act and require a NPDES permit from EPA or an authorized state agency.

[141] Title I and II of the MPRSA (the Ocean Dumping Act) is codified at 33 U.S.C. §§ 1401–1445.

## National Aeronautics and Space Administration

The National Aeronautics and Space Administration (NASA) conducts global change research through its Earth Science Division, which uses airborne and satellite observations to conduct world-spanning investigations of earth systems and the carbon cycle. NASA is currently rolling out the Earth System Observatory (ESO), a constellation of multiple satellites that together will provide key information to understand the Earth system and the associated global changes and guide mitigation and resilience efforts, including forest fire detection, vegetation and aquatic health monitoring, disaster response, food security, and many other application areas. The ESO is an outcome of the 2017 Decadal Survey, which is led by the National Research Council of the National Academies of Sciences, Engineering, and Medicine (NASEM) and provides guidance to NASA on new observing priorities.

NASA's Program of Record includes several missions providing, among other things, information on CDR either directly or derived via modeling activities. The Plankton, Aerosol, Cloud, ocean Ecosystem mission (PACE) provides global-scale measurements of phytoplankton distribution, community composition, and rates of change through time. The Global Ecosystem Dynamics Instrument (GEDI) and ICESat-2 missions both use lasers to measure terrestrial and aquatic ecosystem structure—which can be related to biomass. The Orbiting Carbon Observatory (2 and 3) are providing information on atmospheric column concentrations of carbon dioxide as a basis for inferring carbon sources and sinks. The Carbon Monitoring System supports foundational science that helps address user needs including forest and blue carbon ecosystem management. The EMIT instrument, initially designed to map the prevalence of key minerals in dust-producing deserts, can also measure carbon dioxide and methane hotspots. NASA has also invested in large field campaigns to assess the state of carbon in terrestrial and marine ecosystems. These include quantifying forest biomass at local and regional scales and understanding how marine ecosystem structure influences the fate of carbon captured in the surface ocean to depths relevant for sequestration on climate-relevant timescales. NASA works closely with international partners through the Committee on Earth Observation Satellites (CEOS), the Group on Earth Observations (GEO) and the Coordination Group for Meteorological Satellites (CGMS).

## National Science Foundation

NSF funds basic research in a wide variety of areas, many of them relevant to CDR and the carbon cycle. NSF's investments will enhance understanding of the effectiveness of nature-based climate solutions, including terrestrial, freshwater, coastal, and ocean ecosystems that provide carbon sequestration and storage. One example is NSF's call for proposals on research to address the twenty-first century global challenge of climate change by seeking to increase understanding of CDR and Solar Radiation Modification science, governance, and consequences.[142] Further, NSF has received funding from other agencies such as DOE to fund research in areas such as direct air capture. In addition, NSF maintains the National Ecological Observatory Network which collects and integrates environmental data from 81 field sites across the United States and makes it available to researchers.

[142] $CO_2$ Removal and Solar Radiation Modification Strategies: Science, Governance and Consequences (nsf23151) | NSF - National Science Foundation. (2023). Nsf.gov. https://www.nsf.gov/pubs/2023/nsf23151/nsf23151.jsp

## U.S. Global Change Research Program

The U.S. Global Change Research Program (USGCRP) is a program mandated by Congress to coordinate Federal research, responses, and investments in the field of climate and integrated Earth systems change. USGCRP facilitates collaboration across 15 Federal agencies to maximize efficiencies in climate and global change research and provide the information the country needs to respond to climate and global change. The USGCRP submits a quadrennial National Climate Assessment to the President and Congress. The fifth National Climate Assessment was published in November 2023.[143]

The Carbon Cycle Interagency Working Group (CCIWG), coordinates and facilitates Federal carbon cycle research and provides leadership to the USGCRP on carbon cycle science priorities. This function was conducted in conjunction with and supported by the U.S. Carbon Cycle Science Program (USCCSP) under USGCRP auspices till September 31, 2022. CCIWG and USCCCSP have since operated independently. Established in 1998, the CCIWG represents Federal agencies that fund and conduct U.S. and international carbon cycle research across terrestrial, atmospheric, oceanic, and societal systems and interfaces. The USCCSP, in collaboration with the CCIWG and associated science communities, advanced, facilitated, and co-produced science-based information and resources to support and inform decisions, and to communicate findings broadly among and with national and international science communities and stakeholders, such as via the State of the Carbon Cycle Report (USGCRP 2007, 2018).

In 2021, CCIWG established the Interagency CDR Research Coordination (I-CDR-C) work stream through USCCSP to explore, advance, and inform interagency coordination strategies. I-CDR-C remains a fully Federal interagency workstream under CCIWG. Activities include the first Federal interagency CDR Data Call 2020–2021 which developed the first Federal CDR research compendium of activities across land, ocean, atmosphere, and societal dimensions. This includes observations and management activities pertinent to studying, informing, and evaluating CDR practices, technologies, and strategies. Prior joint CCIWG and USCCSP efforts on CDR include the following:

- Second State of the Carbon Cycle Report (USGCRP, 2018): Encompassing 19 chapters across four interconnected sections (I. Synthesis, II. Human Dimensions of the Carbon Cycle, III. State of Air, Land, and Water, IV. Consequences and Ways Forward), the North America-wide sustained climate assessment report includes CDR science advances and gaps across the 19 thematic chapters.
- Interagency Research Calls: Periodic joint solicitations by the CCIWG have supported over $100M in interdisciplinary research since 2004 to improve the understanding of changes in the distribution and cycling of carbon among land, ocean, and atmospheric reservoirs, and how that understanding can inform a scientific foundation for societal responses to global environmental change.

143 U.S. Global Change Research Program. (2023). Fifth National Climate Assessment. Nca2023.Globalchange.gov. https://nca2023.globalchange.gov/

## U.S. National Laboratories

Several National Labs have developed CDR capabilities. Those labs include:

| Lab | Description of core capabilities |
|---|---|
| **Argonne National Laboratory** | Development and scale up, driving forward CDR and carbon capture and conversion (CCC) in four key areas: (1) new materials and process development and scale up; (2) technoeconomic and life cycle analysis; (3) modeling and simulation; and (4) advanced characterization. Argonne is well-equipped to synthesize catalysts (e.g., nonprecious metals), sorbents (e.g., MOFs), and membrane materials (e.g., nonfluorinated anon exchange membranes and proton exchange membranes) and incorporate these into electrolysis system devices to evaluate their performance. With extensive capabilities in materials and processes scale-up research and development, Argonne's Materials and Engineering Research Facility (MERF) bridges the gap between bench and field-scale applications by integrating processes and optimizing operating conditions to minimize costs and environmental footprint of new technologies. Argonne's CDR research encompasses a wide array of approaches, including direct air capture, bio(geo)chemical processes and pathways, biomass carbon removal and storage, and enhanced mineralization (accelerated weathering for $CO_2$ sequestration from biogas). Argonne is a part of the Northwestern University-led Direct Air Capture Hub.<br><br>Argonne covers the entire $CO_2$ value chain by assessing cost effectiveness of capture and conversion from diverse point sources and direct air capture plants. Argonne's Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) model evaluates environmental sustainability of CDR and CCC technologies. Additionally, Argonne leads in quantifying regional impacts and offering economic analysis through JOBS tools.<br><br>Argonne has strong capabilities in various types of simulation and modeling powered by our leadership-class computing including atomistic modeling (first principles and molecular dynamics) as well as continuum and process modeling of materials and processes for thermochemical, electrochemical, and photochemical $CO_2$ reduction and conversion to predict and evaluate CDR and CCC technologies performance. Argonne's Advanced Photon Source (APS) offers many opportunities to study thermochemical or electrochemical catalyst properties using synchrotron X-rays. The APS has an extensive array of advanced characterization methods coupled with analytical instruments for in situ and operando measurement of materials' (e.g., catalysts and sorbents) activity, selectivity, and stability. |

| Lab | Description of core capabilities |
|---|---|
| **Lawrence Berkeley National Laboratory** | LBNL deploys a broad science-to-systems framework for accelerating decarbonization, with large portfolios across technology sectors such as clean energy systems, industrial decarbonization, carbon replacement, and carbon management. Regarding the latter, LBNL strategic research efforts encompass multiple advanced carbon management technologies, such as geologic carbon storage at scale, CDR via direct air capture and carbon mineralization, nature-based carbon removal, carbon conversion and utilization, and methane monitoring and mitigation. Our advanced modeling and monitoring capabilities are laying the scientific groundwork for large-scale and secure geologic $CO_2$ sequestration, with an emphasis on maximizing storage capacity and reducing associated risks. Initiatives such as the CIWE Energy Earthshot Research Center are advancing clean hydrogen and carbon sequestration technologies in alignment with DOE's Energy Earthshots Initiative. The Joint BioEnergy Institute is one of the four DOE Bioenergy Research Centers whose mission is to advance science, engineering, and technology to support the maximum possible conversion of carbon from lignocellulosic biomass to biofuels, bioproducts, and biomaterials through carbon negative biorefining.<br><br>Several innovative CDR approaches are under development at LBNL, focusing for example on the discovery of new adsorbent materials and elucidating the fundamental chemical and physical processes of $CO_2$ adsorption. In collaboration with UC Berkeley, LBNL conducts a feasibility study for developing CALDAC, a California-based Direct Air Capture hub. The newly established RESTOR-C Energy Earthshot Research Center is pioneering plant- and microbe-based strategies to enhance atmospheric carbon fixation and store it in soil for over a century, aiming to sequester gigatons of carbon in depleted U.S. agricultural lands. The Lab has several projects, such as the DOE $CO_2$ Reduction and Upgrading for e-Fuels Consortium, that are focused on the abiotic, biotic, and hybrid conversion of $CO_2$ into biofuels as well as long-lived (>100 years) bioproducts and biomaterials. These efforts are augmented by the exploration of chemical and biological approaches to carbon removal and fixation, focusing on sustainability in resource management. |

| Lab | Description of core capabilities |
|---|---|
| **Los Alamos National Laboratory** | Work on CDR techniques started at LANL in the 1980s and in 1990 the first research in the field of direct air capture was completed, paving the way to direct air capture as a technology to remove $CO_2$ from the atmosphere. New developments in capture materials based on techniques such as membrane separation, amine and other solvent and sorbent separation, and porous materials have continued till today. At present, LANL has expertise in direct air capture; biological capture methods, particularly algae and plants; underground storage such as by mineralization; surface storage, for example by soil carbon sequestration; carbon sequestration in oceans; and system performance analyses such as under specific meteorological conditions. The Laboratory has extensive expertise in economic assessment and storage assessment on local-, regional-, and national scales which are important for deployment of removal techniques. |
| **National Energy Technology Laboratory** | The National Energy Technology Laboratory (NETL)—the only government-owned, government-operated laboratory in DOE's National Laboratory complex—has three research campuses located in Albany, OR, Morgantown, WV and Pittsburgh, PA. As FECM's National Laboratory and the only lab within the DOE complex dedicated to carbon management research, NETL has been integral to DOE's CDR research, development, and demonstration endeavors. By leveraging competencies in geological and environmental Systems, materials engineering and manufacturing, energy conversion engineering, systems analysis and Engineering, and computational science and engineering, NETL has several notable and critical contributions in the current state of CDR technologies—NETL is well-positioned for continued impact. Highlighted contributions include:<br>1. **NETL Launches Direct Air Capture Center to Accelerate Commercialization and Deployment.** NETL began operation of the first direct air capture test system, one of a broad suite of testing capabilities within the Center which will provide a national resource to accelerate the deployment of direct air capture technologies through collaboration with industry, academia, and entrepreneurs. Current efforts within the Center include benchmark establishment with the National Institute of Standards and Technology, joint industry testing, and academic partnerships. Five agreements have been signed with industry for testing thus far.<br>2. **NETL Conducts Preliminary Screening Technoeconomic and Lifecycle Analyses for Enhanced Rock Weathering and Marine CDR**. The enhanced rock weathering study included cases based on igneous rock and industrial waste starting materials and indicated relatively low potential removal costs approaching \$100/tonne are possible. The marine CDR study for electrochemical approaches, which is more preliminary, pointed to much higher costs of removal. These studies are a crucial step in establishing intermediate objectives approaching the Carbon Negative Shot goal of \$100/tonne carbon removal. |

| Lab | Description of core capabilities |
|---|---|
| **National Energy Technology Laboratory** (continued) | 3. **NETL Direct Air Capture Case Studies Updated on the Way to the Creation of Baseline Studies.** NETL is improving its direct air capture solvent and sorbent case studies, which were published in 2022. Improvements include expansion of the studies to a third case, mineralization looping, and various refinements addressing issues like water co-adsorption and reflecting advancements in technology and practice in the two years since the original studies were released.<br>4. **NETL Leverages Award-winning Material and Process Development to Increase Industry Collaboration and Broaden Impact.** Long-term investment in material and process development for point source and direct air capture by FECM has produced a suite of capture technologies, like the R&D100 award winning basic immobilized amine sorbent, at a variety of technology readiness levels. To facilitate commercialization of these technologies, build the NETL brand in the area of CDR, ensure technology-market fit, and strengthen relationships with industrial partners to improve exchange of information, NETL has begun to incorporate corporate partners at all stages of research and development.<br>5. **NETL Probes Feasibility of CDR Technologies.** To inform FECM investments and optimize the impact of research and development dollars, NETL is performing technoeconomic and lifecycle assessments of classes of technologies of interest to the CDR program. The goal is to understand the potential cost impact and fundamental limitations of these classes of technologies. Currently planned studies include microwave regeneration of direct air capture materials and passive air contactors.<br>6. **NETL Builds Broad Collaboration to Elucidate Potential Emissions Issues with Direct Air Capture.** Many direct air capture technologies make use of amine-based materials, which can decompose and escape into the environment. With support from FECM and OTT, NETL has built a multi-laboratory collaboration to examine amine degradation under direct air capture conditions for a variety of materials. The effort will begin by creating better mechanistic understanding of degradation pathways and will lead to the development and validation of accelerated aging protocols, designed to shorten the needed time to evaluate new materials and processes. |

| Lab | Description of core capabilities |
|---|---|
| **National Renewable Energy Laboratory** | For CDR, NREL's scope couples experimentation, multi-scale modeling, and analysis to develop next-generation CDR technologies, establish frameworks and best practices for robust MMRV of CDR, and evaluate technology trade-offs at the systems level to inform decision making. We work closely with industrial partners and communities to enable a path to market, whether that be for development of technologies for ex-situ mineralization of mine tailings or for establishing MMRV best practices for BiCRS approaches. NREL is working on robust and coherent representations of CDR technology attributes across energy systems and integrated assessment models, facilitating comparable and comprehensive CDR evaluations (for regional and national level decision making). Linking sub-regional climate data projections to low carbon energy supply models, NREL works on prospective techno-economic and life cycle assessments to evaluate potential CDR siting and deployment trade-offs with regional level detail. Finally, given the rapid rate of change in the carbon management industry, our team is passionate about supporting workforce development. In partnership with FECM, we host Mickey Leland Energy Fellows, coordinate collegiate prize competitions, participate in Energy I-Corps, lecture to university groups and K-12 teachers, and help host the Research Experience in Carbon Sequestration. |
| **Oak Ridge National Laboratory** | The science and technology of chemical separations, which are foundational to many carbon management and CDR technologies, have been a key competency of ORNL since its establishment in 1943 as part of the Manhattan project.<br><br>Today, ORNL leverages SC investments in its base programs in biological and environmental sciences (synthetic biology and natural systems), and in basic energy sciences (catalysis and chemical transformations, novel separations, chemically selective capture and electromagnetic release of $CO_2$, integrated direct air capture and hydrogen-free conversion, interfacial and photochemical control of $CO_2$ binding, transport and release in direct air capture), as well as its user facilities, to enable translational research in energy technologies, including carbon management and CDR. User programs at the Center for Nanophase Materials Sciences and the Spallation Neutron Source, provide members of the carbon management community inside and outside the DOE complex, with access to sophisticated instruments and expertise not available elsewhere. |

| Lab | Description of core capabilities |
|---|---|
| **Oak Ridge National Laboratory** (continued) | In 2022, ORNL initiated a Transformational Decarbonization Initiative as part of its Laboratory Directed Research & Development Program with research priorities in scalable, cost-efficient technologies for CDR and point source $CO_2$ capture, soil carbon storage, integrated and earth systems modeling of CDR and geo-engineering, and decision sciences to focus on research and development needs and priorities with process- and systems-level analyses. Successfully completed projects from this initiative to convert carbon emissions into value-added products are currently being funded by FECM to continue advancing the development of these technologies.<br><br>Other projects currently funded by DOE's FECM program at ORNL include the development of technologies for using building heating, ventilation and air conditioning equipment for direct air capture, decarbonization analysis of mobile sources, demonstration of additively-manufactured multi-functional carbon capture devices, the use of aqueous amino acids for direct air capture, synthesis of carbon-neutral methanol from direct air capture and carbon-free hydrogen, and porous catalytic polymers for $CO_2$ capture and conversion to value-added chemicals.<br><br>Through its Innovations Crossroads program, which is a lab-embedded entrepreneurship program, ORNL hosted SkyNano, a company that recently opened a production facility in Knoxville to manufacture carbon products via electrochemical conversion of $CO_2$, and Holocene Climate Corporation, which is currently licensing ORNL's developed guanidine-based solvents for $CO_2$, which won a R&D 100 award in 2021.<br><br>ORNL collaborates with its core universities and other organizations on decarbonization pathways in the southeast and Appalachian regions. |
| **Pacific Northwest National Laboratory** | PNNL has stewarded FECM Carbon Management mission for over 25 years, leveraging core laboratory capabilities to accelerate development and deployment of safe, secure $CO_2$ capture and geologic storage technologies. From its inception during the post-war Hanford site cleanup, PNNL has cultivated an innovation-focused subsurface science capability that remains a natural fit for the subsurface chemistry, fate and transport, and sensing challenges facing the geologic $CO_2$ storage industry. We have worked to build coalitions and communities through leadership roles on multi-lab programs (NRAP, SMART, SUBTER), regional development initiatives (Big Sky, MRCSP, CUSP), field programs (Wallula, FutureGen 1, FutureGen 2, Mountaineer, ADM), and phased development programs like CarbonSAFE. We continue to prioritize LDRD investments targeting innovations in mineralization storage, subsurface sensing, and data inversion, proofs-of-concept to derisk FECM investments in these essential areas. |

| Lab | Description of core capabilities |
|---|---|
| **Pacific Northwest National Laboratory** (continued) | PNNL discoveries have given DOE the lowest-cost post-combustion capture solvent (EEMPA) and opened an entirely new field of study with reactive capture and conversion of $CO_2$—single-pot chemistry approaches that use catalysts to convert $CO_2$ to useful products like methanol while simultaneously regenerating the solvent for re-use. And, through our focus on industry-partnered R&D, we work to ensure that we are doing science that is relevant to the processes, markets, and regulatory environments into which they must be deployed as part of the portfolio of carbon management technologies needed to meet atmospheric $CO_2$ targets.<br><br>Leveraging capabilities stewarded at PNNL as DOE's flagship chemistry laboratory, our CDR portfolio focuses on materials development, characterization and engineering, and scale-up. PNNL technologies include sorbent-based materials (SAMMS) developed, optimized, and engineered for deployment in submarine breathing air applications currently in use by the U.S. Navy. Through partnerships with private U.S. companies, PNNL's sorbent platform is being adapted for use in other applications like building air handling systems, with researchers supporting industry development via process flow modeling, CFD, contactor design and sorbent tuning. We've recently demonstrated the world's first successful pairing of the sorbent platform with PNNL's Integrated $CO_2$ Capture and Conversion (IC3) framework, directly converting carbon from the atmosphere into olefins, important feedstocks for long-lived carbon products. In collaboration with industry at our Sequim campus—a marine research facility unique across the DOE complex—we are working to develop, optimize, demonstrate, scale, and deploy marine CDR solutions like Ebb Carbon's ocean alkalinity enhancement technology. |
| **Sandia National Laboratory** | Leveraging investments across all its mission areas, SNL's Fossil Energy and Carbon Management Program addresses the DOE's strategic vision to mitigate the environmental impacts of fossil fuel extraction and use, facilitating the transition to a low carbon energy future while maintaining energy security for the nation. In this domain, SNL emphasize carbon removal, capture, and sequestration, as well as monitoring above and below the surface to ensure reduced emissions and to minimize the carbon load in the atmosphere.<br><br>Sandia has several current, externally funded projects examining the safe storage and transport of $CO_2$, as well as internally funded projects investigating new methods of CDR including direct air capture, membrane-based carbon removal and reactive capture and conversion. Sandia's solutions draw on world-leading capabilities in geomechanical testing from nano- to macroscales, subsurface access and sensing, microsystems, electromagnetic-seismic- |

| Lab | Description of core capabilities |
|---|---|
| **Sandia National Laboratory** (continued) | infrasound sensing and interpretation, robotics and downhole tools, chemical separation and material science, data structures, exascale computing, and risk-based decision making. Sandia has active research in biological solutions for carbon capture, conversion, and upgrading including the optimization of algal cultures for biomass production, engineering of non-canonical chassis organisms to upgrade carbon-based intermediates to useful products, and development of coupled chemical-biological processes for the conversion and upgrading of biomass. Sandia is also leveraging its chemistry and materials science expertise to investigate capture and storage in cement-based materials. |
| **SLAC National Accelerator Laboratory** | SLAC's approach to carbon management and CDR research is built on translational research in fundamental physics, chemistry, biology, materials science, and geoscience to develop technological solutions for real-world applications that are cognizant of scalability, economics, energy efficiency, and supply chain. SLAC's approach includes strong engagement between the research community and industrial partners. Our sustainable chemistry research includes the development of catalysts and chemical processes to utilize new feedstocks (including $CO_2$, waste plastic, and biomass) in order to realize net-zero production of fuels and chemicals. SLAC's world leading characterization facilities (LCLS X-ray free-electron laser, SSRL synchrotron, Cryo-EM cryogenic electron microscopy, MeV-UED ultrafast electron diffraction) are utilized to understand the fundamental mechanisms governing activity, selectivity, and degradation for the rational design of catalysts and processes to drive translational outcomes. We harness these same characterization facilities to understand biological $CO_2$ capture by complex organisms with an aim to translate nature's chemical control and use of $CO_2$ into economical bioreactors and for the design of biomimetic and biohybrid catalysts that outperform their chemical counterparts. SLAC has additional research in improved batteries for transportation and the electric grid, modernizing the power grid, the prevention of wildfires caused by high-voltage transmission lines, water desalination, energy efficient computing, and 3D printing to manufacture materials with less waste. SLAC is also seeing increased interest in carbon management and CDR from its user community of scientists for LCLS, SSRL, and Cryo-EM. SLAC is involved in consortia such as Bio-optimized Technologies to Keep Thermoplastics out of Landfills and the Environment, the Liquid Sunlight Alliance, and National Alliance for Water Innovation.<br><br>SLAC and SRI International recently led a project for FECM on CDR innovation and produced a 75-page report that identified 15 emerging technologies having the potential to significantly impact the trajectory of CDR within the next decade. |

| Lab | Description of core capabilities |
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| **SLAC National Accelerator Laboratory** (continued) | SLAC has additional CDR programs in nature-based and enhanced bioscience solutions, chemistry, materials, and geoscience. SLAC also has research in adjacent fields like technoeconomic analysis, scaling, energy systems, and circular economy. Stanford University has additional programs including the Stanford Sustainability Accelerator, which just funded 16 projects on removal of atmospheric $CO_2$ and other greenhouse gases. |

# Appendix B. Acronyms

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| ACEP | Agricultural Conservation Easement Program (Department of Agriculture) |
| AGARDA | Agriculture Advanced Research and Development Authority (Department of Agriculture) |
| AMO | Advanced Manufacturing Office (Department of Energy) |
| ARPA-E | Advanced Research Projects Agency – Energy (Department of Energy) |
| ARRI | Appalachian Regional Reforestation Initiative (Department of the Interior) |
| ARS | Agricultural Research Service (Department of Agriculture) |
| BECCS | Bioenergy with carbon capture and storage |
| BETO | Bioenergy Technologies Office (Department of Energy) |
| BLM | Bureau of Land Management (Department of the Interior) |
| BOEM | Bureau of Ocean Energy Management (Department of the Interior) |
| BPMED | Bipolar membrane electrodialysis |
| BSEE | Bureau of Safety and Environmental Enforcement (Department of the Interior) |
| CCC | Civilian Climate Corps |
| CCS | Carbon capture and storage |
| CCIWG | Carbon Cycle Interagency Working Group (U.S. Global Change Research Program) |
| CCUS | Carbon capture, utilization, and storage |
| CDR | Carbon dioxide removal |
| CEQ | Council on Environmental Quality (Executive Office of the President) |
| CFP | Community Forest Program (Department of Agriculture) |

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| CIG | Conservation Innovation Grants (Department of Agriculture) |
| CMS | Carbon Monitoring System |
| $CO_2$ | Carbon dioxide |
| $CO_2e$ | Carbon dioxide equivalent |
| CRP | Conservation Reserve Program (Department of Agriculture) |
| CSAF | Climate-Smart Agriculture and Forestry Strategy (Department of Agriculture) |
| CSP | Conservation Stewardship Program (Department of Agriculture) |
| DAC | Direct air capture |
| DACS | Direct air capture with storage |
| DHS | Department of Homeland Security |
| DOC | Direct ocean capture |
| DOD | Department of Defense |
| DOE | Department of Energy |
| DOI | Department of the Interior |
| EERE | Office of Energy Efficiency and Renewable Energy (Department of Energy) |
| EO | Executive order |
| EOR | Enhanced oil recovery |
| EPA | Environmental Protection Agency |
| EQIP | Environmental Quality Improvement Program (Department of Agriculture) |
| ERS | Economic Research Service (Department of Agriculture) |
| ESO | Earth System Observatory (National Aeronautical and Space Administration) |
| FAST | Fixing America's Surface Transportation Act |
| FECM | Office of Fossil Energy and Carbon Management (Department of Energy) |
| FIA | Forest Inventory and Analysis (Department of Agriculture) |
| FLEP | Forest Land Enhancement Program (Department of Agriculture) |
| FLP | Forest Legacy Program (Department of Agriculture) |
| FOARAM | Federal Ocean Acidification Research and Monitoring Act |
| FSA | Farm Service Agency (Department of Agriculture) |
| FSP | Forest Stewardship Program (Department of Agriculture) |
| FTAC | Fast Track Action Committee |

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| FWS | Fish and Wildlife Service (Department of the Interior) |
| GCAM | Global Change Analysis Model (Pacific Northwest National Laboratory) |
| GHG | Greenhouse gas |
| $GTCO_2$/yr | Gigatons (Billion metric tons) of carbon dioxide per year |
| IAM | Integrated Assessment Model |
| IEA | International Energy Agency |
| IPCC | Intergovernmental Panel on Climate Change |
| LCA | Life cycle assessment |
| LCFS | Low-carbon fuel standard |
| LUC | Land Use Change |
| mCDR | Marine Carbon Dioxide Removal |
| MPRSA | Marine Protection, Research and Sanctuaries Act |
| MMRV | Measuring, Monitoring, Reporting, and Verification |
| $MtCO_2$/yr | Megatons (million metric tons) of carbon dioxide per year |
| NASA | National Aeronautical and Space Administration |
| NASEM | National Academies of Science, Engineering, and Medicine |
| NASS | National Agricultural Statistics Service (Department of Agriculture) |
| NETL | National Energy Technology Laboratory |
| NIFA | National Institute of Food and Agriculture (Department of Agriculture) |
| NIST | National Institute of Standards and Technology |
| NMFS | National Marine Fisheries Service (National Oceanic and Atmospheric Administration) |
| NOAA | National Oceanic and Atmospheric Administration |
| NOPP | National Oceanographic Partnership Program |
| NPS | National Park Service (Department of the Interior) |
| NRCS | National Resources Conservation Service (Department of Agriculture) |
| NREL | National Renewable Energy Laboratory |
| NSF | National Science Foundation |

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|---|---|
| OAE | Ocean alkalinity enhancement |
| OAP | Oceanic acidification program |
| OCS | Outer continental shelf |
| OM | Organic matter |
| OSMRE | Office of Surface Mining Reclamation and Enforcement (Department of the Interior) |
| PNNL | Pacific Northwest National Laboratory |
| RCPP | Regional Conservation Partnership Program (Department of Agriculture) |
| RFS | Renewable Fuel Standard Program (Environmental Protection Agency) |
| ROOTS | Rhizosphere Observations Optimizing Terrestrial Sequestration Program (Department of Energy) |
| SDO | Standards development organization |
| SFLR | Sustainable Forestry African American Land Retention Program (Department of Agriculture) |
| TRL | Technology Readiness Level |
| UCF | Urban and Community Forestry Program (Department of Agriculture) |
| UIC | Underground Injection Control (Environmental Protection Agency) |
| UNFCCC | United Nations Framework Convention on Climate Change |
| USCCSP | U.S. Carbon Cycle Science Program (U.S. Global Change Research Program) |
| USDA | U.S. Department of Agriculture |
| USDA-FS | U.S. Department of Agriculture Forest Service |
| USE IT | Utilizing Significant Emissions with Innovative Technologies Act |
| USGS | U.S. Geological Survey (Department of Interior) |
| USGCRP | U.S. Global Change Research Program |
| WHIP | Wildlife Habitat Incentives Program (Department of Agriculture) |
| WPTO | Water Power Technologies Office (Department of Energy) |

# Appendix C. Glossary

**Carbon Capture** – A process that captures carbon dioxide emissions from concentrated point sources like cement plants, coal- or natural-gas fired power plants and either reuses or stores it so it will not enter the atmosphere. (Source: https://www.energy.gov/carbon-capture-utilization-storage)

**Carbon Dioxide Removal (CDR)** – The Energy Act of 2020, Section 5002(a), defines CDR as the capture of carbon dioxide directly from ambient air or, in dissolved form, from seawater, combined with the storage of that carbon dioxide, including through (1) direct air capture and storage; (2) enhanced carbon mineralization; (3) bioenergy with carbon capture and storage; (4) forest restoration; (5) soil carbon management; and (6) direct ocean capture. (Source : https://www.congress.gov/116/plaws/publ260/PLAW-116publ260.pdf). The IPCC defines CDR as human-caused activities that remove carbon dioxide from the atmosphere and durably store it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical $CO_2$ sinks and direct air capture and storage but excludes natural $CO_2$ uptake not directly caused by human activities. (Source: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Annex_VII.pdf)

**Decarbonization** – The process of reducing carbon dioxide emissions associated with electricity, industry, transport, or other human actions, with the goal of achieving zero carbon dioxide emissions.[144] (Source: https://www.ipcc.ch/sr15/chapter/glossary/)

**Durability** – In the context of $CO_2$ storage, durability refers to the ability to last over time without leaking or deteriorating, thus preventing the removed $CO_2$ from re-entering the atmosphere or ocean.

**Mitigation** – Processes that reduce the amount and speed of future climate change by reducing the emissions of heat-trapping greenhouse gases or removing them from the atmosphere. (Source: https://toolkit.climate.gov/content/glossary)

**Net-Zero** – A state in which human-caused carbon dioxide emissions are balanced by human-caused carbon dioxide removal.[145] Net-zero can be used to refer to the world as a whole, or applied to a specific locality, process, or timeframe. (Source: https://www.ipcc.ch/sr15/chapter/glossary/)

**Permanence** – The longevity of removed $CO_2$ in the storage medium; how long the $CO_2$ remains stored. (Source: https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter11.pdf)

**Resilience** – The capacity of social, economic, and environmental systems to cope with a hazardous event, trend, or disturbance, responding and reorganizing in ways that maintain their essential function, identity, and structure while also maintaining the capacity for adaptation, learning, and transformation. (Source: https://www.ipcc.ch/sr15/chapter/glossary/)

**Verifiability** – The proving, to a standard still to be decided, of the results of monitoring. (Source: https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_annex2-1.pdf)

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[144] Decarbonization requires reduction of all greenhouse gases.

[145] Achieving net-zero requires addressing all greenhouse gases, including $CO_2$, methane, and other gases with high global warming potentials.

# Appendix D. Legislative Language

This report is submitted to the Committee on Energy and Natural Resources of the Senate and the Committees on Energy and Commerce and Science, Space, and Technology of the House of Representatives in response to Section 5002 of the Consolidated Appropriations Act, 2021 (Pub. L. 116-260, Div. Z, Tit. V, codified at 42 U.S.C. § 16298e). Section 5002(a)–(e) provide:

(a) DEFINITION OF CARBON DIOXIDE REMOVAL.—In this section, the term "carbon dioxide removal" means the capture of carbon dioxide directly from ambient air or, in dissolved form, from seawater, combined with the sequestration of that carbon dioxide, including through—

(1) direct air capture and sequestration;

(2) enhanced carbon mineralization;

(3) bioenergy with carbon capture and sequestration;

(4) forest restoration;

(5) soil carbon management; and

(6) direct ocean capture.

(b) REPORT.—Not later than 180 days after the date of enactment of this Act, the Secretary of Energy, in consultation with the heads of any other relevant Federal agencies, shall prepare a report that—

(1) estimates the magnitude of excess carbon dioxide in the atmosphere that will need to be removed by 2050 to achieve net-zero emissions and stabilize the climate;

(2) inventories current and emerging approaches of carbon dioxide removal and evaluates the advantages and disadvantages of each of the approaches; and

(3) identifies recommendations for legislation, funding, rules, revisions to rules, financing mechanisms, or other policy tools that the Federal Government can use to sufficiently advance the deployment of carbon dioxide removal projects in order to meet, in the aggregate, the magnitude of needed removals estimated under paragraph (1), including policy tools, such as—

(A) grants;

(B) loans or loan guarantees;

(C) public-private partnerships;

(D) direct procurement;

(E) incentives, including subsidized Federal financing mechanisms available to project developers;

(F) advance market commitments;

(G) regulations; and

(H) any other policy mechanism determined by the Secretary to be beneficial for advancing carbon dioxide removal methods and the deployment of carbon dioxide removal projects.

(c) SUBMISSION; PUBLICATION.—The Secretary shall—

(1) submit the report prepared under subsection (b) to the Committee on Energy and Natural Resources of the Senate and the Committees on Energy and Commerce and Science, Space, and Technology of the House of Representatives; and

(2) as soon as practicable after completion of the report, make the report publicly available.

(d) EVALUATION; REVISION.—

(1) IN GENERAL.—Not later than 2 years after the date on which the Secretary publishes the report under subsection (c)(2), and every 2 years thereafter, the Secretary shall evaluate the findings and recommendations of the report, or the most recent updated report submitted under paragraph (2)(B), as applicable, taking into consideration any issues and recommendations identified by the task force established under subsection (e)(1).

(2) REVISION.—After completing each evaluation under paragraph (1), the Secretary shall—

(A) revise the report as necessary; and

(B) if the Secretary revises the report under subparagraph (A), submit and publish the updated report in accordance with subsection (c).

(e) TASK FORCE.—

(1) ESTABLISHMENT AND DUTIES.—Not later than 60 days after the date of enactment of this Act, the Secretary shall establish a task force—

(A) to identify barriers to advancement of carbon dioxide removal methods and the deployment of carbon dioxide removal projects;

(B) to inventory existing or potential Federal legislation, rules, revisions to rules, financing mechanisms, or other policy tools that are capable of advancing carbon dioxide removal methods and the deployment of carbon dioxide removal projects;

(C) to assist in preparing the report described in subsection (b) and any updates to the report under subsection (d); and

(D) to advise the Secretary on matters pertaining to carbon dioxide removal.

(2) MEMBERS AND SELECTION.—The Secretary shall—

(A) develop criteria for the selection of members to the task force established under paragraph (1); and

(B) select members for the task force in accordance with the criteria developed under subparagraph (A).

(3) MEETINGS.—The task force shall meet not less frequently than once each year.

(4) EVALUATION.—Not later than 7 years after the date of enactment of this Act, the Secretary shall—

(A) reevaluate the need for the task force established under paragraph (1); and

(B) submit to Congress a recommendation as to whether the task force should continue."