U.S. Department of ENERGY

U.S. Department of Energy

Carbon Management Strategy

October 2024

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Executive Summary

The U.S. Department of Energy's (DOE's) Carbon Management Strategy ("Strategy") provides a comprehensive roadmap for the remainder of the decade that outlines the diverse tools and approaches DOE will use to develop and deploy carbon management solutions in line with President Biden's climate, economic, and social priorities. Carbon management—an umbrella term that encompasses the suite of technologies used for capturing, transporting, converting, and storing carbon dioxide (CO_2), as well as removing it directly from the atmosphere—is a critical component of the DOE's climate change mitigation strategy.[1]

The United States will need to rapidly deploy carbon management in the near-term to achieve net-zero greenhouse gas emissions in the power sector by 2035 and economy-wide by 2050. Concurrently, President Biden has directed agencies to implement carbon management policies responsibly so that they deliver clear benefits to communities and workers and provide robust environmental protections. DOE is focusing on implementing near-term programmatic activities that lay the groundwork for scaling carbon management in the future in alignment with these overarching policy goals.

The Strategy is focused on near-term actions that can position carbon management to scale as needed in subsequent decades. DOE's near-term strategy through 2030 incorporates the following five components:

1. Focusing research, development, demonstration, and deployment funding on priority use cases;
2. Building out CO_2 transportation and storage infrastructure where it likely will be needed most in the future;
3. Supporting the implementation of effective and evidence-driven policies and regulations related to carbon management at other federal agencies;
4. Engaging communities and workers to ensure projects deliver benefits and mitigate potential risks to public health and the environment; and
5. Supporting climate diplomacy efforts to accelerate the adoption of carbon management at scale globally in a way that aligns with the Paris Agreement.

Interwoven across all five of these components are a set of analysis and communications activities designed to provide insights into carbon management technologies that help inform investments in the field. Public-private partnerships, especially in the form of cost-share requirements for funding applicants, are central to this Strategy. DOE's analysis work is designed to catalyze private investment in the field and forms the foundation

[1] The term "carbon management" is sometimes defined to include or exclude a variety of different decarbonization pathways for managing carbon dioxide emissions. In this strategy, DOE uses a commonly accepted definition that includes point source carbon capture, use, and storage along with technological methods for carbon removal like direct air carbon capture, transport, conversion, and storage. See the definition and scope section of the strategy for more details.

for partnerships with other governments and civil society organizations to ensure that carbon management projects can be effectively regulated and deliver benefits to communities and the workforce.

This five-pronged approach was informed by extensive stakeholder engagement with communities and organizations that bring a wide range of views about the role carbon management should play in decarbonizing the economy. Using this feedback, DOE's Strategy is designed to enable the communities that are most eager to deploy carbon management projects to do so with the greatest climate, economic, and environmental benefit, while actively addressing the concerns expressed about the safety and efficacy of this suite of technologies.

DOE is funding a variety of technologies to assist in decarbonization in the industrial and power sectors. These approaches include carbon management as well as electrification, fuel switching, materials substitution, efficiency, and other emissions reductions measures. In parallel, DOE is working to envision and develop transformative emissions reductions approaches that will create new options in the long term.

Furthermore, this Strategy includes the prioritization of projects that have community and workforce benefit plans that place stakeholders and local communities at the center of project development efforts, ensuring DOE's investments result in tangible benefits for communities. DOE is also investing significantly in research and development to continuously improve the environmental, health, and safety of carbon management projects and is working to provide information about carbon management in a robust and clear way to a wide range of stakeholders.

These activities will help carbon management solutions develop alongside other emissions reduction technologies as rapidly as needed to meet climate targets, while delivering benefits for communities in line with the Biden Administration's commitment to equity and justice and local environmental protection.

This Strategy is intended to inform a wide range of stakeholders about DOE's carbon management programmatic priorities in the coming years. Its purpose is to provide a comprehensive summary of the tools the Department will use to support the scale up of carbon management solutions and provide clarity regarding DOE's priorities. Further, this strategy is designed to assist stakeholders involved in carbon management better understand how to engage with DOE based on their needs for support in the coming years.

It is anticipated that this Strategy will foster more extensive discussions between DOE and external stakeholders, which will help lead to highly impactful collaborations between the Department and the carbon management community.

Introduction

Carbon management technologies initially emerged within the oil and gas sector, primarily for production purposes rather than as a climate solution. Early operations in the oil and gas sector proved that carbon capture, transport, and permanent storage could be deployed at scale. Since 1991, DOE has been investing in research and development activities to advance carbon management technologies primarily as a tool to reduce CO_2 emissions.

Successful demonstrations have confirmed that that carbon management can provide a valuable component in the broader climate solutions toolkit. Currently, 18 commercial-scale carbon capture, conversion, and storage projects across a range of industrial and power emissions sources are in operation in the United States, with approximately 50 million metric tons per year (Mt/y) of capture capacity online around the world.[2, 3]

However, the pace of development and deployment for carbon management technologies as a climate solution has lagged significantly behind other emission reduction technologies like renewable energy and electric vehicles, primarily due to a lack of policy support for large-scale deployment.[4, 5] According to the International Energy Agency 2023 "Tracking Clean Energy Progress Report," carbon management remains "not on track" to meet the Agency's net-zero emissions scenario by 2050.[6]

In addition, some legacy industry infrastructure has led to cumulative pollution burdens with direct health impacts on communities, leading to a lack of trust for carbon management infrastructure as a climate tool in some communities.[7] In response, DOE is prioritizing responsible deployment of carbon management project with bilateral community engagement and transparency, environmental stewardship, and minimizing health and safety risks while maximizing benefits for communities.

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2 U.S. Carbon Capture Activity and Project Map – Clean Air Task Force

3 Carbon Capture, Utilization, and Storage Projects Explorer – Data Tools – IEA

4 What went wrong? Learning from three decades of carbon capture, utilization and sequestration (CCUS) pilot and demonstration projects – ScienceDirect

5 Historically, voluntary deployments (i.e., deployments in the absence of regulatory requirements) have either required significant government support as has been the case in Europe, and with a small number of demonstration projects in the United States, or they have occurred within the context of oil production. See the Carbon Capture Coalitions 2023 Federal Policy Blueprint and the International Energy Agency's (IEA's) Energy Technology RD&D Budgets Data Explorer – Data Tools for more context.

6 Tracking Clean Energy Progress 2023 - IEA

7 Johnston, J., Cushing, L. Chemical Exposures, Health, and Environmental Justice in Communities Living on the Fenceline of Industry. Curr Envir Health Rpt 7, 48–57 (2020). https://doi.org/10.1007/s40572-020-00263-8

Analyses of decarbonization scenarios are clear—carbon management technologies are essential to achieving net-zero greenhouse gas emissions by mid-century. These technologies contribute meaningfully to nearly all of the Intergovernmental Panel on Climate Change's 1.5˚C aligned climate scenarios and are critical to the U.S. Long-Term Strategy, which aims to achieve net-zero emissions by 2050.[8] In particular, most analyses show the necessary role carbon management has in removing historical emissions and addressing residual emissions from the hardest-to-abate emission sources.[9]

Over the past few years, the U.S. policy framework for carbon management has advanced significantly. The passage of the Infrastructure Investment and Jobs Act (IIJA), commonly referred to as the Bipartisan Infrastructure Law (BIL) in 2021 provided over $12 billion in funding for carbon management projects.[10] Furthermore, in 2022, the Inflation Reduction Act (IRA) reformed the 45Q tax credit to include a significant increase in the value of the incentive for various carbon management activities in the United States. These incentives, alongside the established regulations for geologic storage of CO_2, make the United States one of the most attractive investment environments for carbon management projects globally.

In April 2023, DOE published its Carbon Management Liftoff Report to provide an initial perspective on how and when carbon management technologies could reach full commercial potential in the way they were first envisioned back in 1991—as interconnected industrial systems designed primarily to reduce CO_2 emissions from large emitters to residual levels and to enable large-scale removal of CO_2 from the atmosphere. This Strategy builds on the analysis as identified in the Carbon Management Liftoff Report to outline the approach and specific actions DOE is pursuing to accelerate the deployment of carbon management as a climate solution, including its deployment of over $12 billion in Bipartisan Infrastructure Law investments Congress provided for carbon management.

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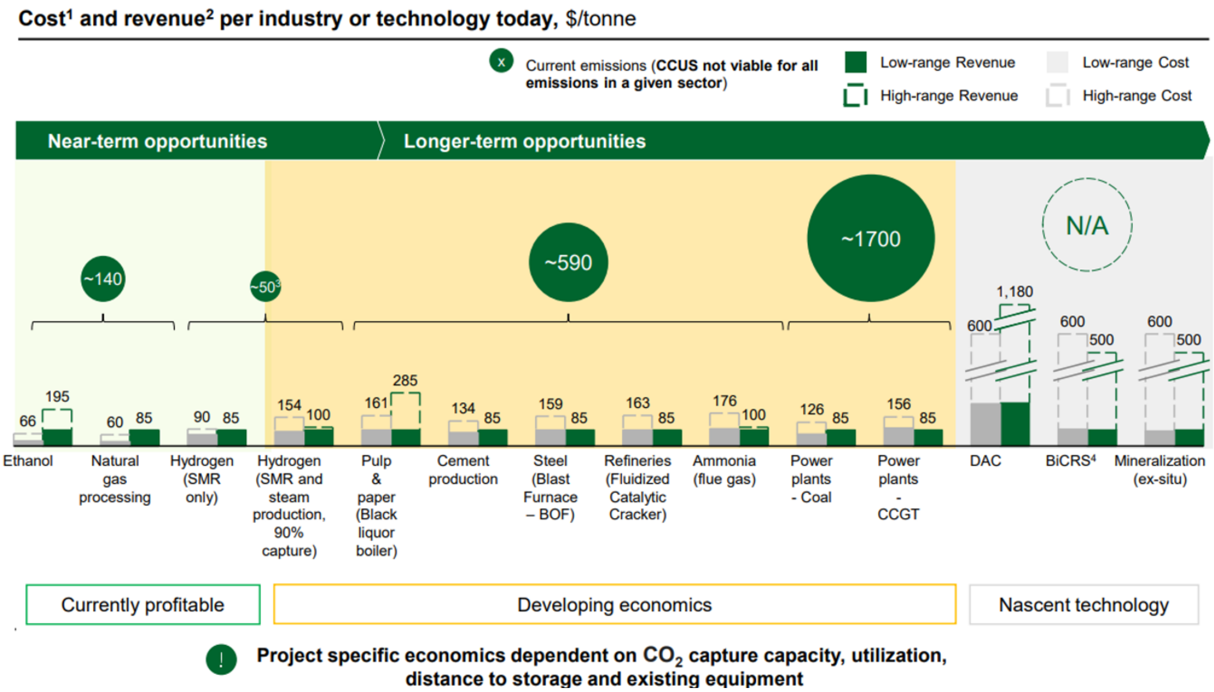
[8] The Intergovernmental Panel on Climate Change (IPCC) 2023 Climate Change Synthesis Report shows carbon management contributing meaningfully to three of four 1.5 °C-aligned climate scenarios—excluding the one scenario that models significant reduction in global demand and industrialization. In the other scenarios, carbon management contributes emissions reductions and removals at the 10 billion tonnes CO_2 per year ($GtCO_2$/y) scale. In the U.S. Federal Government's own analysis of pathways to net-zero emissions domestically (Long-Term Strategy of the United States: Pathways to Net Zero Greenhouse Gas Emissions by 2050), carbon management contributes to mitigation at the 400 million tonnes CO_2/year scale at a minimum, with some scenarios showing up to 20% of U.S. emissions abated through these solutions.

[9] Industrial Decarbonization - Pathways to Commercial Liftoff (energy.gov)

[10] 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."

Figure 1: 2022 DOE analysis of project profitability from Commercial Liftoff Report[11]



range of economic activity, but DOE does not have the funding to scale carbon management solutions as needed for climate goals alone. DOE is focused on guiding the industry toward achieving the most significant climate impact; delivering benefits for communities, workers, and regional economies; and avoiding negative public health and environmental impacts.

Throughout the current decade, DOE's Strategy centers on providing opportunities for scaling carbon management where it will most likely be required. This will be accomplished through funding a portfolio of targeted research, demonstration, and deployment projects, along with thorough analysis and stakeholder engagement to ensure responsible deployment.

This Strategy is organized into the following sections:

1. **Definition and Scope**
2. **History**
3. **Structure and Budget of DOE Offices**
4. **Vision**
5. **Strategic Approach**
6. **Key Initiatives**
7. **Conclusion**
8. **Appendix**

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[11] See Pathways to Commercial Liftoff: Carbon Management – U.S. Department of Energy for additional notes related to costs, revenues and industry/technology considerations.

Definition and Scope

Carbon management is an umbrella term that encompasses carbon capture (from industry and power generation), transport, conversion, and storage, hydrogen with carbon management, and carbon dioxide removal, all aimed at climate mitigation.[12] This document focuses on a subset of carbon management solutions including:

- CO_2 capture, both from exhaust of stationary emissions sources (e.g., power plants and industrial facilities), and directly from the atmosphere using technologies such as direct air capture;
- CO_2 transportation, via pipelines and other transportation modes such as trucks, trains, barges, and ships;
- CO_2 conversion into value-added products such as building materials, fuels, and chemicals; and
- Geologic CO_2 storage in deep underground rock formations.[13]

While this Strategy discusses the intersection of biomass energy and point-source carbon capture, it does not provide a comprehensive strategy for biomass energy and products where those systems are not coupled to point-source carbon capture. In addition, this Strategy discusses some carbon dioxide removal strategies, such as direct air capture and storage and biomass carbon dioxide removal, but it does not present a comprehensive strategy for carbon dioxide removal. More comprehensive strategies for biomass and for carbon dioxide removal are available in other DOE documents.[14]

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[12] DOE recognizes that the breadth of the term "carbon management" can lead to challenges when trying to communicate about specific projects. This Strategy uses the term carbon management when discussing the interconnected system of technologies, but attempts to specify the capture, transport, conversion, and/or storage technology when discussing specific pieces of the value chain.

[13] In most cases, DOE's funding for integrated carbon management projects does not exclude applications that are coupled to the practice of enhanced oil recovery for geologic storage of CO_2. However, DOE does prioritize projects for its funding that use dedicated geologic storage, both to maximize the climate benefit of DOE funding and to align with DOE's understanding of the industry's preferred business model for geologic storage. DOE's congressionally mandated research and development program on EOR is focused on improving the environmental sustainability of enhanced oil recovery operations.

[14] DOE's Biomass Research and Development strategy can be found on DOE's website, 2023 Multi-Year Program Plan , and the Carbon Dioxide Removal Strategy is forthcoming in Interagency Task Force Report to Congress.

Clean Fuels and Product Energy Earthshot

DOE's Carbon Management Strategy directly overlaps with our Clean Fuels and Products Shot (the Shot), launched in May 2023. The goal of the Shot is to develop cost-effective fuels and products from sustainable carbon sources to achieve greater than 85% lower net greenhouse gas emissions by 2035. By 2050, the Shot aims to meet projected demand for 100% of aviation fuel; 50% of maritime, rail, and off-road fuels; and 50% of hydrocarbon chemicals. The projected demand of fuels and products for these sectors in 2050 is approximately 400 million metric tons (MMT) per year. Large amounts of sustainable carbon-based resources are required to meet this goal. DOE anticipates it can be achieved with approximately 1,050 MMT per year of available biomass and waste feedstocks, as projected by the 2023 Billion-Ton Report, and approximately 450 MMT per year of CO_2-based feedstocks. This Strategy document only discusses the approach DOE is pursuing for CO_2-based approaches and biomass approaches coupled with carbon capture, conversion, and/or storage. A more detailed discussion for the biomass-only approaches are included in the Multi Year Program Plan prepared by DOE's Bioenergy Technologies Office.

Furthermore, this Strategy does not focus on the management of other greenhouse gas emissions such as methane. DOE's research into reducing methane emissions is a focus in the Office of Resource Sustainability which is a part of the Office of Fossil Energy and Carbon Management (FECM). It is also important to note that DOE's definition of carbon management does not include all the efforts to replace the processes that emit CO_2 as a byproduct in the first place, such as replacing fossil energy with solar, wind, batteries, or nuclear; replacing boilers with heat pumps; and creating circular systems that reuse and recycle non-CO_2 based materials. Additionally, DOE defines "carbon management" differently from the more colloquial use of the term to describe the exercise of calculating, tracking, and reducing an organization's "carbon footprint."

History

Carbon capture technology has a long history of deployment at scale in the United States, primarily via its oil and gas industry roots. Below is a condensed timeline of how carbon management technology has evolved from its invention in the 1930s, to its commercial deployment in the oil and gas industry in the 1970s, to the modern industry focused on reducing emissions for the primary purpose of addressing climate change at large scale.

- In the **1930s**, monoethanolamine solvents were first deployed for acid gas separation in the oil and gas industry and later became the first generation of carbon capture systems.[15]
- In **1972**, carbon capture was first deployed at industrial scale. It was used for enhanced oil recovery, which is the practice of using CO_2 to extract more oil from depleted oil wells. Historically, the oil industry primarily used naturally occurring CO_2 found in reservoirs deep underground for this practice. As natural gas processing systems happen to involve a technique for separating out CO_2 using amine solvents, the idea emerged to use this same technique to capture CO_2 emissions to be able to use them for enhanced oil recovery. In this first deployment, CO_2 was captured from five natural gas processing facilities in Texas, transported through more than 80 miles of onshore pipeline, and then stored about 3,000 feet below ground as part of the enhanced oil recovery process.[16]
- In **1977**, the idea first emerged to repurpose these technologies to address "the problem of CO_2 control in the atmosphere."[17] Because CO_2 remains trapped deep underground permanently in enhanced oil recovery operations, engineers explored the concept of adapting CO_2 capture technology to a wider range of CO_2 emissions sources and using dedicated geologic storage reservoirs not associated with oil production.

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[15] An Introduction to Carbon Dioxide Separation and Capture Technologies – mit.edu

[16] Global CCS Institute 2021 Annual Report

[17] The idea was first proposed in 1977 by Italian physicist Cesare Marchetti: Marchetti, C. On geoengineering and the CO problem. *Climatic Change* 1, 59–68 (1977) – DOI.

- In **1991**, DOE contracted with the Massachusetts Institute of Technology to begin to research[18] if basic capture, transport, and storage technologies could be repurposed as a climate solution. For the next two decades, DOE collaborated with universities, private geologic surveys, and other research partners to validate the hypothesis that CO_2 can be injected and stored in different types of geologic formations, the subsurface movement of CO_2 and resulting changes in geologic storage reservoirs can be monitored, and the long-term fate of CO_2 within geologic storage reservoirs can be predicted, managed, and prevented from atmospheric release.[19]
- In **1999**, the idea of direct air capture and storage as a carbon removal mechanism was discussed at a conference panel partially funded by DOE.[20]
- In **2000**, the Weyburn project became the first onshore carbon capture and storage project to use anthropogenic CO_2 and employ extensive monitoring efforts.
- Throughout the **2000s**, DOE and partners around the globe invested in improving capture technologies from their origins in oil and gas refining. They had to be turned into tools capable of capturing CO_2 at large scale and costs that would one day make them commercially deployable outside of the context of oil and gas production. Over time, DOE research expanded beyond amine-solvents to include sorbent, cryogenic, membranes, and other techniques. In parallel, DOE expanded research and development activities related to characterizing and commercializing CO_2 storage resources across the United States.
- In **2008**, the Energy Improvement and Extension Act of 2008 (Division B of P.L. 110-343) added the 45Q tax credit for CO_2 sequestration to the tax code.[21]
- The **2009** American Recovery and Reinvestment Act (ARRA) enabled DOE to support the retrofit of an Archer Daniels Midland ethanol production facility with carbon capture technology in 2010. Almost two decades after DOE's research program began, this project represented the first time CO_2 emissions were captured and then directed to dedicated geologic storage, for the sole purpose of climate change mitigation. Ethanol production emits streams of high-purity CO_2, so it was a good test case; the cost of capture is lower because the CO_2 just needs to be dehydrated and compressed. This project has captured and stored over 3 million tonnes of CO_2 in a dedicated saline formation and continues operating today. In 2010, the Obama Administration released an Interagency Task Force Report on Carbon Capture and Storage.[22]

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18 Jinfeng Ma, Lin Li, Haofan Wang, Yi Du, Junjie Ma, Xiaoli Zhang, Zhenliang Wang, Carbon Capture and Storage: History and the Road Ahead, Engineering, Volume 14, 2022, Pages 33-43, ISSN 2095-8099 – DOI. H. Herzog, CO Capture, Reuse, and Sequestration Technologies for Mitigating Global Climate Change. *MIT Energy Laboratory*.

19 Safe Geologic Storage of Captured Carbon Dioxide: Two Decades of DOE's Carbon Storage R&D Program in Review Note some carbon storage projects have been halted due to concerns such as the Salah Oil Field project in Algeria where "injection started in 2004 and [was] suspended in 2011 due to concerns about the integrity of the seal. During the project lifetime 3.8MT/CO2 was successfully stored in the Krechba Formation. No leakage of CO_2 was reported during the lifetime of the project". Carbon Capture and Sequestration Technologies @ MIT

20 Carbon Dioxide Extraction from Air: Is It An Option? (Conference) - OSTI.GOV

21 IF11455 - Congress.gov

22 Report of the Interagency Task Force on Carbon Capture and Storage, August 2010 - EPA (epa.gov)

- In **2013**, the carbon capture retrofit on the Port Arthur Air Products hydrogen production facility became operational at full-scale, using American Recovery and Reinvestment Act funding. Hydrogen production via steam-methane reforming is another process that yields high-purity CO_2 emission streams and proved to be another important test-case. This project uses CO_2 for enhanced oil recovery, storing the CO_2 permanently in the process. This project has captured and stored over 8 million tonnes of CO_2 and continues operating today.
- In **2016**, the Petra Nova at the W.A. Parish Generating Station coal-fired power plant retrofitted with carbon capture became operational at full-scale, with DOE and American Recovery and Reinvestment Act funding. The Petra Nova project was designed to capture 90% of CO_2 from only a portion of the overall emissions at the facility (a 240 MW equivalent slipstream out of the 640 MW unit)—amounting to approximately a 10x technology scale up over what had been previously demonstrated. It met these design targets and was constructed on time. The project, which relied entirely on enhanced oil recovery revenues (i.e., without 45Q tax credits) closed during a period of lower oil prices and reopened in 2023.[23]
- In **2018**, the 45Q tax credit was amended to a form similar to its current design, and DOE began research and development investments in carbon dioxide removal technologies.[24]
- In **2020**, the Utilizing Significant Emissions with Innovative Technologies Act (USE IT Act) was enacted by Congress in the Consolidated Appropriations Act of 2021, and carbon capture, use, and storage projects were included as a covered category in the FAST-41 permitting program.
- In **2021**, with the passage of the Bipartisan Infrastructure Law, DOE's budget for carbon management expanded from approximately $300-500 million annually to an additional $12 billion to be allocated over 2022-2026, including over $3.6 billion in funding for direct air capture. With this expansion, DOE's activities also shifted from primarily research, development, and small-scale demonstrations to include more large-scale pilots, demonstrations, and deployments.
- In **2022**, with the passage of the Inflation Reduction Act, the 45Q tax credit was amended to include a significant increase in the value of the incentives for a variety of carbon management activities in the United States. The Council on Environmental Quality at the White House also issued guidance on how the Biden Administration plans to implement carbon management projects responsibly.[25]

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[23] The Section 45Q Tax Credit for Carbon Sequestration - Congressional Research Service

[24] The Section 45Q Tax Credit for Carbon Sequestration - Congressional Research Service

[25] CEQ Issues New Guidance to Responsibly Develop Carbon Capture, Utilization, and Sequestration - The White House

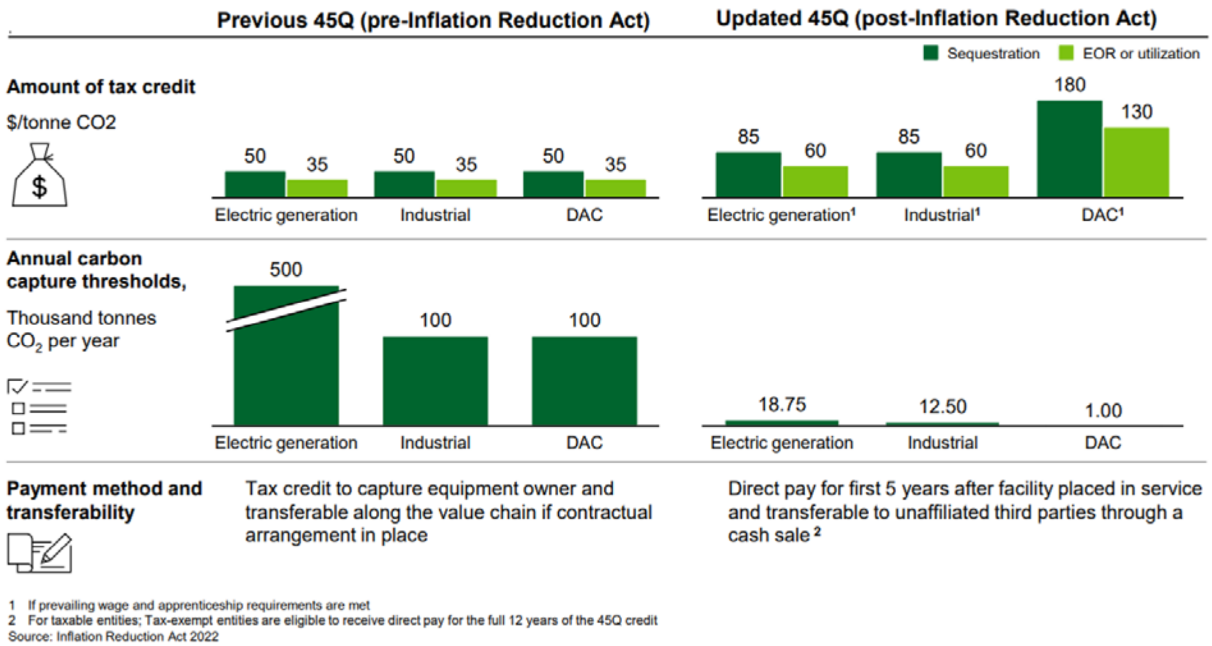
Figure 2: Operational U.S. carbon capture capacity as of March 2024[26]

Project	Operational Date	State	Industry	Capture Rate (Mt/y)	Capture Type	Storage Type
Occidental Terrell	1972	Texas	Natural Gas Processing	0.5	Industrial Separation	Enhanced Oil Recovery
Enid Fertilizer	1982	Oklahoma	Hydrogen / Ammonia / Fertilizer	0.2	Pre-Combustion Capture (Natural Gas Processing)	Enhanced Oil Recovery
ExxonMobil Labarge Shute Creek Gas	1986	Wyoming	Natural Gas Processing	7	Industrial Separation	Enhanced Oil Recovery
Great Plains Synfuels Plant and Weyburn-Midale	2000	North Dakota	Hydrogen / Ammonia / Fertilizer	3	Pre-Combustion Capture (Gasification)	Enhanced Oil Recovery
Core Energy CO_2-Enhanced Oil Recovery South Chester Plant	2003	Michigan	Natural Gas Processing	0.35	Industrial Separation	Enhanced Oil Recovery
Arkalon CO_2 Compression Facility	2009	Kansas	Ethanol	0.5	Inherent Capture	Enhanced Oil Recovery
Longfellow WTO Century Plant	2010	Texas	Natural Gas Processing	5 (Design capacity exceeding 8 Mt/yr, but historical operations have been much lower (<1 Mt/yr))	Industrial Separation	Enhanced Oil Recovery
Gary Climate Solutions Bonanza BioEnergy	2012	Kansas	Ethanol	0.1	Inherent Capture	Enhanced Oil Recovery
PCS Nitrogen Geismar Plant	2013	Louisiana	Hydrogen / Ammonia / Fertilizer	0.3	Pre-Combustion Capture (Gasification)	Enhanced Oil Recovery
Contango Lost Cabin Gas Plant	2013	Wyoming	Natural Gas Processing	0.9	Industrial Separation	Enhanced Oil Recovery
Air Products and Chemicals Valero Port Arthur Refinery	2013	Texas	Hydrogen / Ammonia / Fertilizer	0.9	Pre-Combustion Capture (Natural Gas Processing)	Enhanced Oil Recovery
Coffeyville Gasification Plant	2013	Kansas	Hydrogen / Ammonia / Fertilizer	0.9	Pre-Combustion Capture (Gasification)	Enhanced Oil Recovery

[26] Clean Air Task Force U.S. Carbon Capture Activity Map - Global CCS Institute

Project	Operational Date	State	Industry	Capture Rate (Mt/y)	Capture Type	Storage Type
Archer Daniels Midland Illinois Industrial	2017	Illinois	Ethanol	1	Inherent Capture	Deep Saline Formation
Petra Nova Carbon Capture	2017 (closed in 2020 and reopened 2023)	Texas	Power Generation and Heat	1.4	Post-Combustion Capture	Enhanced Oil Recovery
Red Trail Energy Richardton Ethanol	2022	North Dakota	Ethanol	0.18	Inherent Capture	Dedicated Geological Storage (Under Evaluation)
Harvestone Blue Flint Ethanol	2023	North Dakota	Ethanol	0.2	Inherent Capture	Deep Saline Formation
Heirloom DAC Facility	2023	California	Direct Air Capture	0.001	Ambient Air Capture	Utilization (Concrete)
Celanese Utilization Project	2024	Texas	Chemicals	0.18	Inherent Capture	Utilization

Figure 3: Overview of 45Q enhancements in the Inflation Reduction Act in 2022[27]



Office Structure and Budget

Today, DOE has many offices working on carbon management. Collectively, these offices received over $500 million in annual funding in fiscal year 2023 as well as $12 billion in one-time funding for a range of carbon management activities from the Bipartisan Infrastructure Law (see Figure 5). Additionally, there is over $10 billion in funding from the Bipartisan Infrastructure Law, Inflation Reduction Act, and annual appropriations for related priorities that include opportunities for carbon management, such as clean hydrogen hubs and industrial decarbonization projects.

The majority of annual carbon capture, transport, conversion, and storage funding is deployed by FECM for research and development projects.[28] The majority of the Bipartisan Infrastructure Law funding related to carbon management is deployed by DOE's Office of Clean Energy Demonstrations (OCED). This funding is generally focused on carbon capture pilots and demonstrations, direct air capture hubs, and carbon capture demonstrations as part of hydrogen hubs and industrial demonstration projects. Other Bipartisan Infrastructure Law funding for CO_2 transport and storage is administered by FECM and DOE's Loan Programs Office (LPO).

[27] Pathways to Commercial Liftoff: Carbon Management – U.S. Department of Energy

[28] The Advanced Research Projects Agency for Energy (ARPA-E) has also invested in carbon management through its annual appropriations, though its budget requests are structured in a way that does not prescribe certain levels of investments in this set of technologies. See Appendix for more details on budget.

Figure 4: FECM annual budget for carbon management research and development activities

Program	FY22	FY23	FY24
Carbon Transport and Storage	$97,000,000	$110,000,000	$93,000,000
Point Source Carbon Capture	$99,000,000	$135,000,000	$127,500,000
CO_2 Removal	$49,000,000	$70,000,000	$70,000,000
Carbon Conversion	$29,000,000	$50,000,000	$52,500,000
Hydrogen with Carbon Management	$101,000,000	$95,000,000	$85,000,000

Figure 5: List of Bipartisan Infrastructure Law and Inflation Reduction Act funding related to carbon management

Provision	Total Funding Amount	Selected to Date	Lead	Description
Carbon Storage Validation and Testing	$2,500,000,000	$687,000,000	FECM	Funding for dedicated geologic storage hubs capable of at least 50Mt of storage
Carbon Dioxide Transportation Infrastructure Finance and Innovation (CIFIA)	$2,100,000,000	Selections Pending	LPO + FECM	Loan guarantees and grants for developers to "oversize" CO_2 transport infrastructure to enable greater capture capacity to be added over time.
Carbon Capture Technology Program, Front-End Engineering and Design (FEED)	$100,000,000	$17,000,000	FECM	FEED studies for CO_2 transportation networks capable of connecting multiple CO_2 capture sources and/or storage sites.
Carbon Capture Demonstration Projects Program	$2,500,000,000	$934,000,000	OCED	Funding for at least six integrated capture, transport, and storage demonstrations on power and industrial emissions sources.
Carbon Capture Large-Scale Pilot Projects	$900,000,000	$304,000,000	OCED	Funding for innovative capture pilots, at roughly 10% the scale of a commercial demonstration project.
Regional Direct Air Capture Hubs	$3,500,000,000	$1,200,000,000	OCED	Funding for four Mt/year-scale direct air capture hubs
Direct Air Capture Technologies Prize Competitions	$115,000,000	$3,750,000	FECM	Funding for a $100M commercial prize and a $15,000,000 pre-commercial prize
Carbon Utilization Program	$300,000,000	Selections Pending	FECM	Funding for support for state and local governments to purchase lower carbon products that use CO_2 as a feedstock.
Regional Clean Hydrogen Hubs	$8,000,000,000 total, % to carbon management funding still needs to be determined	$7,000,000,000	OCED	Funding to support clean hydrogen production, with four of the seven selected hubs including carbon management as a component of their strategy.
Industrial Demonstrations	$6,000,000,000 total, $1,400,000,000 of selected projects for carbon management	$6,000,000,000	OCED	Funding to support demonstrations for integrated industrial decarbonization projects, with initial selections supporting carbon management demonstrations in the cement and petrochemical sectors.

More broadly, the Office of Science provides foundational knowledge and state-of-the-art capabilities for theoretical and experimental science related to carbon dioxide removal research across three program offices. Basic Energy Sciences continues support for scientific discoveries and major scientific tools to transform our understanding of CO_2 chemistry, separation systems, and materials, including conversion to durable products (e.g., mineralization), important to carbon management technologies. Biological and Environmental Research supports fundamental systems biology research on: (1) plants and plant microbiomes to capture atmospheric CO_2 and sequester stabilized forms of carbon in biomass and soil; and (2) algal systems to convert gaseous CO_2 waste streams into a broad range of bioproducts. Advanced Scientific Computing Research (ASCR) supports foundational investments in the applied mathematics and computer science tools, methods, and algorithms needed to computationally define realistic physical systems used in carbon dioxide removal and storage models and simulations.

In addition to the offices deploying funding for research, development, and demonstration projects, LPO holds approximately $170 billion of loan authority to provide low-cost capital for commercial-scale projects and has many carbon management projects in its pipeline. Finally, there are several offices within DOE that offer critical, cross-cutting support, including the Office of Energy Justice and Equity, the Office of Policy, and the Office of International Affairs.

Overall, DOE's authorization from Congress is largely focused on science, innovation, and the demonstration of early-stage commercial projects. DOE does not have regulatory authority over carbon management. DOE provides technical assistance and analysis to help other agencies implement regulations and incentives in an evidence-driven manner. Specifically, DOE offices have five primary tools to create optionality for scaling carbon management in the future:

1. Research and development funding, from fundamental science through pilot-scale prototypes;
2. First-of-a-kind commercial demonstration funding;
3. Financing support for infrastructure via a combination of cooperative agreements, grants, and loans to support early build out of commercial-scale capture, transport, conversion, and storage projects;
4. Analysis, including technoeconomic, life cycle assessments, and energy systems modeling to inform climate mitigation planning and private investment into carbon management technologies and projects; and
5. Stakeholder engagement, including with state, tribal, and local governments, community and environmental non-profit organizations, labor unions, academia (including 2- and 4-year universities, Minority Serving Institutions, and other appropriate academic institutions), the private sector, and international diplomatic efforts.

Vision

DOE and other agencies across the federal government have invested in a significant amount of analysis to assess the role carbon management could play in broader decarbonization efforts. This Strategy takes these analyses as inputs and seeks to synthesize DOE's vision rather than redefine it. It relies on the following inputs:

- The expected role of carbon management that has been discussed in other DOE strategies, including the Industrial Decarbonization Roadmap, the Hydrogen Strategy, and the Strategic Vision for the Role of Fossil Energy and Carbon Management in Achieving Net-Zero Greenhouse Gas Emissions.
- The required role, as well as challenges to commercialization, for carbon management has been analyzed and outlined in **five liftoff reports**, namely those focused on carbon management, industrial decarbonization, chemicals and refining, low-carbon cement, and clean hydrogen.
- The activities underway to enable this role have been articulated in the **multi-year program plans** of several DOE offices developing these technologies, including FECM (forthcoming), OCED, and the Bioenergy Technologies Office. LPO also published a Carbon Management Sector Spotlight.
- **Other reports published across the federal ecosystem** have outlined the history, status, and potential role of carbon management, including the:
    - The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050,
    - 2010 Report of the Interagency Task Force on Carbon Capture and Storage,
    - 2021 Council on Environmental Quality Report to Congress on Carbon Capture Utilization, and Storage,
    - 2022 Council on Environmental Quality Guidance to Responsibly Develop Carbon Capture, Utilization, and Sequestration to Agencies on Carbon Capture, Utilization, and Storage, and
    - 2023 Congressional Budget Office Report.

These reports established a shared fact base, affirming that carbon management technologies:

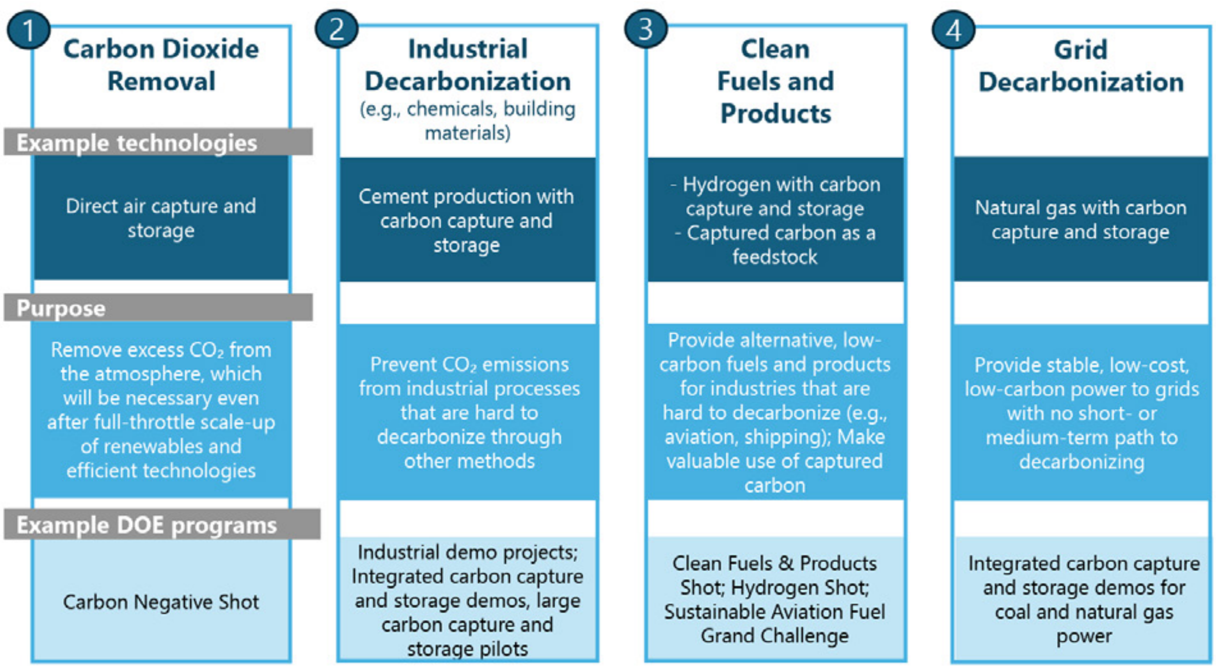
1. **Are necessary for meeting climate goals.** Continued analysis and engagement are required to sharpen the understanding of the likely scale and timing of carbon management in coming decades.
2. **Are economically viable today in the United States within certain use cases and geographies.** Ongoing investment is needed to further reduce the cost of carbon management technologies and unlock their full potential as a climate mitigation strategy.
3. **Represent safe and proven emissions reductions strategies, backed by DOE's experience with the technology and the existing regulatory framework, which ensures safety as projects progress.** Continued investment is needed to continuously strengthen environmental, health, and safety performance and associated regulatory requirements for these technologies.
4. **Offer an opportunity for workers across the United States, especially in communities dependent on fossil fuel jobs today, to transition to high-quality jobs that are aligned with net-zero climate commitments.**

Continued policy support is required to ensure projects translate into high quality jobs in communities where the technologies are deployed.

5. **Are viewed very differently by communities across the United States and will impact some disproportionately.** Continued work is required to communicate the opportunities and risks associated with carbon management in a clear and robust manner, and to ensure projects happen in the communities that want them the most. Given the overlap between existing hard to decarbonize industries, pipelines and disadvantaged communities, such communities are likely to be disproportionately impacted by carbon management and it is therefore vital to actively engage communities as early as possible in planning and project development.[29]

Furthermore, these other documents identify the following four broad use cases for carbon management in climate mitigation efforts:

Figure 6: Four use cases for carbon management



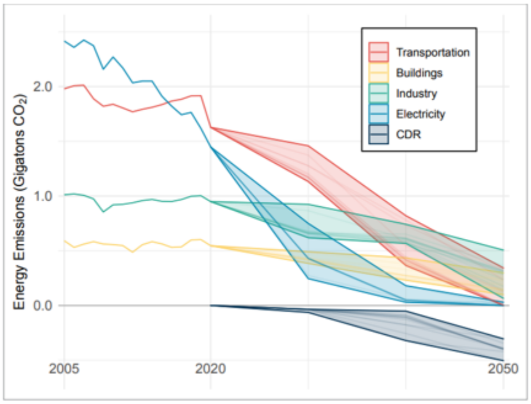
Each of these use cases have shown up with varying estimates for the scale and role required. A non-exhaustive overview of these estimates is provided below.

Carbon Dioxide Removal: The U.S. Long-Term Strategy, published in 2021, assumes that carbon dioxide removal technologies, including but not limited to direct air capture and storage, will be necessary at gigatonne scale to counteract historical and residual emissions. The Carbon Management Liftoff Report

[29] Existing gas transmission pipelines and rights of way are disproportionately in disadvantaged communities (Natural Gas Gathering and Transmission Pipelines and Social Vulnerability in the United States - Emanuel - 2021 - GeoHealth - Wiley Online Library). Power plants, refineries, and chemical manufacturing facilities are also more likely to be in low-income communities of color.

touches on barriers and challenges facing carbon dioxide removal deployment. The [Carbon Negative Shot] is DOE's uniting framework for innovation in carbon removal and the Office of Science has produced a report on [Foundational Science For Carbon Removal Technologies], which identifies key research areas across the agency.

Total CO_2 Emissions: Carbon dioxide removal expected to be required to meet goal of net-zero by 2050

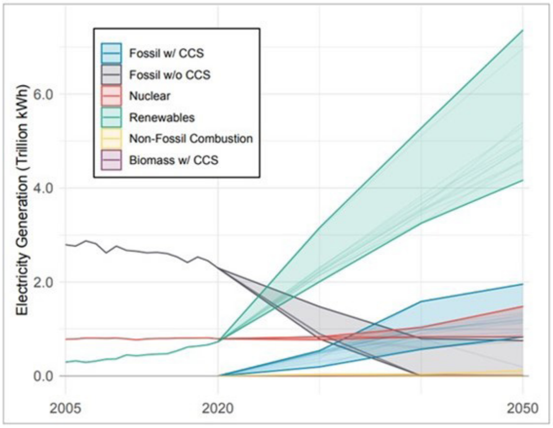


Industrial Decarbonization: The Industrial Decarbonization Liftoff Report focuses on the role that carbon management plays where other decarbonization strategies are infeasible or cost-prohibitive. Similarly, DOE's Industrial Decarbonization Roadmap identifies carbon management as necessary to address the approximately 60% of emissions that cannot be reduced through other measures in the near-term.

Clean Fuels and Products: DOE's Sustainable Aviation Fuel Grand Challenge Roadmap identifies two important roles for point-source carbon capture, use, and storage technologies: applying carbon capture to ethanol and similar biofuel production processes, and using captured CO_2 as a potential feedstock to combine with hydrogen to make lower-carbon intensity fuels. The Industrial Decarbonization Roadmap also identifies an important role for conversion and use of CO_2 as a feedstock, emphasizing that "both carbon utilization and carbon storage will be critical to achieving the final carbon reductions—those not achievable through other decarbonization technologies and strategies." The Clean Fuels and Products Shot is organizing DOE's work on decarbonizing fuels and chemicals across DOE offices. Second, the U.S. Hydrogen Strategy identifies a role for carbon capture in hydrogen production and aims to reduce the cost of clean hydrogen, which would reduce the cost of clean fuels and products from captured CO_2 and hydrogen.

Grid Decarbonization: The U.S. Long Term Strategy, which models a handful of representative scenarios to reach U.S. climate targets, assumes a significant scale-up in renewables, a decline of unabated fossil fuel use, and increasing deployment of carbon capture fitted on existing fossil fuel and biomass power plants. These technologies ultimately stand alongside nuclear energy as another option for supplementing variable renewable power with firmly dispatchable sources.[30] This strategy's scenarios for fossil fuel generation with carbon capture in 2050 range from 0.8-2 trillion kWh (equivalent to roughly 20%-40% of current electricity generation).[31]

Electricity Generation: Fossil with carbon capture and storage (CCS) and biomass with CCS are expected to be important electricity sources in 2025, alongside renewables and nuclear



[30] Executive order # 14057 defines fossil fuel with carbon capture as "electrical energy generation from fossil resources to the extent there is active capture and storage of carbon dioxide emissions that meets EPA requirements"

[31] Electricity generation, capacity, and sales in the United States - EIA

In the above analyses, the amount of carbon management solutions ultimately needed depends most heavily on the success of other alternative decarbonization methods in reducing costs and deploying at scale. In some cases, these alternatives will not be deployable at commercial-scale for several decades, and carbon capture retrofits on existing emissions sources will be an important interim solution. In other cases, carbon management will provide a long-term solution to deliver decarbonized power and heavy industrial processes in places where alternatives face deployment barriers or where solution diversity is beneficial for system reliability. In a last set of cases, no viable alternatives to carbon management may emerge at all. In these cases, point source carbon capture and/or carbon dioxide removal will be necessary to achieve net-zero emissions. It is not yet clear where those deployment needs will emerge most acutely, so developing the options and infrastructure to scale solutions nimbly in the future is the key task in the remainder of this decade.

However, there is consensus across the above reports that the country's overarching capture, transportation, conversion, and storage capacity will need to scale significantly from where it stands today. Below is an approximate deployment scenario for 500 Mt/yr of carbon management by 2050, representing a midpoint estimate for required U.S. deployment needs, and 2030 targets that represent a floor for what early demonstrations and infrastructure is required to deploy carbon management to the levels ultimately necessary by midcentury. [32]

Figure 7: Example pathways to a 2050 deployment[33]

Example Pathways to a 2050 Deployment			
	Today Actuals	**2030** Target	**2050** Estimated range
CO_2 capture capacity (MT/yr)	23M	~50-70M	~300-900M
Tech carbon dioxide removal capacity (MT/yr)	<.01M	~25-30M	~200-700M
Point source capture projects (# projects)	17	~30-100	~250-900
CO_2 pipeline (miles)	5,500	~10,000-15,000	~30,000-96.000
Dedicated CO_2 storage injection* volumes (MT/yr)	19M	~190M	~500-2,000M
Permitted Class VI storage facilities (# facilities)	~8**	~120-140	~400-1,500M
New direct jobs	~5-10K	~200-300K	~1,400-2,900K

*Indicates potential injectivity; actual injectivity contingent upon CO_2 captured
**8 projects with 18 total Class VI wells

While these pathways do not represent DOE's view on what should happen by 2050, they do provide a baseline for envisioning what a midpoint 2050 scenario modeled in this Strategy might entail in terms of commercial development. Considering that potential, the 2030 estimates represent a near-term deployment target that would enable DOE to scale up to any long-term deployment need, providing a foundation for the Department's near-term strategy.

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32 Liftoff Report synthesizes projects to range from 570-1220 MTPA (tonnes per annum). Deployment estimates also based on multi-year program plans.

33 2050 deployment scenario reflects the necessary projected volumes based on analysis from 2023 Carbon Management Liftoff Report; 2030 deployment scenarios reflects estimates based upon internal DOE-FECM analysis, Multiyear Program Plans and Strategic Vision. Today's values based upon: Congressional Budget Office report, EPA Greenhouse Gas Reporting Program, GCCSI Global Status of CCS 2023 Report, and Carbon Management Liftoff Report April 2023.

Near-term Strategy

DOE has designed a near-term carbon management strategy comprised of the following five intertwined objectives to achieve the 2030 vision outlined above.

1. **Focus new innovation investments on priority use cases:** Advance the development of carbon management use cases with the fewest decarbonization alternatives, such that each priority use case: a) has been demonstrated safely and effectively at commercial-scale, and b) is approaching economic-viability based on existing U.S. policy incentives.
2. **Fund regional clusters of transportation and storage infrastructure:** Support the buildout of CO_2 transportation and storage infrastructure in the regions where it is likely needed most–including through support for CO_2 capture projects that can anchor clusters as well as regional specific analysis, engagement, and regulatory support in a way that leads to the greatest economies of scale for future carbon management build-out across key regions.
3. **Support the implementation of effective policy and regulatory frameworks:** Provide technical assistance and detailed analysis to interagency partners working to implement carbon management regulations and incentives.
4. **Engage and protect communities, workers, and their environments:** Support stakeholder engagement and CBPs[34] so that all investments in carbon management protect communities and their environments and provide high-quality jobs across the United States, especially in disadvantaged communities.
5. **Build a foundation for global cooperation:** Collaborate toward scaling carbon management internationally, especially to enable developing economies that have a much younger fossil power and industrial base that will be more challenging to fully retool with renewable and electric alternatives on the timeframe needed to achieve net-zero emissions globally.

All five of these pillars are supported with robust analysis and communications. DOE investments provide a wealth of information about the economics, engineering, and environmental impacts of carbon management technologies. Leveraging this information by conducting detailed analysis on techno-economics, life cycle accounting, and energy systems modeling enables stakeholders across industry, civil society, and other governments to have valuable insights into the state of the field. These insights provide a foundation for outside stakeholders to have a clear understanding of where further public and private investments are most useful for advancing carbon management in line with climate and broader social, economic, and environmental goals.

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[34] DOE's Community Benefits Plan Framework aims to ensure that projects that receive federal funding, particularly from the Bipartisan Infrastructure Law and Inflation Reduction Act, generate economic, environmental, and societal benefits for the communities and workers where the projects are located.

1. Focus Innovation on Priority Use Cases

DOE, as explained in the "Key Initiatives" section below, is making investments in carbon management innovation, ranging from funding for fundamental science to pilot and demonstration projects and loan guarantees for early commercial deployments. These innovation funding investments, which are DOE's primary mandate, are spread across the four broad use cases for carbon management technologies identified above: carbon dioxide removal, industrial decarbonization, clean fuels and products, and grid decarbonization.

DOE sees all these use cases as necessary for achieving a clean energy and industrial future. However, there are some areas where carbon management is especially important for decarbonization, where no adequate alternative pathway exists or is likely to emerge in the next decade. These use cases with few alternative pathways and large projected business-as-usual greenhouse gas emissions are the focus for this Strategy, and they are referred in this document as "DOE focus" use cases.

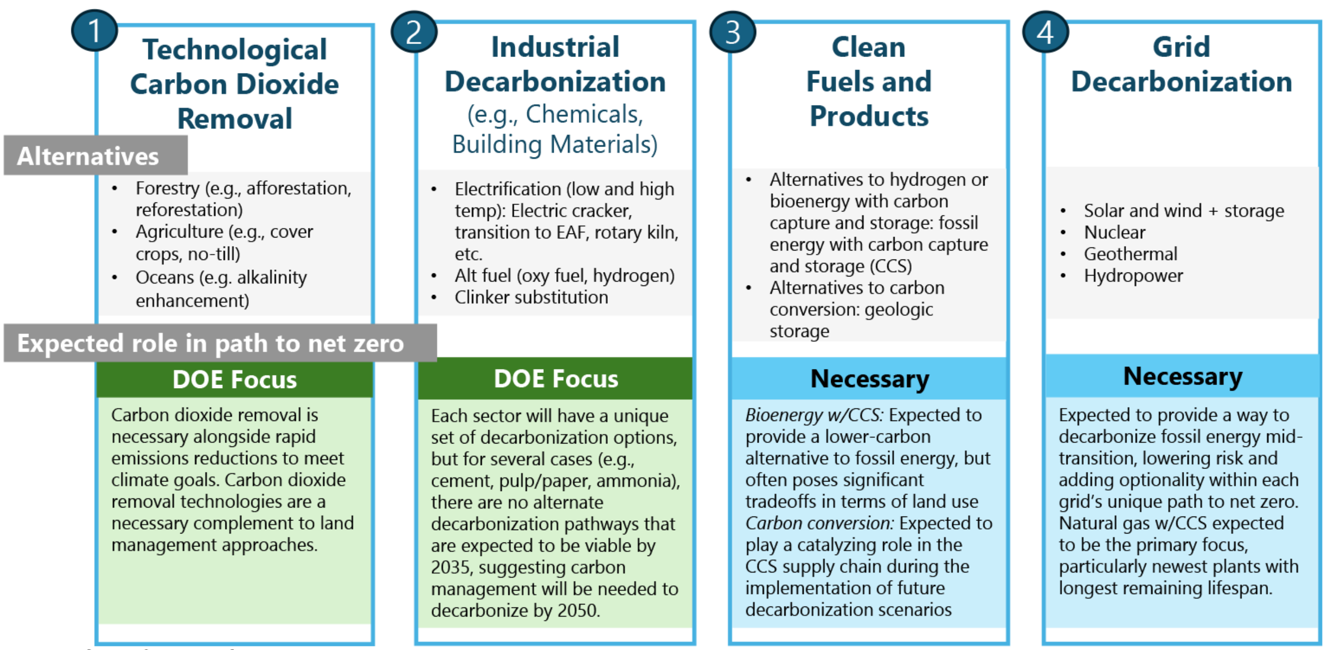
Key examples of these use cases include:

- **Carbon dioxide removal:** Carbon dioxide removal technologies such as direct air capture and storage will be needed as a complement to other carbon removal approaches that rely on land management practice changes, yet technological carbon dioxide removal solutions have yet to be deployed at meaningful commercial scale. Scaling carbon dioxide removal technologies to even the minimum level will likely require a pace of innovation at the high end of other historical examples of technology adoption.[35]
- **Industrial decarbonization:** Point source carbon capture and storage play a critical role in enabling rapid deep decarbonization of many heavy industrial sectors. Carbon capture currently represents the only viable option for commercial-scale full decarbonization of some of the heaviest emitting industries, such as cement and petrochemicals. Other sectors such as pulp and paper and glass manufacturing have relatively smaller process emissions, but also have limited, ready-to-deploy alternatives to carbon capture and storage to reach net-zero emissions today. Deploying carbon capture at commercial scale is necessary to stay on track with industrial decarbonization targets, since alternative technology options have only recently started to emerge at scale and emissions must be mitigated at existing industrial assets with long expected remaining lifetimes.DOE also believes it is essential to support early commercialization of other use cases where the ultimate need will depend much more heavily on the pace of deployment for other decarbonization approaches and local considerations. These other use cases are referred to as "necessary" throughout this Strategy. Such use cases include:
    - **Clean fuels and products**: While biomass-based fuels and chemicals offer significant potential, CO_2 based alternatives offer an important, complementary strategy to meet our projected demand for clean fuels and products. Carbon capture and use technologies are necessary to complement biomass-based fuels and products, so that CO_2-based products can be scaled at the level needed in future decades. In the long-run, atmospheric CO_2 will need to be utilized to achieve net-zero synthetic fuels and chemicals, though CO_2 sourced from fossil fuels emissions will be helpful for developing innovative CO_2 conversion technology.

[35] Dataset on the adoption of historical technologies informs the scale-up of emerging carbon dioxide removal measures | Communications Earth & Environment (nature.com)

- **Power generation**: Renewable energy is emerging as the lowest cost energy source in most places in the world, and costs are expected to continue to fall relative to fossil fuels for the indefinite future. However, carbon capture and storage also provides important options for clean firm power in the future if renewable deployment is not as rapid as is needed to meet net-zero power sector goals while maintaining necessary system reliability and overall costs.[36] Point source carbon capture systems can also be designed to operate flexibly to help fill supply gaps associated with variable renewables and take advantage of low-cost electricity in times of high renewable supply.

Figure 8: Priority use cases for carbon management



In the near-term, it is essential to safely demonstrate carbon management at commercial scale, covering its wide array of possible use cases. Even the lowest-cost use cases, such as ethanol and hydrogen, encounter challenges related to achieving financing and community support. As a result, DOE is working to provide innovation support to expedite the transition from pilot to demonstration scale across key use cases. This approach allows for learning at smaller scales before investing in full-scale projects to steward taxpayer funding as judiciously as possible.

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[36] On the Path to 100% Clean Electricity - DOE

In parallel, DOE is focusing innovation funding on bringing down the cost, providing benefits to early-adopter communities and workforces, and further reducing environmental impacts of the "focus" use cases that will deliver the highest climate benefit and are least likely to reach commercial adoption without additional government support. Key topic areas include:

- Advancing next-generation, less energy-intensive carbon capture technologies such as membranes, cryogenic, chemical looping, next generation sorbents, and hybrid systems;
- Developing a wider diversity of carbon dioxide removal technologies; and
- Supporting front-end engineering and design studies to reduce costs across heterogeneous facility locations and designs.[37]

Figure 9: Technology areas for carbon management[38]

	Use-case	Sector/Source	Current U.S. Emissions (MMT CO_2)	Estimated Cost Range ($/tonne)
1	Carbon Dioxide Removal	Direct Air Capture with Storage	N/A	600-1,180
2	Industrial Decarbonization	Cement	66	90-140
		Petrochemicals	55	90-170
		Fertilizer	36	100-180
		Refining	244	90-170
		Glass	15	No data
		Lime	27	No data
		Pulp and Paper	80	160-290
		Iron/Steel	100	90-160
		Natural Gas Processing	59	60-90
		Liquefied Natural Gas	17	No data
3	Sustainable Fuels and Products	Low-Greenhouse Gas Hydrocarbon Fuel	19	70-200
		Hydrogen	43	90-160
4	Grid Decarbonization	Power Generation	1,585	90-160

[37] Details on DOE's research and development agenda for carbon management are available in the forthcoming Fossil Energy and Carbon Management Multi-Year Program Plan (MYPP), along with the Office of Clean Energy Demonstration's MYPP.

[38] EPA FLIGHT Database; Manufacturing Energy and Carbon Footprints (2018 MECS) - Department of Energy; Pathways to Commercial Liftoff: Carbon Management – U.S. Department of Energy

DOE applies the analysis capabilities of its national laboratories and broader research, development, and demonstration network to focus its investments on priority use cases. Technology use cases for innovation and investment are selected based on analyses which inform their cost competitiveness, life cycle greenhouse gas benefits, market potential, and implications for other environmental, safety, workforce, justice, and domestic energy security considerations. These analyses continue as technologies move from lower to higher technological readiness levels and move toward greater degrees of certainty. Analyses

are regularly updated to address emerging issues, and DOE is incorporating lessons learned from a recent Government Accountability Office report to ensure that funding has the greatest probability of translating into impactful projects. These analyses are also critical for informing external stakeholders in industry about the commercial prospects for various carbon management technologies.

DOE national laboratories serve as a front line for independent and rigorous analysis to develop research requirements for funding opportunity announcements and to provide benchmarks for evaluating and selecting the most promising projects for research, development, demonstration, and deployment funding. For example, federal researchers within the national laboratories work closely with the research program teams to provide the analysis needed to inform targets and the structure and approaches for calculating metrics of research, development, and demonstration project success.

For a given pathway, these analyses include techno-economic assessments of cost and performance trajectories, detailed life cycle assessments of environmental impacts, and energy systems and market modeling to assess the extent and effects of potential deployment. By identifying research needs, deployment barriers, and potential impacts on integrated energy markets and local communities, these analyses help both government and private sector actors to optimally steward their investments. These analyses also inform the way the decarbonization benefits of technologies are measured and reported. For example, active efforts on measurement, monitoring, reporting, and verification for carbon dioxide removal projects are helping identify the most promising investments while addressing barriers to the commercialization of these technologies.

Research, development, and demonstration project teams also perform analyses of their technologies at various stages of projects. At the outset, typically techno-economic analysis of costs and life cycle analysis of greenhouse gas and other environmental considerations are used to guide the system design. Later, analysis is used to benchmark the achievement of project goals. This continuous evaluation cycle of the technology's benefits ensures federal innovation investments lead to the greatest impact possible.

2. Fund CO_2 Transport and Storage Infrastructure that Enables Scale in the Future

Even if key use cases like carbon capture on cement and direct air capture become increasingly cost-effective from the standpoint of the capture technologies, they will not be deployable in 2030 and beyond without the infrastructure, commercial dynamics, bridge-to-bankability, and public support to enable widespread project development. In particular, many communities have deep concerns about new pipeline projects of any kind, and building out this infrastructure rapidly will require technical excellence and community trust and collaboration.[39]

Today, it is challenging for many emitters to assess the incremental cost of carbon capture without an adequate picture of the transportation and storage infrastructure that will be available in their region. As a result, DOE is focused on scaling transportation and storage infrastructure, by both investing directly in that infrastructure where it is likely needed most, and by supporting capture projects with near term profitability that can incentivize its buildout and defray overall system costs in the future. To this end, DOE is investing heavily in front-end engineering and design (FEED) studies using Bipartisan Infrastructure Law funding across a range of carbon capture project types and geographies, as a lower cost and high leverage way to catalyze project development. DOE is also investing in pre-FEED studies with non-Bipartisan Infrastructure Law funding to engage the transport industry thinking about project development as early as possible. The pre-FEED studies support advancements in infrastructure engineering and conceptual design needed for large-scale transport projects.

DOE is focusing on funding CO_2 transportation and storage clusters and corridors by prioritizing funding in regions where that infrastructure will be needed long-term, including for capture sources that are not economical today, but have few decarbonization alternatives.

Role for Clustered Infrastructure

Around the world, there is wide agreement around the economic benefits of creating carbon management "hubs" or "clusters" of emitting facilities linked to shared CO_2 transportation and storage infrastructure. Once a group of CO_2 storage wells has been developed and is connected to pipelines, waterborne shipping, rail, or trucking systems, it becomes easier to keep connecting more and more capture sources to that system. The more capture sources get connected to this transportation and storage infrastructure, the more costs are shared, the cheaper it becomes to install carbon capture, and the more emitters choose to do so.

These benefits are not just the result of sharing the physical infrastructure; it is also easier to learn from the experience of neighbors (e.g., sharing or consulting the same capture technology developers and operators). This can also create long-lasting careers as the installation of carbon capture infrastructure is not a one-off project, but rather a new pillar of the regional economy.

Finally, these clusters also help streamline the transition between mid-term carbon capture and long-term carbon capture, as within these clusters, the same transport and storage infrastructure used in the nearer term for coal and natural gas carbon capture can be used for, and enable the emergence of, carbon capture for industrial processes and hard-to-abate emissions.

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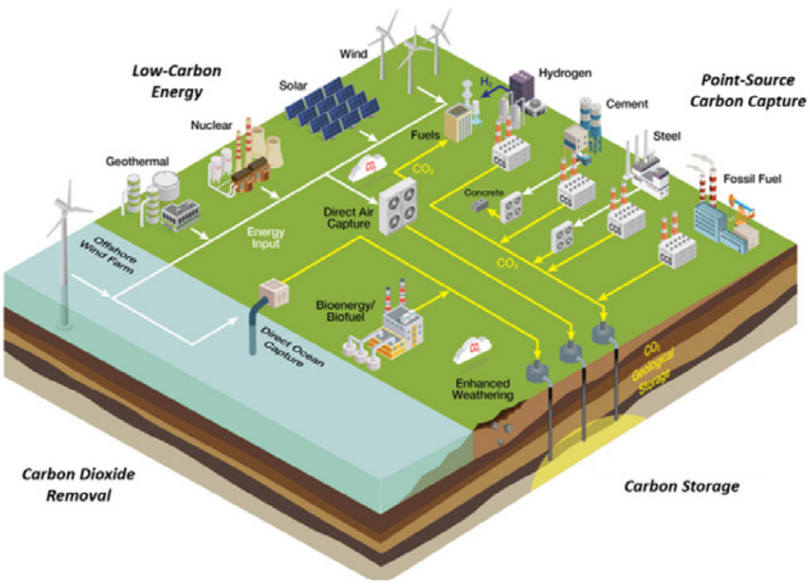
[39] Siting Challenges for Carbon Dioxide (CO_2) Pipelines (congress.gov)

At the same time, clusters of industrial activity historically have led to cumulative pollution that has resulted in communities that are overburdened and experiencing health impacts.[40] Carbon management hubs must be designed to minimize and mitigate not only their direct, project-level environmental impacts, but their broader regional impacts to avoid disproportionately impacting already burdened communities with inequitable environmental, health, and safety outcomes.[41]

DOE views these hubs as likely to emerge over time, as individual capture and storage sites add new capacity to become small clusters, which then link into regional hubs via large-scale transportation infrastructure.

- **Near-term:** First-of-a-kind demonstrations of point-source capture technologies in integrated, retrofit, single-source-to-single-sink carbon capture and storage demonstration projects.
- **Medium-term:** Clusters emerge in which multiple point-source or carbon dioxide removal sources feed a single high-capacity reservoir while net-zero flexible power and integrated industrial decarbonization approaches are being demonstrated.
- **Longer-term:** The clusters will be linked to form a network of regional hubs fed by multiple net-zero power and industrial sources.[42]

Figure 10: Example cluster of carbon management infrastructure



Emerging Clusters

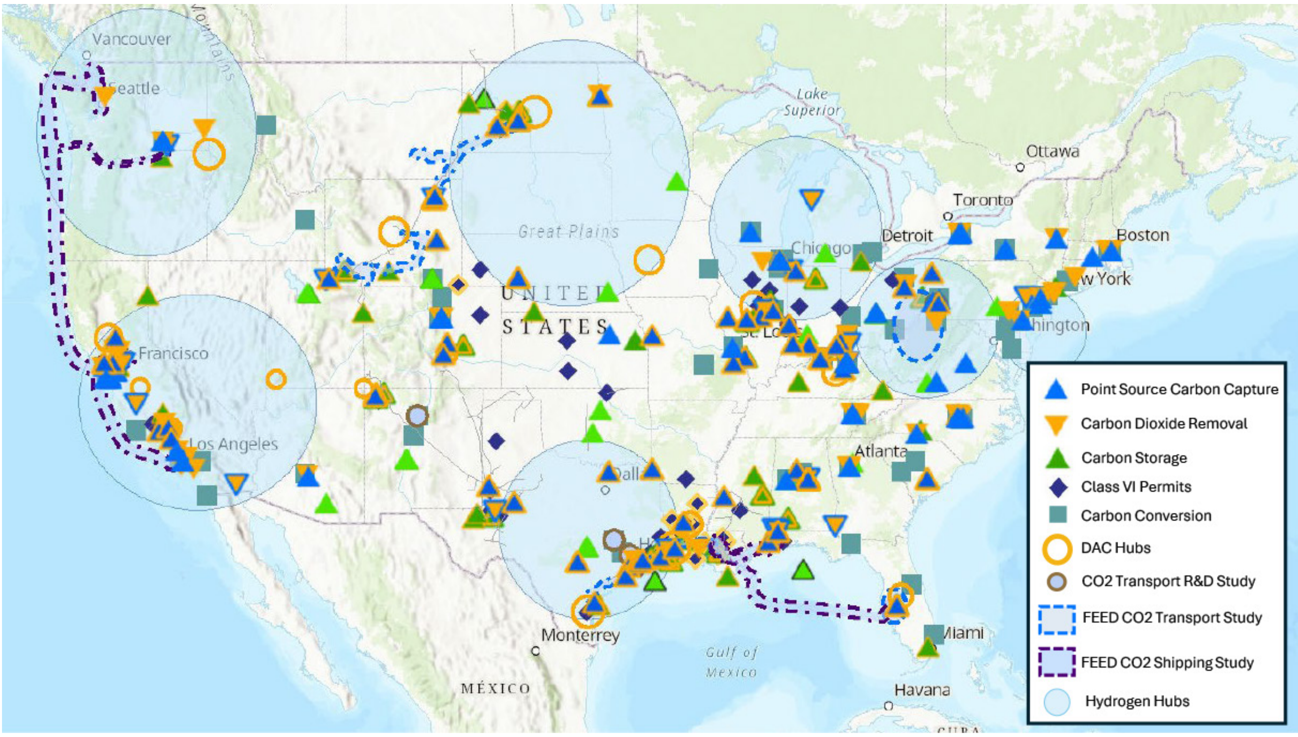
Several clusters are already beginning to emerge through ongoing DOE funding, initial rounds of deployment via Bipartisan Infrastructure Law funding, and other projects leveraging the 45Q tax credit. Some of these clusters overlap with DOE's selected carbon capture demonstrations and large scale-pilots, direct air capture hubs, industrial demonstrations program projects and regional clean hydrogen hubs. This presents possible opportunities for shared transport and storage infrastructure, as well as citing CO_2 conversion projects.

[40] Chemical Exposures, Health, and Environmental Justice in Communities Living on the Fenceline of Industry | Current Environmental Health Reports (springer.com); Aligning Industrial Decarbonization Technologies with Pollution Reduction Goals to Increase Community Benefits | ACEEE

[41] Aligning Industrial Decarbonization Technologies with Pollution Reduction Goals to Increase Community Benefits | ACEEE

[42] Based upon DOE-FECM internal multiyear program planning for Point Source Capture program.

Figure 11: DOE-funded carbon management projects as of March 2024[43]



Regional Efforts

DOE does not have a single "carbon hubs" program, but instead is supporting the emergence of CO_2 capture, transport, conversion, and storage clusters through a series of related initiatives:

- The Carbon Storage Assurance Facility Enterprise (CarbonSAFE) Program has \$2.5 billion in funding from the Bipartisan Infrastructure Law to support the development of CO_2 storage hubs.
- The Carbon Dioxide Transportation Infrastructure Finance and Innovation (CIFIA) Program provides \$2.1 billion in grant and loan support from the Bipartisan Infrastructure Law to support the development of CO_2 transportation infrastructure needed to link clusters of CO_2 capture projects with CO_2 storage hubs. Loans and loan guarantees from the LPO must have a reasonable prospect of repayment to DOE, so this program has the potential to deliver billions of dollars in loans for supporting transport infrastructure.
- The Regional Direct Air Capture Hubs Program provides \$3.5 billion in support for direct air capture development.
- The Regional Initiatives Program provides technical assistance to facilitate coordination and engagement among key stakeholders within each geography; there are distinct programs underway in the Southeast, Midwest/Northeast, West, and Great Plains regions respectively.
- The Carbon Matchmaker Tool was launched to enable project developers to self-identify their project sites and seek partnerships across the value chain, to facilitate the formation of clusters. Additionally,

[43] DOE Carbon Management RD&D

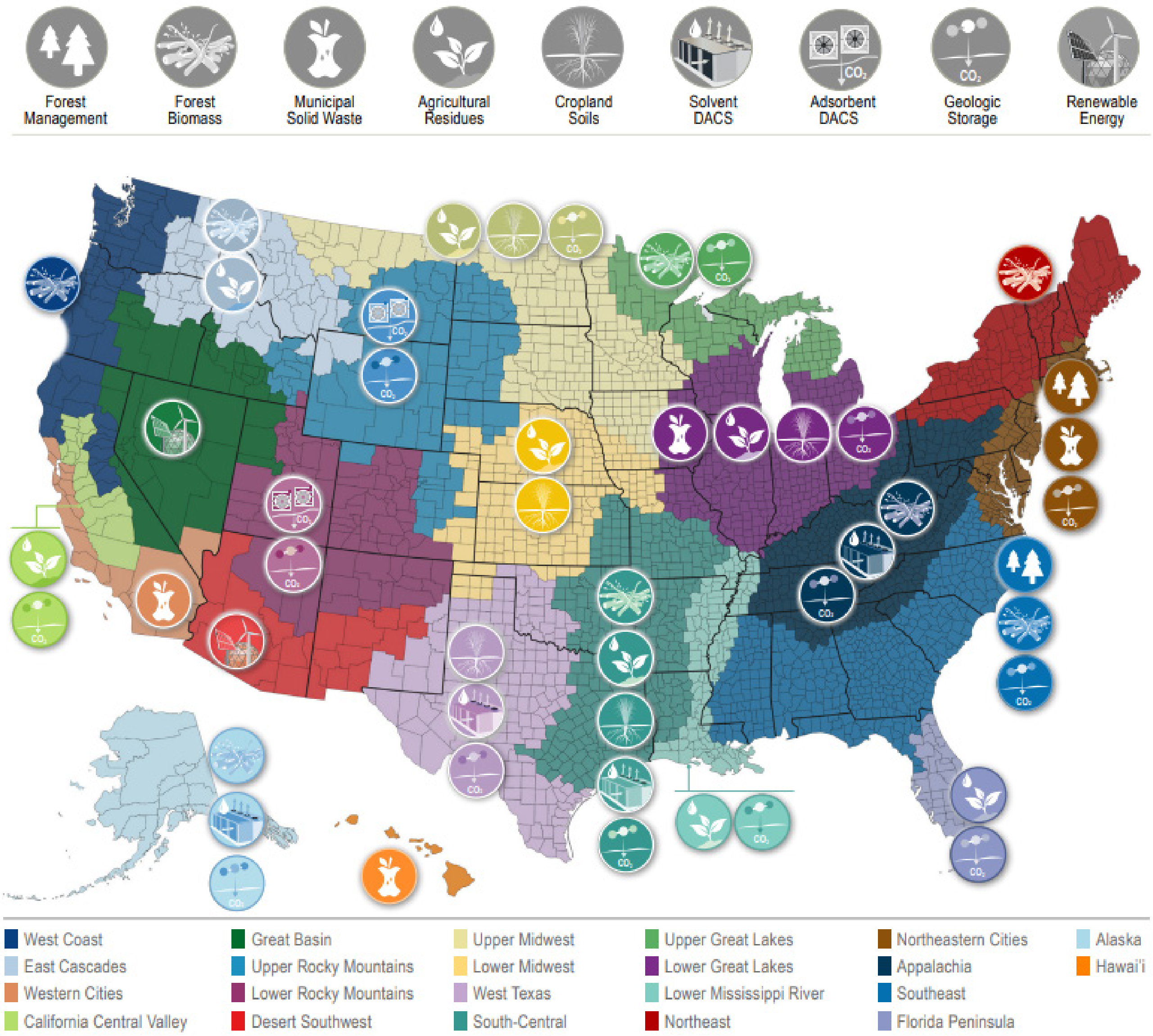
DOE is funding analysis using tools such as Los Alamos National Laboratory's (LANL) SimCCS tool and the National Energy Technology Laboratory's (NETL's) CO_2 transport planning tools to help developers understand where carbon management clusters and transportation corridors will prove most economic.

- The Communities Local Energy Action Program (LEAP) Program provides funding to low-income, energy communities, matching these communities with technical assistance providers to help them develop energy transition plans that may include carbon management among other strategies.
- DOE's Office of Energy Justice and Equity is launching a program in 2024 called the Regional Energy Democracy Initiative which will form a consortium of academic institutions, legal services, community and workforce organizations and economic development organizations to support communities and DOE projects in the development and implementation of Community Benefits Plans. It will be focused on the Gulf Coast in Texas and Louisiana where there are multiple federally funded carbon management projects, grid hardening and manufacturing and hydrogen projects occurring simultaneously.
- The Community Workforce Readiness Accelerator for Major Projects (RAMP) initiative, launched in 2024 by DOE's Office of Energy Jobs, will establish and bolster workforce partnerships by offering: community workforce fellowships, technical assistance, and capacity building opportunities in select geographies across the US. Its goal is to connect local workers, including those from historically marginalized communities to employment opportunities in energy projects, including those focused on carbon management.
- The U.S. National Hydrogen Strategy seeks to develop hydrogen hubs that "where appropriate, could serve as joint clean hydrogen and carbon capture, use, and storage hubs"—providing another opportunity to create clustered infrastructure. These hubs have been sited among existing clusters of heavy emitters, and four of the seven are currently designed to employ carbon management to decarbonize the hydrogen production itself. These hubs serve to support buildout of CO_2 transportation and storage infrastructure in regions where that infrastructure will be needed far beyond hydrogen production. Clean hydrogen production clusters will also improve the economics of CO_2 conversion activities for low-carbon fuels and chemicals.
- DOE has also conducted analysis on carbon management supply chains associated with clusters of projects.

Diverse Geographies and Offtake

The United States is advantaged in its ample geologic storage both on and offshore, as well as its potential for abundant, low-cost clean electricity to power a CO_2 conversion industry for low-carbon fuels and chemicals. U.S. clusters will be geographically diverse and offer a range of off-take options for CO_2 capture providers. Offshore storage and conversion technologies have proven successful in Europe and other geographies around the world and are expected to play an important role domestically long-term. On the carbon dioxide removal side, DOE's Lawrence Livermore National Laboratory Roads to Removal Report details geographic opportunities for carbon dioxide removal project development.

Figure 12: Regional opportunities for CO_2 removal[44]



Analyses to Forecast and Assess Deployment of CO_2 Transport and Storage Infrastructure

DOE conducts and sponsors analyses to forecast and assess deployment scenarios of CO_2 transportation and storage networks, including the potential impact of technological advances and policy scenarios. Analyses are also completed to evaluate the economic and environmental attributes of CO_2 transport and storage infrastructure design choices for a particular project. Tools to conduct these analyses have been developed by national laboratories.

[44] Regional Opportunities - roads2removal.org

NETL's CO_2 Transport Cost Model calculates the cost of transporting CO_2 along a defined route, and NETL provides planners with a curated compilation of critical decision information about areas that are favorable for pipeline routing. NETL is also developing an environmental and social justice database aligned to carbon storage systems that will aid stakeholders in decision making around key future infrastructure placement (e.g., carbon capture and storage injection locations) while helping contextualize these analyses against past and present-day social and environmental attributes.

FECM and NETL developed a carbon transport, use, and storage plug-in sub-module for the National Energy Modeling System, which is used by the U.S. Energy Information Administration to develop its Annual Energy Outlooks.

LANL developed the SimCCS tool, which takes user-provided CO_2 source, sink, and transportation data and determines the most cost-effective carbon capture and storage system design, including transportation routes. LANL also developed CO_2-PENS, a software tool that links together physics-based process-level modules that describe the entire CO_2 sequestration pathway, starting from capture at a power plant and following CO_2 through pipelines to the injection site and into the reservoir.

The Lawrence Livermore National Laboratory generated a Multimodal CO_2 Transportation Cost Model. This model is a detailed bottom-up life cycle assessment and cost analysis of truck and rail transport of CO_2 in the United States. The model includes an analysis of direct and indirect CO_2 emissions to determine costs per net tonne of CO_2 transported.

3. Support Effective Policy Emergence

DOE, while it does not have regulatory authority for carbon management, engages with the many federal agencies who are shaping the future of carbon management regulation and incentives implementation. Agencies such as the U.S. Environmental Protection Agency (EPA), the U.S. Department of Transportation, the U.S. Department of Interior, and the U.S. Department of the Treasury are shaping the regulations and incentives that will define the protocols and parameters ensuring these projects are implemented safely for communities and with net climate benefits. The White House's Council on Environmental Quality leads an interagency working group on carbon capture, use, and storage which reports to the National Climate Task Force.

Figure 13 outlines DOE's role alongside other agencies. DOE's main contribution is through research, development, demonstration, analysis, and supporting project implementation. In addition, DOE has a critical role in providing technical assistance to agencies regulating and incentivizing all aspects of the carbon management value chain.[45] Finally, DOE leads several international diplomatic collaborations aimed to accelerate carbon management innovation and deployment globally.

[45] For more information on the regulatory landscape for carbon management and the role of each agency, refer to the Congressional Budget Office's report, "Carbon Capture and Storage in the United States | Congressional Budget Office (cbo.gov)"

Figure 13: Carbon management interagency roles[a]

Federal Agency	Summary of Role	Research, Development, and Innovation	Regulatory	Land Management	International Capacity Building and Collaboration
U.S. Department of Agriculture (USDA)					
Forest Service	Manages national forests and grasslands under multiple-use, sustained-yield mandates and is the largest forestry research organization in the world.			✓	
Rural Utility Service	Offers loan guarantees for carbon capture projects at rural electric power generation facilities.	✓			
U.S. Department of Commerce					
Commercial Law Development Program	Commercial Law Development Program is a division of the U.S. Department of Commerce that helps achieve U.S. foreign policy goals in developing and post-conflict countries through commercial legal reforms.				✓
International Trade Administration	Promotes U.S. exports through market intelligence, industry engagement, and trade promotion.				✓
National Institute for Standards and Technology	Develops measurement science, standard reference materials, data, and models to support CO_2 transport and quantification of greenhouse gas emissions and removals. Convenes stakeholders to develop consensus standards through internationally recognized standards bodies to facilitate monitoring, reporting, and verification, and trade.	✓			
National Oceanographic and Atmospheric Administration (NOAA)	Partnered with DOE-FECM for first year of research and development on ocean-based carbon dioxide removal. NOAA software used for dispersion studies. Regulates potential impacts to marine environments and marine species per Coastal Zone Management Act, Endangered Species Act, Marine Mammal Protection Act, Magnuson-Stevens Fishery Conservation and Protection Act, National Marine Sanctuaries Act, and Marine Debris Act.	✓	✓		✓
U.S. Department of Defense					
Army Corps of Engineers	Permitting authorization for Clean Water Act Section 404. Manages real estate access.		✓	✓	
U.S. Department of Energy					
	20+ years of research, development, and demonstration on carbon management technologies; provides technical assistance and capacity building to facilitate global adoption of carbon capture, use, and storage.	✓			✓
U.S. Department of Interior					
Bureau of Land Management	Manages surface and pore space access on federal public lands			✓	
Bureau of Ocean Energy Management (BOEM)	Authority to grant leases, RoWs, and easements for subsurface sequestration of carbon dioxide on the Outer Continental Shelf (OCS). With BSEE, working jointly to develop a regulatory framework for carbon sequestration on the OCS.		✓	✓	

Federal Agency	Summary of Role	Research, Development, and Innovation	Regulatory	Land Management	International Capacity Building and Collaboration
Bureau of Safety and Environmental Enforcement (BSEE)	Oversees the operational aspects of carbon sequestration on the OCS including permitting of wells, equipment and facilities, inspection, and enforcement. With BOEM, working jointly to develop a regulatory framework for carbon sequestration on the OCS.		✓		
Fish and Wildlife Service	Implements Fish and Wildlife Coordination Act, which requires Federal agencies undertaking projects affecting water resources to consult with the Fish and Wildlife Service and the appropriate State wildlife agency with NOAA. Implements Endangered Species Act: consultation must occur to prevent Federal action that may jeopardize an endangered or threatened species or result in destruction or adverse modification to critical habitat.		✓		
United States Geologic Survey	Conducts geologic and biologic research and assessments of CO_2 sequestration, utilization, and removal. Internationally, provides technical assistance with capacity building and geologic sequestration resource assessments	✓			✓
U.S. Department of State					
	Supports international deployment of carbon management technologies and advances U.S. commercial leadership through diplomatic engagements and technical assistance and capacity building programs.				✓
U.S. Department of Transportation					
Pipeline and Hazardous Materials Safety Administration	Regulates pipeline safety for supercritical fluid CO_2 pipelines, which includes design, construction, operation, emergency response. Issues solicitations, funds, and manages research and development to inform regulations and improve pipeline safety.	✓	✓		
U.S. Department of the Treasury					
Internal Revenue Service (IRS)	Implements tax credit programs, such as carbon capture, use and storage, sustainable aviation fuels, and hydrogen.		✓		
U.S. Environmental Protection Agency (EPA)					
	Office of Water Underground Injection Control Program regulates carbon dioxide injection into the subsurface to protect underground sources of drinking water. Office of Air and Radiation develops national programs, policies, and regulations for monitoring and controlling air pollution, including the Greenhouse Gas Reporting Program and new source performance standards.		✓		
Permitting Council (FPISC)					
	Responsible for overseeing federal agencies' implementation of the FAST-41 process for FAST-41 covered projects, including carbon capture, conversion and storage.		✓		

[a] Non-exhaustive list.

Collaboration among U.S. government agencies is crucial to meet decarbonization goals. Historically, partnerships with other agencies have enhanced DOE's ability to successfully develop and deploy carbon management technologies. In addition, DOE's leadership on interagency coordination on carbon management facilitates alignment and efficiencies across the federal government. DOE is continually working to build and maintain these cross-agency relationships, share technical information and expertise, and work with other departments on carbon management. Included below are some of these critical efforts:

(1) Federal Carbon Capture and Storage Workforce Capacity Building and Technical Assistance
FECM provides capacity-building support to federal agencies involved in carbon management. DOE leverages the expertise of national laboratories to provide technical assistance and capacity building support to the EPA Class VI Underground Injection Control program, including evaluation of subsurface modeling and review of geologic site characterization associated with Class VI permit applications.

DOE also provides technical support to the Internal Revenue Service in the implementation of the 45Q tax credit by reviewing life cycle analyses that are submitted by taxpayers for applications that utilize captured carbon oxides. Lastly, DOE coordinates technical and regulatory carbon management trainings with broad interagency participation.

(2) Interagency Information-Sharing and Collaboration
DOE also coordinates government-wide efforts to enhance carbon capture, use, and storage interagency communication and collaboration. DOE leads active engagement with more than 160 carbon capture, use, and storage staff-level contacts from ten federal agencies and has initiated discussions and ongoing collaboration on focused carbon capture and storage topics such as land management and CO_2 transport.

Additionally, DOE plays a key role in interagency task forces. The Consolidated Appropriations Act, in 2021, called for DOE to establish a carbon dioxide removal task force. Separately, in 2023, DOE signed a Memorandum of Understanding with the White House Council on Environmental Quality to administer two carbon capture, use, and storage permitting task forces mandated by the Consolidated Appropriations Act, 2021. The permitting task forces, which consist of both interagency and external stakeholders, focus on improving the permitting process associated with carbon capture, use, and storage.

Other interagency task forces that DOE contributes to include:

- Carbon Capture, Use, and Storage Interagency Working Group led by the Council on Environmental Quality;
- Greenhouse Gas Measurement, Monitoring, and Information System working group;
- U.S. Global Change Research Program;
- Interagency Carbon Dioxide Removal Task Force co-chaired by DOE, EPA, the U.S. Department of Agriculture, the U.S. Department of the Interior, and the National Oceanic and Atmospheric Association;
- Interagency Carbon Transport Topic Team.

Recently, DOE has expanded its suite of tools for supporting innovation to include "demand side" approaches, such as direct procurement of carbon dioxide removal credits[46] and the facilitation of low-carbon hydrogen offtake.[47] These tools are designed to complement more conventional "supply side" funding of technology innovation and pave the way for future government programs to incentivize carbon management solutions at greater scale.

(3) Analysis Activities Inform Policymakers and Support Existing Policies

DOE is conducting a wide range of analysis activities to inform policymakers and stakeholders and to guide the development of the frameworks needed to support the scale up of carbon management technologies. DOE analysts are building consensus and providing guidance around the methods for tracking the greenhouse gas benefits of carbon management technologies. For example, NETL has developed the CO_2 Utilization Lifecycle Analysis Guidance Toolkit and the 45Q Lifecycle Assessment Guidance Toolkit to guide the industry and stakeholders to a rigorous and common understanding of the proper accounting of life cycle greenhouse gas emissions for CO_2 capture, use, and storage projects. NETL also supports the Internal Revenue Service in the evaluation of the life cycle accounting studies in connection with applications for 45Q tax credits. Similarly, a version of Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) Model is used to calculate the carbon intensities for hydrogen pathways in connection with the 45V tax credits for Clean Hydrogen (45VH2-GREET). DOE also developed a GREET model to support the 40B tax credit for Sustainable Aviation Fuels (40BSAF-GREET) and is developing a GREET model to support Climate Smart Agriculture practices under the Clean Fuel Production Credit (the 45Z tax credit).

DOE is also sponsoring analysis in measuring, monitoring, reporting, and verification for various carbon dioxide removal pathways. This effort helps develop the analytical methods needed to support credible quantification of greenhouse gas credits for carbon dioxide removal technologies such as direct air capture with storage, mineralization, CO_2 storage in concrete, marine carbon dioxide removal through growth and sinking of macroalgae, and biomass carbon dioxide removal and storage. This work involves combining development of physical measurement methods and coupling with approaches to develop the life cycle inventories used as the basis for life cycle assessment models.

Finally, DOE supports the creation and regular updates to baseline studies of carbon management technologies such as point source capture for industrial and power sector decarbonization, as well as carbon transport and storage. These studies track the performance, costs, and life cycle environmental considerations for these pathways.[48] They are originally developed to inform DOE and its stakeholders regarding the potential for commercialization, key performance metrics and benchmarks, and to identify key barriers to be addressed with continued research, development, and demonstration. DOE baseline reports are often used secondarily by regulatory agencies, such as EPA, to inform assessments of technologies' costs, performance, and other considerations used to develop policies and regulations. Other reports are designed to catalyze private investment in the field, such as the liftoff reports and insights paper.

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[46] Carbon Dioxide Removal Purchase Pilot Prize | Department of Energy

[47] DOE Selects Consortium to Bridge Early Demand for Clean Hydrogen, Providing Market Certainty and Unlocking Private Sector Investment | Department of Energy

[48] DOE is also developing processes to assess equity and cumulative impacts, which will be detailed in a forthcoming Environmental Justice Strategy Plan led by DOE's Office of Environmental Justice and Equity. This type of analysis is aligned with recommendations from the White House Environmental Justice Advisory Council: https://www.epa.gov/system/files/documents/2023-11/final-carbon-management-recommendations-report_11.17.2023_508.pdf

4. Engage and Protect Communities, Workers, and their Environments

It is imperative to deploy carbon management in ways that benefit local communities, including creating high-quality jobs, ensuring health and safety, and protecting air and water quality.[49] Today, many communities that have hosted energy infrastructure in the past do not trust that industry and regulators will make community health, safety, and economic vitality a top priority. At the same time, many workers face uncertainty associated with both the continuity of jobs in a decarbonizing energy system, as well as the health, safety, training, and compensation of existing and new industries.

DOE is working with environmental justice leaders and other federal agencies to ensure that these projects are implemented justly and effectively. In the United States, industrial and fossil fuel infrastructure are disproportionately sited in low-income communities and communities of color.[50]

In many cases, these same energy communities will present opportunities to host carbon management infrastructure. This overlap is rooted in the following factors:

- **Geologic CO_2 storage**: Some geologic formations that may be suitable for CO_2 storage are located nearby existing oil and gas production.
- **Carbon capture for industrial or power plant emissions**: In two of the four use cases for carbon management, industrial facilities (e.g., production of chemicals and building materials) and fossil power plants may consider implementing carbon capture systems. This means that communities living alongside these facilities may be proximate to new carbon capture infrastructure.
- **Carbon transportation**: In some cases, new CO_2 pipelines may be routed using existing rights of way and in parallel to existing pipelines, and pipelines for fossil fuels can in some cases be converted into CO_2 pipelines. This could mean that communities already located near pipeline infrastructure could host CO_2 pipelines as well.

Given the linkage of new carbon management projects to existing energy communities, it is essential to partner with communities to ensure an equitable and just energy transition.

As a result, DOE is prioritizing engagement with communities and workers to demonstrate and strengthen community and workforce benefits for carbon management projects, while addressing environmental, health, and safety concerns. In addition, DOE is working with communities to provide robust technical evidence of the opportunities and risks associated with carbon management projects in a way that is accessible to community stakeholders.

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[49] For an example of community engagement supporting project development see: Putting Community at the Center of the Carbon Capture Conversation - Carbon Action Alliance and for a meta review of community perceptions of carbon management see: Community acceptance and social impacts of carbon capture, utilization and storage projects: A systematic meta-narrative literature review | PLOS ONE

[50] Industrial Decarbonization Liftoff Report, p 64. D.J.X. Gonzalez, A. Nardone, A.V. Nguyen, R. Morello-Frosch, J.A. Casey, Historic redlining and the siting of oil and gas wells in the United States. J. Expo. Sci. Environ. Epidemiol., 33 (1) (2023), pp. 76-83. J.E. Johnston, E. Werder, D. Sebastian, Wastewater disposal wells, fracking, and environmental justice in southern Texas Am. J. Public Health, 106 (3) (2016), pp. 550-556. Natural Gas Gathering and Transmission Pipelines and Social Vulnerability in the United States - Emanuel - 2021 - GeoHealth - Wiley Online Library, Chemical Exposures, Health, and Environmental Justice in Communities Living on the Fenceline of Industry | Current Environmental Health Reports (springer.com)

Not only is community and worker engagement important from the standpoint of delivering on President Biden's commitments to advancing economic, environmental, and energy justice, but it is increasingly important as a determinant of project development success. Local rejections and bans on new CO_2 transport and storage projects in recent years have threatened projects with delays or cancellations, underscoring the importance of robust community engagement early and often in the project development process.

Included below are the five pillars that represent how DOE is approaching community engagement.

(1) Project-Specific Community Benefits Planning

One major effort to institutionalize responsible carbon management deployment practices is through DOE's Community Benefits Plan (CBP) Framework. This framework aims to ensure that projects that receive federal funding, particularly from the Bipartisan Infrastructure Law and Inflation Reduction Act, generate economic, environmental, and societal benefits for the communities and workers where the projects are located.

DOE-funded carbon management projects are required to develop CBPs. These CBPs are scored in merit review alongside the technical project information, which means that the quality of the plan directly influences project selection. CBPs are also a key implementation metric that is negotiated after selection

and reported on throughout the life of the project. In LPO, CBPs are integral to the due diligence evaluation leading up to a conditional commitment to fund the project.

As noted in Figure 14, the CBP framework is based on a set of four priorities: (1) engaging communities and labor, (2) investing in America's workforce through quality jobs, (3) advancing diversity, equity, inclusion, and accessibility, and (4) implementing the Justice40 framework to ensure benefits flow to disadvantaged communities.

Justice40

Justice40 is a whole of government approach to address inequalities in American communities by ensuring that disadvantaged and underserved communities benefit from Federal investments in climate and clean energy. Justice40 is being implemented using the Climate and Economic Justice Screening Tool (CEJST), a nation-wide mapping tool that evaluates communities' relative vulnerability to climate change and pollution, as well as energy security, workforce development, access to transport, and other factors. According to the CEJST, 37% of U.S. communities are disadvantaged and approximately 27% of the U.S. population live in disadvantaged communities.[50] Justice40 requires that at least 40% of the benefits of U.S. climate spending be directed to disadvantaged communities. All carbon management spending is covered by Justice40 because these clean energy investments can benefit disadvantaged communities. DOE is implementing Justice40 through CBPs and has identified eight policy priorities for carbon management and other programs to provide benefits to disadvantaged communities:

1. Decrease energy burden in disadvantaged communities.
2. Decrease environmental exposure and burdens for disadvantaged communities.
3. Increase parity in clean energy technology (e.g., solar, storage) access and adoption in disadvantaged communities.
4. Increase access to low-cost capital in disadvantaged communities.
5. Increase clean energy enterprise creation and contracting (MBE/DBE) in disadvantaged communities.
6. Increase clean energy jobs, job pipeline, and job training for individuals from disadvantaged communities.
7. Increase energy resiliency in disadvantaged communities.
8. Increase energy democracy in disadvantaged communities.

CBPs provide a framework for addressing the multifaceted drivers of inequity and seek to ensure that the transition to clean energy improves economic and environmental prospects for all American communities.

[51] Justice40 Initiative | Department of Energy; Explore the map - Climate & Economic Justice Screening Tool (geoplatform.gov); Justice40 Initiative | Environmental Justice | The White House

Figure 14: Overview of DOE's Community Benefits Plan framework

Because CBPs are part of the application process for carbon management projects, applicants must invest meaningful time and resources upfront to consider, and then state in their funding application how they will engage communities and labor; establish workplace standards for quality jobs and conduct workforce development; advance diversity, equity, inclusion, and accessibility; and ensure benefits and mitigate or eliminate potential impacts to communities. In evaluating these CBPs, DOE consults with practitioners who work in engagement, environmental justice, labor, and diversity, equity, inclusion, and accessibility.

For the Industrial Demonstrations Program, DOE published guidance that touches on how to develop the plans. Additional communications include a webinar and frequently asked questions. CBPs are also a key element of project negotiation, where DOE negotiates with the developer to ensure a strong CBP above and beyond the initial proposal.

The enforcement mechanism for these plans is tied to DOE's ongoing evaluation at each funding stage-gate. For example, projects with multiple budget periods are initially funded for the first budget period, with future budget periods contingent upon satisfactory performance and Go/No-Go decision review. At the Go/No-Go decision points, DOE evaluates project performance and other factors to decide whether to continue funding the project, recommend redirection of work under the project, place a hold on federal funding for the project, or discontinue funding the project.

Through close collaboration between developers and local communities, CBPs can evolve into Community Benefit Agreements, which are legally binding commitments between community groups and developers, stipulating the benefits a developer agrees to fund or furnish in exchange for community support of a project. DOE does not require Community Benefit Agreements but encourages them as an outcome of developing a

CBPs. These commitments are defined by the parties to the agreement, and can help settle disputes ahead of project deployment, strengthen civic participation, empower workers, secure the required workforce, and equitably align the resources and needs of local workers and communities with the benefits and opportunities of new projects.

While DOE only has the authority to require CBPs for projects it selects for funding or financing, the goal is to create a blueprint for responsible deployment that industry can follow regardless of whether a project is receiving federal funding support. Ideally, strong CBPs result in formal agreements that commit participating parties to create lasting benefits that will continue after DOE's involvement in a project ends.

(2) Ensuring Carbon Management Projects Robustly Mitigate Environmental, Health, and Safety Risks
DOE has conducted years of research focused on safety of carbon management technologies and will continue to do so. Research areas include: air pollutants at capture sites, pipeline network modeling, and modeling impacts of stored CO_2 to protect underground sources of drinking water. The goal of this research is to inform both regulators and project developers of the best practices to limit all risks to communities' air and water quality and health and safety, and to be able to answer these questions as they arise in communities hosting infrastructure. Safety risks associated with carbon management are manageable through robust environmental health and safety protocols and regulatory accountability, and further research offers opportunities for continuous improvement in the future.

Some of the most common safety concerns include:

- **Pollutants from existing infrastructure being retrofitted**: In many cases, the installation of point source carbon capture systems can remove the overwhelming majority of air pollutants, including non-CO_2 pollutants, from power and industrial infrastructure.[52] This is because these plants' entire air-pollution waste streams must be treated prior to carbon capture, removing non-CO_2 pollutants (e.g., sulfur oxides, nitrogen oxides, volatile organic compounds, mercury, and particulate matter). This suggests carbon capture presents a meaningful opportunity to reduce the health risks power and industrial infrastructure can pose to surrounding communities by reducing the emissions of co-contaminants—particularly if deployment can be focused on the cleanest facilities today.

  There are three primary exceptions. First, depending on the way the infrastructure had been regulated historically, there are some cases in which a plant's air emissions may come from multiple point sources, and thus some would continue even after a carbon capture retrofit on a portion of the facility. Second, scaling a unit to provide heat and power to carbon capture equipment has the potential to increase non-CO_2 emissions, although most of these additional emissions would be mitigated or adequately controlled by equipment needed to meet existing clean air regulatory requirements. Third, even when carbon capture systems can address emissions at the point source for fossil power plants, they do not address upstream emissions associated with their production (e.g., natural gas flaring); if carbon capture retrofits prolong the lifespan of fossil infrastructure, they can contribute to prolonging harmful non-CO_2 pollutants associated with that infrastructure unless accompanied by improved regulation of the

[52] Air Pollutant Reductions From Carbon Capture - Clean Air Task Force and Carbon Capture: Carbon Capture's Role in Removing Pollutants - Carbon Capture Ready

upstream industry. For the grid decarbonization use case, this is a critical consideration when assessing carbon management versus alternatives and reiterates the importance of complementary policy to reduce methane leakage throughout the natural gas supply chain in the short-term. To this end, FECM has a partnership with the U.S. Department of the Interior focused on identifying and closing abandoned and orphaned wells, which complements the EPA's Methane Emissions Reduction Program.

- **Secondary non-CO_2 emissions**: For both point-source and direct air capture projects, secondary air pollutants could result from amine-based capture technologies (e.g., solvents and sorbents) being deployed.[53] Monitoring and reporting requirements, mitigation strategies,[54] engineering process operation controls and the development of regulations or standards around these pollutants will be essential as these technologies scale. Direct nitrosamine emissions measured in pilot campaigns have been reported to be at acceptable levels and can be mitigated by engineering process operation controls.[55] Atmospheric reactions of amines present an additional pathway for nitrosamine formation which requires monitoring. Similarly, other degradation products, such as ammonia, can participate in atmospheric reactions to form hazardous compounds. Therefore, atmospheric photochemistry and dispersion modeling is required to determine the fate of direct emissions and quantify potential air quality impacts that arise during atmospheric reactions.

  At DOE, the following efforts are underway to effectively measure, mitigate and evaluate the impacts of secondary emissions of carbon capture solvents and sorbents:

  - A workshop was convened in June 2023 to discuss the air quality impacts associated with carbon capture and to identify research needs. The workshop also resulted in clarifying how engineering process controls can be applied to large scale and demonstration projects to prevent nitrosamine emissions.
  - Monitoring and reporting data on non-CO_2 pollutants has been made a requirement for many project funding opportunities.
  - Research and development priorities include: lab-scale testing of the degradation of capture materials to inform requirements and monitoring; enhancement of existing photochemical air quality models to include new emissions species and degradation pathways; development of a mobile test unit at the NETL's Research and Innovation Center that will measure secondary emissions during pilot campaigns; development of technologies that can be used to mitigate secondary emissions, including tools to predict these emissions with machine learning.

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[53] In the case of amine-based solvents, these emissions may include parent amines and amine aerosols, as well as compounds that arise from degradation reactions, which include ammonia, aldehydes and nitrosamines.

[54] Control measures to mitigate secondary emissions include solvent selection, as well as process features such as sparging to remove dissolved oxygen, carbon treating and reclaiming methods), pre-treatment methods and the use of water wash and acid wash configurations. Several approaches to managing secondary emissions have been implemented in pilot campaigns, most of which are summarized in reviews by Buvik (2021) and Rochelle (2024).

[55] Air pollution impacts of amine scrubbing for CO2 capture - ScienceDirect

- **Pipeline safety**: CO_2 pipeline rupture can be avoided and mitigated through proper design, construction, operation, monitoring, maintenance, and emergency response.[56] Although high-concentration CO_2 can pose significant health risks upon exposure, CO_2 pipelines have been used since the 1970s to transport tens of millions of tons of CO_2 per year, often across distances of hundreds of miles, with no reported fatalities.[57] Pipeline safety is currently regulated by the U.S. Department of Transportation's Pipeline and Hazardous Materials Safety Administration (PHMSA). Examples of PHMSA oversight include inspecting for compliance with proper corrosion control monitoring and ensuring operator qualification.[58] PHMSA does not prescribe the location or routing of pipelines. State and local governments, which have authority over the siting and routing of CO_2 pipelines, may consider other non-safety related factors when considering their location. DOE has consulted with PHMSA regarding its ongoing rulemaking following the 2020 CO_2 pipeline rupture in Satartia, Mississippi. In this incident, over 200 people were evacuated and at least 45 were hospitalized from exposure to CO_2. In 2022, PHMSA proposed a record civil penalty and compliance order terms against the company that operated the pipeline at the time, and PHMSA announced that it was initiating a rulemaking process to update standards for CO_2 pipelines, including requirements related to emergency preparedness, and response.[59] In addition, DOE is planning a research and development consortium for CO_2 transport that will catalogue worldwide research investments and track progress in resolving technical challenges.
- **Security of geologic storage**: Geologic storage has over a 50-year history of safe operation, which includes numerous onshore storage projects in the United States with enhanced oil recovery and offshore storage projects abroad, such as the Sleipner facility off the coast of Norway. While leakage of CO_2 into underground water reservoirs can impact the pH of water, which could lead to negative health outcomes for those that drink the water, global monitoring efforts to date have confirmed that leakage events are rare and can be mitigated with routine industry practices.[60] EPA's Class VI Underground Injection Control Program is focused on ensuring CO_2 storage does not contaminate underground sources of drinking water. It is also focused on ensuring the permanence of the CO_2 storage, to validate carbon sequestration claims for relevant tax credits like 45Q. Through an interagency agreement between EPA and FECM, several national laboratories with deep expertise in carbon storage support this program's implementation, including developing trainings and conducting technical reviews of the geologic characterization and subsurface modeling portions of permit applications. DOE also supports the National Risk Assessment Partnership to support long-term risk management of geologic storage, as well as the Science-informed Machine Learning to Accelerate Real-Time (SMART) Decisions in Subsurface Applications Program.

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[56] US Department of Transportation. (2021). All reported incidents, *PHMSA 2001-2020*.

[57] Compare this statistic with natural gas infrastructure: According to the Department of Transportation between 2001 and 2020, industrial incidents in natural gas gathering and transmissions pipelines resulted in: 36 fatalities, 164 injuries, and approximately $2.5 billion in costs (US Department of Transportation, 2021)

[58] See "PHMSA Letters to Wolf Carbon, Summit, and Navigator Clarifying Federal, State, and Local Government Pipeline Authorities.pdf (dot.gov)." Federal safety standards apply to both interstate and intrastate pipeline facilities…A state authority that submits a certification to PHMSA may assume exclusive regulatory authority for the safety of its intrastate pipelines…PHMSA's national regulatory program relies heavily on the efforts of these state partners, who employ roughly 70 percent of all pipeline inspectors and whose jurisdiction covers more than 80 percent of regulated pipelines."

[59] In March 2024, PHMSA transmitted a notice of proposed rulemaking to the White House Office of Management and Budget (OMB) for pre-publication review. Additionally, in April 2024 another pipeline leak occurred in Sulphur, LA. This event triggered a shelter in place and no residents were reported injured. https://www.kplctv.com/2024/04/04/residents-near-bankens-road-north-sulphur-askedshelter-place/

[60] https://www.netl.doe.gov/carbon-management/carbon-storage/faqs/permanence-safety

Further, EPA's Class VI Underground Injection Control Program provides strong safeguards around potential geologic storage risks. When states are granted primacy over Class VI storage permitting from EPA, it is on the condition that their permitting program continue to uphold, if not expand, the requirements within EPA's process. In this regard, Class VI permitting operates similarly to how EPA administers state primary over Class I-V Underground Injection Control permitting. EPA regularly updates a public-facing website to create transparency.[61]

- **Track record of project developers**:For any infrastructure project, safety and environmental performance are ultimately dependent on adherence to protocols by the project developer or operator. Many project developers are not trusted by communities because of concerns over previous interactions and/or poor safety records.[62] In some cases, state regulatory agencies have not enforced accountability for these developers (e.g., allowing them to abandon and fail to plug wells, called "orphan wells"); some of these regulators have lost community trust as well. Consistent compliance with environmental laws such as the Clean Air Act and occupational health and safety regulation is expected from selected projects, and noncompliance weighed heavily at Go/No-Go decision points for continued funding.

(3) Supporting Community Education, Engagement, and Programming

In addition to implementing its portfolio and project-specific negotiations, DOE is working to lay the groundwork for more community-led carbon management conversations through education and technical assistance. As a part of these efforts, DOE is engaging with communities and stakeholders across the country where significant project development is expected to occur to ensure community and stakeholder participation, understand and address concerns, and increase awareness regarding funding and opportunities available.

One aspect of this work includes hosting and sponsoring workshops, which aim to educate communities about carbon management technologies and upcoming funding opportunities. During the workshops, DOE is focused on two-way engagement, in which communities and stakeholders are not only informed, but also have the opportunity provide input and shape the design and development of projects and infrastructure that affect them.

In November 2023, FECM sponsored the Carbon Management Dialogue in Houston, Texas, in partnership with former Houston Mayor Sylvester Turner, Rice University, Climate Now, and local community organizations. This two-day, in-person and virtual event facilitated shared learning and relationship building by convening over 150 people from diverse backgrounds—industry, environmental justice advocacy, academia, community leadership, local and federal government—to have a constructive dialogue about how carbon management projects in the Greater Houston Region can advance in a way that is responsible and respectful of community input.[63] This event, and the many other engagement events (e.g., workshops, webinars, and site visits) that DOE either hosts or sponsors, aligns with the Department's broader priority of placing stakeholders and local communities at the center of project-development efforts, ensuring that DOE's investments result in tangible benefits for communities.

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61 Current Class VI Projects under Review at EPA - EPA

62 For a review of enforcement and compliance issues see: Nextgencompliance

63 A recording of the Carbon Management Dialogue event is available to view here: (7805) Carbon Management Dialogue: Greater Houston Area – YouTube

The second aspect of this work includes providing technical assistance to communities where carbon management projects are under consideration. Technical assistance is the practice of sharing technical expertise with other stakeholders, including states, regulators, developers, and universities, in the carbon management ecosystem. Ongoing technical assistance projects include the Regional Initiatives Program and the Communities LEAP, discussed above.

In addition to DOE's own direct facilitation of technical assistance and community engagement, DOE recognizes the importance of partnering with and supporting other members of the ecosystem who may be more embedded within the communities considering hosting this infrastructure. Included below are some examples of these important partners.

- **State, local, and tribal governments:** State and tribal governments have emerged as key leaders on carbon management. States and tribes play a key role in permitting where and how carbon management projects happen, especially for CO_2 transport and storage. State energy financing institutions can also be powerful catalysts of projects. However, while many states have structures (e.g., state geologic surveys and economic development boards) to support education and outreach to communities with high potential for hosting carbon management projects, many states and tribes do not have the resources to dedicate to these conversations. This is one area where DOE's Regional Initiatives Program seeks to provide support. States and tribes are also often best positioned to facilitate partnerships across the value chain within specific localities where projects are under development.
- **Universities:** Universities are also essential leaders for improving public awareness around carbon capture, transport, and storage, as well as being sites and hosts of important community conversations around specific projects. Universities receive millions of dollars in funding from DOE each year for research on carbon management technologies. They are often well-positioned as trusted experts to work with communities and help answer their questions about carbon management technologies and approaches, including associated benefits and in addressing and mitigating potential risks to human health and the environment. Efforts will be made to work with a diverse body of universities, including 2- and 4-year institutions of higher learning, as well as Minority Serving Institutions, in order to work with as many communities and researchers as possible.
- **National laboratories:** DOE oversees 17 national laboratories around the country, each of which has a longstanding relationship with its surrounding community. A majority of national laboratories have research and development programs related to carbon management. These laboratories, which are longstanding employers and key stakeholders in the advancement of carbon management technologies, can provide a sound scientific basis of carbon management projects and technologies for community discussions. See the Select National Laboratory Efforts on Carbon Management Appendix for an overview of national laboratory efforts on carbon management.

Other important stakeholders facilitating education and public engagement around carbon management include the following:

- **Unions:** Labor unions have a central role in developing the skilled workforce that will build necessary carbon management infrastructure. Unions partner with employers on joint labor-management registered apprenticeship programs to train the next generation of skilled trade workers. Unions also provide continuing education and safety training to ensure skilled workers already in the industry are prepared for carbon management jobs. Union members have also been important community leaders in areas where projects are sited, helping to answer questions about the purpose and value of the projects, while advocating for them to be developed in ways that benefit both the local workforce and other constituents.

- **Project developers**: Private sector stakeholders who are leading the way on carbon capture are also taking steps to improve public education and community engagement. Additionally, all developers applying for DOE funding and completing CBPs are devoting substantial resources toward community engagement even before their project has been selected, setting a high standard for the industry moving forward.
- **Environmental justice groups**: Environmental and social justice groups, both national and local, are important advocates for both communities. Some of these groups have raised concerns about carbon management projects. The White House Environmental Justice Advocacy Council (WHEJAC), which includes representatives from major environmental justice groups and has provided valuable guidance, has emphasized the importance of robust policy safeguards to ensure that carbon management projects are developed responsibly.[64] As the industry scales, on-going, two-way engagement with these groups and other stakeholders representing locally affected communities can support information-sharing and transparency to encourage informed dialogue about what responsible deployment looks like in each locality. In this spirit, DOE initiated a contract in 2024 with the National Academies of Science, Engineering, and Medicine to conduct a study on the safety, societal considerations, and impacts of Carbon Management.
- **Pore space owners**: Carbon management may present novel and important economic opportunities for communities to monetize CO_2 storage resources under their land. Pore space leases are estimated to provide billions of dollars of revenue both to state and local governments and to landowners; for instance, recent leases in Texas are estimated to provide $10 billion for the state's Permanent School Fund.[65] Community education as well as legal and technical assistance will be required to ensure value from CO_2 storage resources accrues fairly to landowners and local communities. DOE is currently conducting pore space valuation research, and the Bureau of Land Management has published guidance on carbon storage on federal lands.[66]
- **Finance**: Project investors and insurance companies require information about carbon management technologies, policies, regulations, and the broader market ecosystem in order to steward capital effectively towards projects.

(4) Quality Jobs and Workforce Development

The deployment of gigatonne-scale carbon management by 2050 will create and protect numerous jobs across the United States. The Carbon Management Liftoff report identified potential for around

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64 White House Environmental Justice Advisory Council Recommendations: Carbon Management Workgroup (epa.gov)

65 "Commissioner Buckingham Secures $10 Billion for Texas Students with Historic State Land Carbon Capture and Storage Leases."

66 "Bureau of Land Management Issues Guidance on Authorizing Carbon Sequestration on Public Land."

200,000-300,000 "job years"[67] to be created by 2030.[68] These jobs are primarily in the fields of raw material generation (e.g., chemicals, steel, and cement), engineering and design, construction, and operation and maintenance. Welders, electricians, metal workers, fabricators, installation, maintenance, and repair technicians and other construction and manufacturing trades workers are also required and will need to be recruited and trained to be prepared for upcoming carbon management projects.

With the right policy support, carbon management projects can lead to high-quality job creation across the United States, especially in areas with heavy concentration of fossil fuel industry today. Many of the skills and experiences of workers in fossil fuel industries can readily translate to carbon management, presenting workers in these areas with future employment opportunities. DOE is leading efforts such as the Interagency Working Group on Coal and Power Plant Communities and Economic Revitalization to support workers in these regions.

One key part of promoting quality jobs and workforce development is the CBP framework, discussed above. DOE asks project developers applying to DOE funding opportunities to engage with community and labor organizations and demonstrate how projects support quality jobs and support equitable pathways into employment for workers from groups underrepresented in the energy sector and disadvantaged communities. Of particular importance to carbon management industries are the need for workforce development, safety standards, family-sustaining wages and benefits, and empowerment, representation, and a voice on the job that support workforce continuity for project completion while contributing to enduring community benefits.

DOE also encourages proactive, bi-directional engagement with community and labor stakeholders that may be embedded in a range of formal agreements between a project developer/owner, impacted community groups, and relevant labor unions. Once projects are selected to receive DOE funding, months or years of lead time are typically required to train up a local workforce. A lack of a local workforce may put projects on a path to hiring non-local workforces with prior experience. In addition, the project-based nature of approximately 90% of the jobs created for construction of carbon management projects adds to the importance of ensuring workforce continuity. Labor agreements provide certainty to unions who can recruit apprentices knowing there will be work available for them to receive on-the-job training and continued employment upon graduation as a journey-level worker. The 45Q tax credit for carbon management has prevailing wage and apprenticeship provisions, which, if not met, mean that projects receive only 20% of the full credit. After the construction phase, labor engagement remains key to ensuring workforce continuity and worker participation in on-going training and workplace health and safety during facility operations and maintenance.

In addition to the CBP framework, DOE has multiple programs for workforce development, including:

1. **University training programs:** In November 2023, FECM released a request for information to seek input on various questions regarding workforce development efforts through new curricula on carbon management informed by community knowledge and values. Information received from this request for information may be used by FECM's University Training and Research (UTR) program to develop a pipeline of underrepresented students in the carbon management workforce, broaden the network of

[67] A "job year" is one new year of work for one person; a new construction job that lasts five years is five "job years."

[68] The Rhodium Group estimates that each million-ton direct air capture plant alone will need 278 workers for its operation, along with at least 3,000 jobs from its investment (e.g., equipment manufacturing, construction, and engineering). Larsen, J. et al. "Capturing New Jobs," Rhodium Group, 2020.

higher-education institutions with curricula focused on carbon management, and generate learning materials on how carbon management can be enhanced by incorporating the perspectives of different cultures and communities throughout the United States.

- **Diversity in workforce development**: DOE has partnerships with several Historically Black Colleges and Universities (HBCUs) and other Minority Serving Institutions (MSIs) through the HBCU-MSI program, which is one of two sub-programs under the UTR program. In January 2024, FECM announced an investment of over $17 million for university-projects involving training of students in science, technology, engineering, and mathematics and humanities disciplines. Of the 30 U.S. colleges and universities involved in these projects, 19 are designated as minority-serving institutions, including HBCUs, Tribal Colleges and Universities, Alaska Native and Native Hawaiian-Serving Institutions, Hispanic-Serving Institutions, and Asian American, Native American, and Pacific Islander-Serving Institutions. For the first time, five UTR-funded projects will establish "visiting scholar programs" involving multi-institution collaborations for student exchanges from MSIs.
- **Training students and recent graduates**: DOE hosts several student programs highlighted on DOE's science, technology, engineering, and math (STEM) webpage. Among these programs is the Mickey Leland Energy Fellowship Program (MLEF), a highly-competitive summer fellowship program where participants receive hands-on experience and are mentored by researchers from DOE and its national laboratories. Also of note is the Research Experience in Carbon Sequestration (RECS) Program, an annual intensive program where participants are immersed in classroom instruction, site visits, communications training, and hands-on field activities.
- **Registered apprenticeship and apprenticeship readiness**: Deploying new infrastructure like carbon management requires skilled trades workers. In addition to its long-standing research mission, DOE has supported registered apprenticeships to introduce training in new technologies and apprenticeship readiness programs to recruit and support workers from groups underrepresented in the skilled trades for apprenticeship completion. For instance, FECM, in collaboration with DOE's Office of Technology Transitions and ENERGYWERX established the Capacity Building for Repurposing Energy Assets initiative that will help energy communities build technical capacity and prepare their workforce to help revitalize energy systems, address environmental impacts, and tackle challenges associated with energy assets (e.g., power plants, coal mines, and oil and gas well lands) that have retired, or are slated for retirement. Among the first cohort of selected awards was a grant to the City of Beulah, North Dakota's Department of Economic Development to partner with North Dakota's Building Trades Unions, the Nueta Hidatsa Sahnish College, and Talon Metals to implement an apprenticeship readiness program.

(5) Responsible Project Development from Non-DOE Funded Projects

A final pillar of DOE's engagement with communities is FECM's Responsible Carbon Management Initiative. Released for public comment in 2023, it aims to extend the practices embodied in the CBP framework to projects funded entirely by the private sector. The initiative is aligned with guidance from the White House Council on Environmental Quality and the Justice40 initiative. It aims to recognize and encourage project developers to pursue the highest levels of safety, environmental stewardship, accountability, community engagement, labor standards, and societal benefits in carbon managementprojects. It emphasizes transparency and learning through greater data and information sharing among industry, governments, communities, and other stakeholders. Public comments were collected on a draft set of eleven principles for responsible carbon management and DOE is continuing to refine them.

5. Engage International Stakeholders

Scaling up carbon management technologies is a global challenge that requires international coordination and collaboration. FECM and DOE's Office of International Affairs have a long history of engaging with international partners to advance carbon management technology and deployment. Their strategy involves:

1. Elevating carbon management to an appropriate role in international climate policy to unlock greater national-level policy support for the field;
2. Assisting partners with building capacity and developing effective regulatory environments for carbon management in emerging markets;
3. Leveraging global capabilities, including testbeds, research networks, and research and development funding, to accelerate innovation, share learnings from commercial projects, and target funding to fill the largest innovation gaps;
4. Catalyzing concessionary finance to enable innovation and deployment globally; and
5. Promoting the development of rigorous and consistent measurement, reporting, and verification protocols, cross-border transport standards, and standards for geologic storage-based industries.

DOE's international engagement takes the form of multilateral and bilateral partnerships, as well as funding for the participation of U.S. scientists in major carbon management field projects worldwide. Bilaterally, FECM collaborates with more than 30 countries to support U.S. interests in carbon management to develop enabling environments in emerging markets, exchange information and best practices to leverage domestic investments, and facilitate responsible deployment globally.

Multilaterally, major initiatives include the following:

- **Carbon Management Challenge:** The Carbon Management Challenge is a joint effort and call to action by countries worldwide to accelerate the deployment of carbon capture, removal, use, and storage technologies. Participating countries recognize that limiting warming to 1.5°C with minimal overshoot requires a dramatic increase in the pace and scale of deployment of carbon management technologies and infrastructure.

  To date, 19 countries plus the European Commission have joined the Carbon Management Challenge, which was launched at the April 2023 Major Economies Forum, to accelerate the scale up of carbon capture, conversion, and storage and carbon dioxide removal as necessary complements to aggressive deployment of other zero-carbon technologies and energy efficiency.

  Carbon Management Challenge participants consist of national governments of countries of extraordinary diversity that encompass every region of the world, leading renewable energy producers with no fossil fuels, the largest oil and gas producers, and key developing nations—all committed to advancing projects by 2030 that are collectively capable of capturing and storing one gigatonne of CO_2 annually, which independent analysts at organizations like the International Energy Agency see as the minimum needed to be on track to meet Paris Agreement goals by mid-century.[69]

69 While not directly related to the Carbon Management Challenge, DOE is also working with international governments to develop a shared and broadly credible global framework for estimating greenhouse gas emissions emissions across the international supply chain for natural gas. This international MMRV framework for natural gas can be leveraged to maximize emissions reductions when natural gas is used in combination with carbon capture technology globally.

- **Clean Energy Ministerial Carbon Capture, Utilization, and Storage (CCUS) Initiative**: The objective of the Clean Energy Ministerial CCUS Initiative is to accelerate carbon management as a viable CO_2 mitigation option, facilitate diffusion of knowledge on technologies, regulations, and policies, and lead to strategic partnerships to accelerate both near and longer-term investment in carbon management.

  As an action-oriented platform, the Initiative does not perform analysis, but serves to bring government, industry, and the financial and investment sectors together. The Clean Energy Ministerial CCUS is co-led by the United States, represented by FECM, and consists of 15 countries.

- **Mission Innovation Carbon Dioxide Removal**: The goal of Mission Innovation Carbon Dioxide Removal is to enable carbon dioxide removal technologies to achieve a net reduction of 100 million tonnes of CO_2 per year globally by 2030. To achieve this goal, the Mission has identified innovation priorities around the enhanced understanding of local and global carbon dioxide removal potential, the advancement of research and development for carbon dioxide removal technologies, and global demonstration projects.

  Mission Innovation Carbon Dioxide Removal focuses on technological carbon dioxide removal approaches, including direct air capture, biomass with carbon dioxide removal and storage, and enhanced mineralization, as a complement to broader emissions reduction efforts. Through multilateral collaboration between its nine members, the Mission enhances the systems that lead to negative emissions through an emphasis on secure carbon dioxide storage and conversion into long-lived products.

- **CETPartnership:** FECM participates in joint research and development through the CETPartnership, which is an initiative co-funded by the European Union that brings together public and private stakeholders in the research and innovation ecosystems, from European and non-European countries and regions. The CETPartnership aims to foster transnational innovation ecosystems and overcome a fragmented global research and innovation landscape. It evolved out of the Accelerating Carbon Capture and Storage Technologies initiative.

International Energy Agency Greenhouse Gas Research and Development Programme (IEAGHG): IEAGHG funds research into the development and deployment of carbon capture and storage technologies. IEAGHG focuses on technologies that can reduce our carbon emissions and mitigate climate change. It is a not-for-profit organization, and all the work is subject to peer review ensuring that it remains impartial and unbiased.

Across this international collaboration, an important theme has begun to emerge—rather than acting as a headwind or an alternative to a transition away from traditional energy infrastructure, carbon management is emerging as an essential complement to clean and renewable energy strategies. For example, around half of the countries that have joined the Carbon Management Challenge already derive over 50% of their electricity from low- and zero-carbon sources (e.g., renewables, biomass, waste, and nuclear).

Iceland, Sweden, Norway, Kenya, Brazil, Mozambique, Denmark, Canada, Romania, and the United Kingdom, have reached 100%, 99%, 96%, 90%, 88%, 82%, 81%, 69%, 65%, and 57% shares, respectively, of low- and zero-carbon resources in their electricity mix. Denmark plans to have 90% of its electricity from wind and solar by 2030.

The United Kingdom has the largest offshore wind capacity installed in the world, outside of China. Few of these countries are net-exporters of fossil energy. As net-zero planning and implementation have progressed, carbon management has been identified as a necessary tool alongside other mitigation strategies.

Major oil and gas producers, including Saudi Arabia and the United Arab Emirates, are also investing heavily in these technologies as they plan for a market that favors low-carbon energy options. Their profitable energy sectors provide the capital needed to build a robust network of carbon management projects, often leveraging bilateral and multilateral relationships.

DOE's international engagement efforts also involve partnering with other federal agencies. For example, the U.S. Department of Commerce's Commercial Law Development Program, supported by the U.S. Department of State's Bureau of Energy Resources, provides technical assistance and commercial legal reforms in developing and post-conflict countries, including advising on carbon management regulatory systems. DOE also supports the State Department with carbon management efforts in many climate negotiations, including on the Paris Agreement negotiations.

Key Initiatives

See Figure 15 for an overview of DOE offices' programming across four carbon management use cases:

Figure 15: DOE offices' programming across key carbon management use case

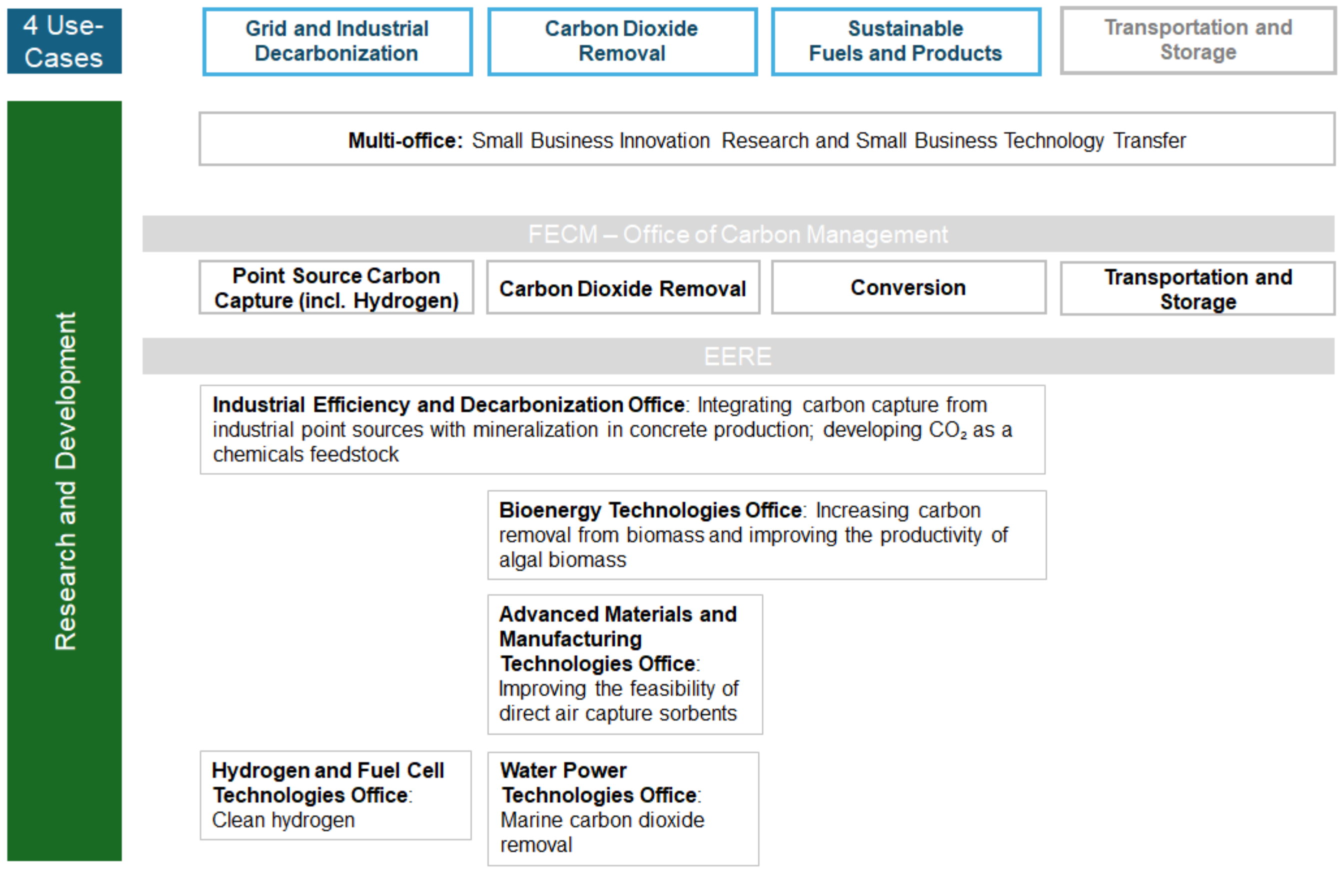
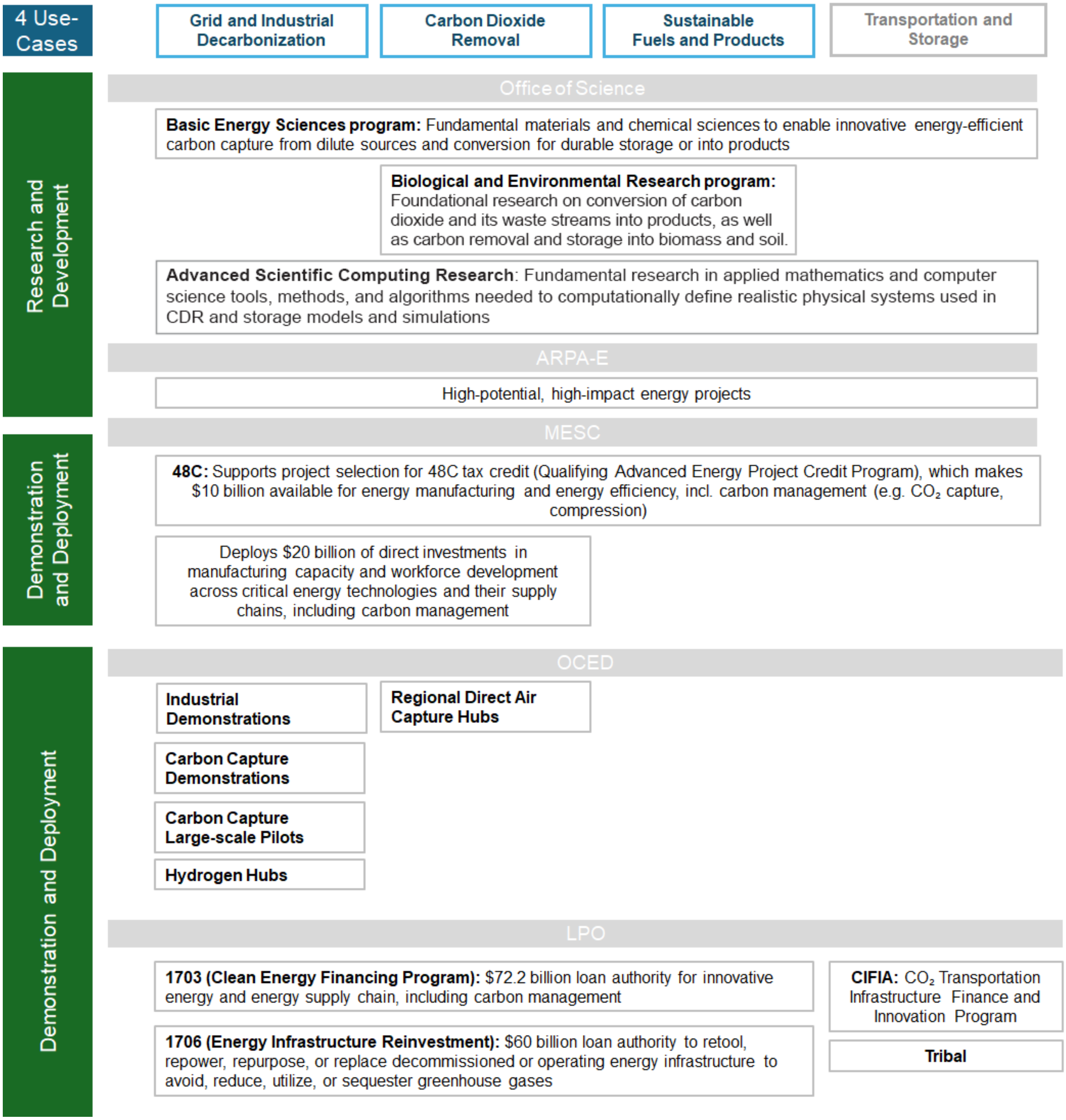
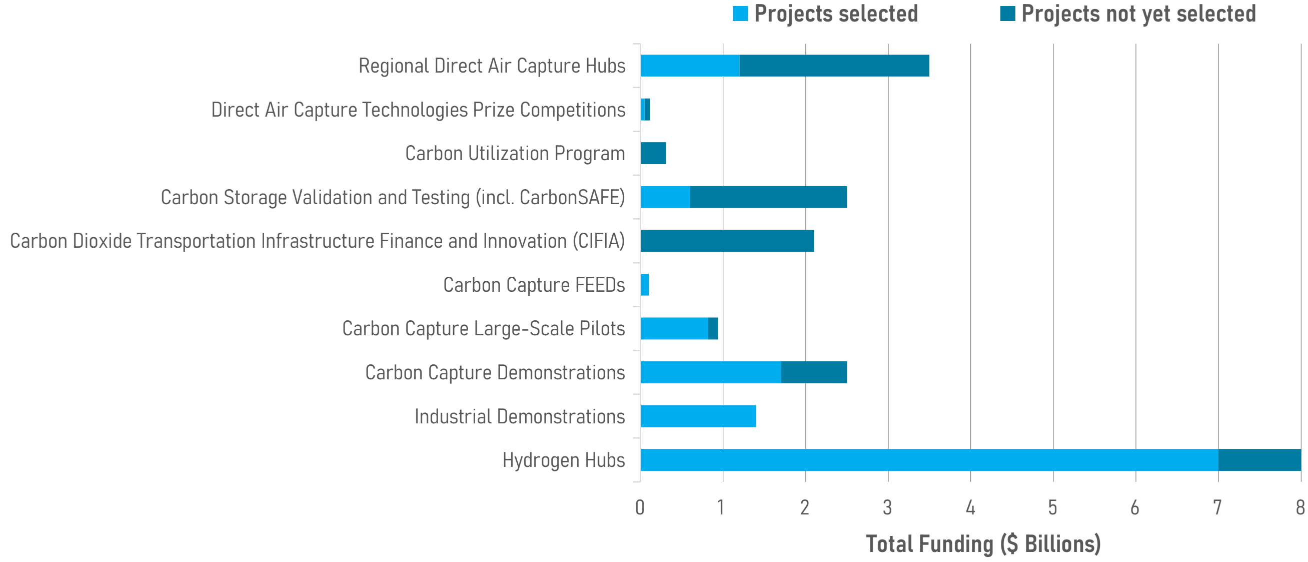


Figure 15: DOE offices' programming across key carbon management use case (continued)



Across these offices and provisions, over $12 billion in dedicated carbon management funding was appropriated by Congress in the Bipartisan Infrastructure Law to be spent between fiscal years 2022-2026, with additional related funding from Bipartisan Infrastructure Law and Inflation Reduction Act included as part of the hydrogen hubs and industrial decarbonization provisions. Of this funding, roughly half has been awarded as of April 2024.

Figure 16: DOE Bipartisan Infrastructure Law funding for carbon management projects, as of April 2024[70]



Note: Assumes 20-30% of Hydrogen Hubs and Industrial Demonstrations funding is allocated to carbon management. Does not include Base Appropriations.

The latest funding opportunities related to carbon management can be found on the following DOE webpages:

- Office of Fossil Energy and Carbon Management
- Office of Science
- Office of Energy Efficiency and Renewable Energy:
  - Industrial Efficiency and Decarbonization Office
  - Bioenergy Technologies Office
- Advanced Research Projects Agency-Energy
- Office of Clean Energy Demonstrations
- Manufacturing and Energy Supply Chains
- Loan Program Office

[70] 4 of the 7 Hydrogen Hub projects selected for negotiations include funding for carbon capture and storage, but total amount of funding for carbon capture depends on ongoing negotiations.

Conclusion

As DOE looks toward allocating the remaining Bipartisan Infrastructure Law funding and evolving its annual carbon management program, this Carbon Management Strategy will frame DOE's approach to meeting the challenge of deploying these technologies amidst considerable uncertainty.

Today, while carbon management systems like point-source capture and direct air capture have been successfully demonstrated, relying on them in the way needed to achieve a clean energy and industrial future requires significant progress across the five strategic priorities outlined:

1. Adapting them for use cases with fewest decarbonization alternatives and building innovative new technologies to further reduce costs of capture, transportation, conversion, and storage;
2. Scaling transportation and storage infrastructure;
3. Supporting the implementation of effective policy frameworks;
4. Demonstrating community, workforce, and environmental benefit; and
5. Paving the way for international adoption.

Achieving these five priorities will turn carbon management into a meaningful option for climate mitigation at scale. This Strategy will be re-evaluated and updated as the industry matures and as our decarbonization picture becomes clearer over the coming decades. As the projects being designed today become operational facilities, both their potential and their limitations will become more tangible. Instead of 18 operating facilities, there will be dozens. The goal is that around the United States, emitters, workers, and communities will be able to point to them and attest to the CO_2 they removed, and the jobs they created.

Along the way, these technologies will continue to complement the other essential tools required to meet the climate challenge. Carbon management is essential for reducing emissions as these other decarbonization approaches scale. Across both Intergovernmental Panel on Climate Change scenario models and the very real climate impacts felt due to CO_2 already emitted, the evidence is overwhelming that carbon management is needed.

Appendices

Rationale and Key Initiatives for Priority Use Cases

Below is a **non-exhaustive** overview of some of the key carbon management use cases DOE is focused on in the near-term.

Carbon Dioxide Removal

Carbon dioxide removal is needed to address residual emissions from sectors such as agriculture and long-haul transport, as well as the legacy emissions that remain in the atmosphere. While there is a wide range of estimates of how much carbon dioxide removal will be needed, developing and scaling methods of removing carbon from the atmosphere and storing it permanently must begin.

It also remains to be seen which carbon dioxide removal pathways, including biogenic, geochemical, and chemical, will scale at different paces and in different locations. The "Roads to Removal" report led by Lawrence Livermore National Laboratory outlines which pathways are likely best suited to each region in the United States. What does seem clear, however, is that scaling all three of these pathways will be essential to meet the climate challenge.

Each pathway is constrained by different factors. For example, biogenic carbon dioxide removal is constrained by access to sustainable biomass, geochemical carbon dioxide removal is constrained by access to alkaline materials, and chemical-based carbon dioxide removal, like direct air capture, is constrained by availability of low-carbon energy.[71] Given these limitations, and the vast scale at which CO2 must be removed, all these methods will be required, regardless of the pace of the broader energy transition.

Furthermore, carbon dioxide removal will require novel policies and safeguards to ensure that it scales as rapidly as needed, but in a way that avoids (1) substituting for direct emissions reductions and (2) negatively impacts communities and the environment. To that end, DOE is working in parallel to develop technologies for potential compliance policies in the future.

A comprehensive strategy of the full carbon management value chain is forthcoming in DOE's Carbon Dioxide Removal Task Force Report to Congress as mandated in the USE IT Act of 2020.

Carbon Dioxide Removal, Research and Development: DOE's Carbon Negative Shot is advancing innovation in carbon dioxide removal pathways that will capture CO_2 from the atmosphere and store it at gigaton scales for less than $100/net metric ton of CO_2-equivalent.

71 "Applied Innovation Roadmap for Carbon Dioxide Removal," Rocky Mountain Institute, 2023

Carbon Dioxide Removal, Demonstration: One promising carbon dioxide removal approach is direct air capture. With funding from the Bipartisan Infrastructure Law for regional direct air capture hubs, DOE has selected two commercial-scale direct air capture facilities to date, with additional opportunities expected to follow in the coming years. DOE also believes it is imperative to demonstrate the full range of carbon dioxide removal approaches that show promise from our research and development portfolio.

Developing the Market, Procurement: DOE considers government procurement[72] an important potential pathway for funding carbon dioxide removal at scale in the future. To pave the way, DOE is piloting the world's first government procurement program for carbon dioxide removal with the goal of selecting up to ten suppliers from whom to purchase permanent removals. This program will provide transparency for the measurement, reporting, and verification requirements needed to deliver carbon dioxide removal credits across a range of solutions, which will help to establish standards for the voluntary carbon dioxide removal credit purchasing market and for future government programs. DOE will also work with the private sector to address barriers to scaling voluntary carbon dioxide removal credit purchases, via the Voluntary Carbon Dioxide Removal Purchase Challenge, which will likely prove a critical revenue source for carbon dioxide removal developers in the near-term.

Measurement, Reporting, and Verification (MRV): DOE is also focused on preparing these technologies to ensure carbon dioxide removal can be measured in a transparent and robust manner across solution pathways. DOE is investing into MRV technologies (e.g., remote sensors), as well as working to define the protocols and frameworks for MRV in each carbon dioxide removal pathway.

Community Engagement: Carbon removal facilities can both be located in geographies that have large fossil fuel workforces today, as well as in areas with fewer existing emissions sources. This provides opportunities and challenges to ensure that projects avoid additional pollution in heavy emissions areas to date, while also enabling a transition of fossil fuel workers into high-quality jobs aligned with net-zero goals.

Industrial Decarbonization

Also see: FECM Industrial Decarbonization RFI, Industrial Decarbonization Liftoff Report, and Industrial IEDO Industrial Decarbonization RFI, and Industrial Decarbonization Roadmap.

Carbon management is one of the four key tools in the broader industrial decarbonization toolkit. The others include efficiency, electrification, and low-carbon fuels, feedstocks, and energy sources. The role that carbon management plays alongside these other pillars will vary by sector and emissions source, and it will depend heavily on how quickly other decarbonization approaches become deployable. It will also be critical for carbon management projects to help reduce cumulative burden of environmental pollution in existing industrial clusters, while also enabling the opportunities for high-quality job creation for workers in industrial communities today.

[72] There are many potential models that carbon dioxide removal could come to resemble over the long term. Government procurement, in which governments would purchase quotas of removed carbon based upon their jurisdiction's emissions, is one potential model.

The following use cases reflect priority sectors for demonstration and cost-reductions in the near-term. These priorities are based upon both lack of deployable alternatives, and total CO_2 emissions at stake.

DOE Focus: Cement Production

Cement is an industrial sector with few foreseeable paths to zero carbon emissions that do not include carbon capture for the indefinite future. Electrification, efficiency measures, and other interventions, such as supplementary cementitious materials, have potential to decrease cement emissions in the near-term. However, achieving net-zero emissions will rely either on alternative cement chemistries that have yet to be proven at scale or through the addition of carbon capture to the existing production process.[73]

This is largely because 50% of CO_2 emissions are intrinsic to the calcination process itself; either these emissions need to be captured or moving to alternative fundamental chemistries to avoid CO_2 emissions associated with calcium carbonate processing. While many promising efforts are underway to develop novel cement chemistries or processing pathways and must be accelerated, carbon management provides a critical bridge to decarbonize the industry as these novel approaches develop, and carbon capture retrofits will prove an essential strategy for decarbonizing existing assets with long remaining operational lifetimes.

Today, carbon capture for cement is unlikely to be economically viable with the 45Q tax credit alone.[74] One central goal of DOE's research, pilots, and demonstration programs is therefore to bring down these costs such that cement carbon capture projects can become economically viable and begin construction before 2033, which is the current requirement in 45Q.

To this end, FECM is currently funding a small pilot using cryogenic separation at a cement plant in Missouri, and have selected two other cement plants for small pilots of other technologies. In March 2024, OCED announced two projects selected to negotiate for up to $500 million in support of cement carbon capture and storage projects in Indiana and California through the Industrial Demonstrations Program.

In parallel, DOE is funding research and development into alternative capture methods (e.g., oxyfuel capture, capturing just process emissions off pre-calciner/calciner), to test whether these methods could prove more cost-effective than amine processes.[75] Theoretically, these approaches are more efficient and/or capture higher-purity streams within the production process. In addition to the two OCED awards for cement carbon capture projects, four cement decarbonization projects were selected that involve alternative chemistries and other decarbonization technologies beyond carbon capture. Figure 17 shows how the two cement carbon capture projects fit into DOE's broader portfolio of six cement decarbonization projects, which involve other strategies beyond carbon management to reduce industry emissions.

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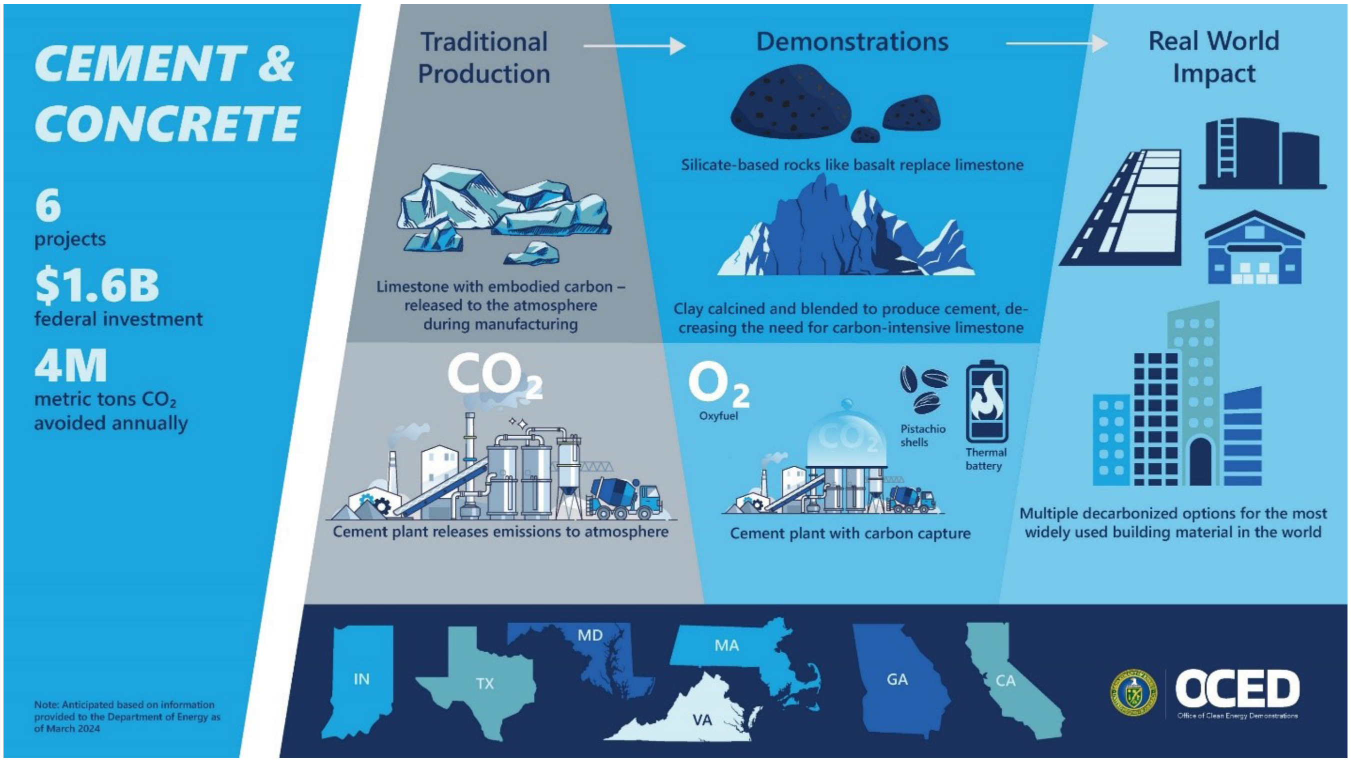
[73] PCA, GCCA, and McKinsey models suggest carbon capture might be needed to drive approximately 50% of abatement (reviewed in Carbon Management Liftoff report, Section 3b)

[74] Modelling in Carbon Management Liftoff Report found the gap is still approximately $25-55 per tonne of cement, but outlook has worsened in the near-term beyond this estimate because of the increased cost of capital due to inflation and interest rates

[75] Industrial Decarbonization Roadmap, September 2022.

Figure 17: OCED selected two carbon capture projects out of six total cement decarbonization projects in line with DOE's commitment to pursue carbon management as part of a broader portfolio of decarbonization approaches.



As the United States develops more cost-effective approaches to carbon capture at cement plants, knowledge-sharing internationally will be an important outcome. Today, 98% of global cement production and emissions occurs outside of the United States.[76] Therefore, a key strategic priority for cement is to foster technical knowledge sharing and export low-cost carbon capture business models. DOE's international engagement programs are continuing to focus on facilitating partnerships required to scale these technologies where they are needed, including in Europe and Asia.

DOE Focus: Pulp and Paper

The application of carbon capture to the pulp and paper industry offers a great opportunity to deeply decarbonize and potentially achieve net-negative CO_2 emissions. Furthermore, recent advancements in the electrification of the calcination process, which is a core step in the pulp mill and one of the main sources of fossil-fuel based CO_2 emissions in the mill, offer potential to generate higher concentration CO_2 stream and reduce the cost of carbon capture in the pulp and paper industry.

OCED recently selected Vicksburg Containerboard Mill in Vicksburg, Mississippi for a large-scale carbon capture pilot project. DOE's Industrial Efficiency and Decarbonization Office also funded a few projects focused on the novel paper and wood drying technologies and innovative pulping and paper forming technologies.

[76] Mineral Commodity Summaries, U.S. Geological Survey, January 2022

DOE Focus: Glass

Glass manufacturing is energy- and emissions-intensive as it involves high-temperature processes such as glass melting, where fossil fuels (e.g., natural gas, coal, or oil) are combusted to generate heat required to melt raw materials. Additionally, a portion of the CO_2 emissions in the glass industry are inherent to their processes because of the use of carbonated raw materials such as soda ash (e.g., sodium carbonate) and limestone (e.g., calcium carbonate).

Carbon capture is expected to play a significant role to achieve net-zero emissions in the glass industry because CO_2 emissions in the glass industry cannot be addressed by non-carbon capture efforts alone (e.g., electrification, efficiency and process improvements, fuel switching, and recycle and reuse). There are also opportunities for carbon capture throughout the glass value chain, such as in the trona mining industry in the United States.[77]

While carbon management has been explored and deployed in power generation and various industrial sectors, including cement production, and steel manufacturing, its application in the glass industry has been limited. To date, DOE has only funded one project focused on an engineering-scale testing of carbon capture technology at the Vitro glass facility in Pennsylvania. However, DOE's Advanced Materials and Manufacturing Technologies Office and Industrial Efficiency and Decarbonization Office have funded several applied research, development, and pilot-scale technology validation and demonstration projects aimed at reducing energy usage, improving process optimization and materials efficiency, and advancing manufacturing techniques in several industrial sectors, which could indirectly benefit the glass industry in reducing greenhouse gas emissions.

Clean Fuels and Products

DOE Focus: Decarbonizing Existing Petrochemical Facilities and Oil Refineries

Carbon capture coupled to CO_2 conversion and/or storage offers a significant opportunity to decarbonize existing chemical production in a cost-effective manner while alternative greenfield strategies scale. Carbon capture can offer a low-cost approach for abating several emissions streams on refineries.

Petrochemicals and Refining: Petroleum refining and petrochemicals manufacturing are the primary emitters of CO2 in the hydrocarbon processing industry. Other significant industrial CO_2 emitters include natural gas processing facilities associated with oil and gas production and downstream chemical manufacturers that use the basic commodity chemicals from petrochemicals manufacturing (primarily, ethylene, propylene, butadiene, benzene, toluene, xylene, and methanol) and convert them into other commercial chemicals, polymers, and plastics products. The petrochemicals and refining sectors account for about 38% of all U.S. industrial energy-related CO_2 emissions and are major contributors to overall U.S. CO_2 emissions.

Oil Refining: More than 75% of CO_2 emissions from oil refining are associated with heat and electricity generation. These energy-related emissions can potentially be addressed using non-carbon capture

[77] Holly Krutka: Wyoming Can Still Lead the Way For Energy-Driven Economic Development | Your Wyoming News Source

decarbonization solutions such as efficiency and process improvements, low-carbon electricity, and clean hydrogen. Efficiency and process improvement measures are either already implemented or being actively pursued across the oil refining industry. However, deep-decarbonization of this industry will require an "all of the above" strategy that includes the use of low-carbon electricity, hydrogen, and carbon capture and storage. Importantly refineries are disproportionately located in low-income communities of color, produce significant local pollution and environmental health burdens.[78] Decarbonizing presents an opportunity to abate criteria air pollutants and improve community engagement.[79]

Clean hydrogen and low-carbon electricity are not readily available today at the scale needed by this sector. Since refineries already co-produce hydrogen and electricity for plant operations from natural gas and process off gases, some refiners are moving forward with the use of carbon capture and storage in these processes to produce hydrogen and electricity. In the near- to mid-term, carbon capture and storage can play a critical role to address the CO_2 emissions associated with electricity and hydrogen production in oil refining.

Roughly 80% of the life-cycle CO_2 emissions from oil refining come from the end-use combustion of the transportation fuels. To meet net-zero emissions by 2050, it will be necessary to displace these fossil fuels by either electric, hydrogen, or renewable fuels. These changes have prompted a number of U.S. refiners to either shutter existing refineries or to repurpose them to produce renewable jet and diesel fuels. For example, DOE funded a project with the Phillips 66 refinery in California to capture CO_2 from a hydrogen plant. Projects like these provide a path forward for refiners to transition operations while addressing life cycle emissions from their fuel products.

Additionally, FECM has funded several FEED studies focused on retrofitting hydrogen production facilities (e.g., stream methane reforming and autothermal reforming) associated with refinery operations with commercial-scale carbon capture technologies.

OCED recently selected Delek US Holdings to lead a carbon capture pilot at Big Spring Refinery in Texas that aims to capture 145,000 metric tons of CO_2 per year from the refinery's fluidized catalytic cracking unit.

Petrochemicals: Petrochemicals manufacturing facilities are comparable to petroleum refineries in their size and complexity. They include multiple CO_2 point sources and require hydrogen for the conversion of petroleum refining intermediates into basic commodity chemicals (primarily, ethylene, propylene, butadiene, benzene, toluene, xylene, and methanol). The point sources of CO_2 are often from disparate flue-gas streams in a facility, such as from process heaters, catalytic crackers, and reformers. Carbon capture and storage is critical to address these process-related CO_2 emissions as alternative fuels and electrification options for decarbonization develop. Petrochemical manufacturers are also disproportionately located in low-income and communities of color, decarbonizing this sector present important opportunities to address co-pollutants and improve environmental equity.[80]

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78 Chemical Exposures, Health, and Environmental Justice in Communities Living on the Fenceline of Industry | Current Environmental Health Reports (springer.com)

79 Aligning Industrial Decarbonization Technologies with Pollution Reduction Goals to Increase Community Benefits | ACEEE

80 Industrial Decarbonization - Pathways to Commercial Liftoff (energy.gov)

Similar to oil refining, a vast majority of CO_2 emissions in the petrochemicals production are associated with heat and electricity generation where carbon capture and storage can play a significant role in the near- to mid-term until other technologies including low-carbon electricity and clean hydrogen infrastructure are scaled and become economical. Alternative options such as the use of hydrogen, biofuels, bio-based feedstocks, and recycled feedstocks are gaining attention. The industry also faces the dual task of eliminating waste plastics pollution, which in addition to local environmental pollution negatively impacts the climate.[81]

Recycling of these plastics would have significant impact on reducing CO_2 emissions by reducing emissions along the entire supply chain from raw material extraction and upstream processing and transport. Increased use of biofuels can help reduce energy-related CO_2 emissions, but biofuels are likely to be leveraged first in other high-priority use cases, including transportation in the near-term. The use of bio-based or recycled feedstocks would still produce process-related CO_2 emissions.

Steam methane reforming and autothermal reforming of methane is widely used to produce the hydrogen required for conversion of petroleum refining intermediates into basic commodity chemicals, which are primarily ethylene, propylene, butadiene, benzene, toluene, xylene, and methanol. The flue-gas streams from steam methane reforming and autothermal reforming contain relatively high-concentration of CO_2 (greater than 25%) and several carbon capture and storage projects are already being actively pursued to capture and store CO_2 from these sources. Petrochemicals manufacturing also includes burning of natural gas or tail gas, which contains hydrogen, carbon monoxide, CO_2, nitrogen, and hydrocarbons, in furnaces to produce the heat required for process heaters, catalytic crackers and reformers. The flue-gas streams contain low- concentration of CO_2. Carbon capture and storage for dilute CO_2 streams has not been adequately tested and scaled, but is critical to achieve facility-wide deep decarbonization of the petrochemicals industry.

Additional carbon capture and storage demonstrations on high-concentration CO_2 streams from steam methane reforming and autothermal reforming flue gas will help achieve further performance and cost improvements of capture technologies and make carbon capture and storage projects economical. This coupled with development and build-out of CO_2 pipeline and storage infrastructure can enable facility-wide deployment of carbon capture and storage on both high-concentration and dilute CO_2 flue-gas streams in the petrochemicals sector.

FECM has funded several projects focused on performing FEED studies for retrofitting steam methane reforming and autothermal reforming hydrogen production facilities with commercial-scale carbon capture systems. These projects aim to explore both amine solvents and non-amine capture technologies, including sorbents and cryogenic processes, to further increase carbon capture efficiencies to greater than 95% with minimum impact on the cost of CO_2 capture and hydrogen produced.

OCED recently announced the selection of a number of projects under the Regional Clean Hydrogen Hubs Program focused on carbon capture and sequestration from the steam methane reforming and autothermal reforming facilities for hydrogen production.

81 Industrial Decarbonization - Pathways to Commercial Liftoff (energy.gov)

Downstream Commodity, Performance, and Fine Chemicals: The total CO_2 emissions from downstream manufacturers of chemical products are much smaller than those directly from the manufacturing of the basic commodity petrochemicals discussed above. These manufacturers are also seeking solutions for decarbonizing their facilities but face a different set of challenges due to the smaller amounts of CO_2 being emitted and the distributed nature of these facilities. However, the same decarbonization measures still apply.

At this point in time, the research and development space for carbon capture and storage is less explored than for refining and petrochemicals. Cost reduction at smaller scales through process intensification and modularization, coupled with alternative modes of transporting CO_2 are all possible research, development, and demonstration targets.

Natural Gas Processing: The application of carbon capture and storage to upstream natural gas processing is more advanced and commercial than for other parts of the hydrocarbon processing industry supply-chain. This is a result of several factors, such as familiarity with the use of CO_2 separation process required for well-head gas streams, which also contain CO_2 that must be removed to meet fuel and pipeline specifications. In addition, these plants are usually located in oil and gas production areas and may have access to CO_2 storage.

Numerous carbon capture and storage projects are in planning, design, or under construction in North America by private sector. DOE does not have any carbon capture and storage projects for natural gas processing in its portfolio.

Necessary: CO_2 Conversion to Building Materials, Chemicals, and Fuels: Captured CO_2 can be a valuable feedstock and finding ways to use CO_2 instead of storing it underground can make carbon capture more economically viable, particularly for smaller emissions streams that may be farther from geologic storage options. DOE is exploring ways to use CO_2 as a feedstock for other products.

In this line of research, there is an important distinction between using CO_2 to make a long-lived product, which essentially stores the CO_2, and using v to make fuels. From a climate standpoint, conversion to long-lived products is more directly impactful because it prevents captured fossil carbon from ever reaching the atmosphere or removes captured or biogenic carbon from the atmosphere. However, recycling CO_2 into fuels and short-lived products is beneficial because it reduces the need to use new fossil resources to produce them. Rigorous life-cycle assessments are required to ensure that the energy-intensive processes required to react CO_2 with hydrogen (as well as any indirect market impacts of the CO_2 converted products) do not negate the benefit. DOE is working to continually improve the measurement, reporting and verification technologies and life-cycle assessment models required to design and implement robust regulations around these timescales, especially in the context of claiming the 45Q and the 40B Sustainable Aviation Fuel tax credit. Similar work will also be carried out to credit climate smart agriculture practices in the 45Z Clean Fuel Production Credit.

DOE is focusing on CO_2 conversion for building materials, which is a particularly attractive utilization pathway because of its durability to store CO_2 and its low energy-intensity. CO_2 conversion has multiple approaches, such as the CO_2 can be mixed with concrete to reduce the amount of cement required as an input, which is the part of concrete with the largest carbon footprint. CO_2 can also be reacted with waste streams such as iron slag contributing to waste management. Through research and development DOE is supporting the development of these pathways, as well as providing up to $100 million for the Utilization and Procurement Grant Program for the purchase of carbon utilization products, including building materials.

Another area of focus for DOE is reducing the use of petroleum-based feedstocks by replacing them with waste CO_2 sources. Although converting CO_2 to chemicals and fuels is itself an energy-intensive process, it has the potential to significantly reduce the negative environmental and health impacts associated with petroleum refining. For example, petroleum-based chemicals that may be able to be made with CO_2 instead include polymers, other building block, and specialty chemicals that are inputs to plastics and other products.[82] Demonstrations from pilot to commercial-scale are emerging for chemicals, including methanol, oxalic acid, and ethylene glycol, and earlier-stage research is focused reactive capture approaches that convert emissions directly to value added products. Rigorous life-cycle assessments are required to ensure that the energy-intensive processes required for CO_2-based chemicals and fuels and the converted CO_2 product market impacts do not negate their climate impact.

Necessary: Low-Carbon Hydrogen as a Foundation for Clustered Infrastructure: Hydrogen is expected to play an important role in the decarbonization of some industrial processes and fuels. In line with DOE's National Clean Hydrogen Strategy, DOE has funded seven hydrogen hubs, which will produce hydrogen with a variety of processes, including fossil fuels with carbon capture (sometimes called "blue hydrogen").

Siting these hydrogen hubs in centers of high-density industrial activity enables them to serve as a foundation for clustered carbon management infrastructure. High capture rates (above 95%) and very low upstream methane emissions will be critical for hydrogen produced from natural gas with carbon capture to achieve sufficient life-cycle emissions reductions. Shared CO_2 transportation and storage infrastructure built nearby for hydrogen hubs will create economies of scale and enable the most cost-effective decarbonization options for other industrial sectors to emerge in the future. This approach will also prevent transport and storage infrastructure from becoming stranded assets in cases where hydrogen production from natural gas with carbon capture and storage may not make sense in the long term.

Additionally, carbon capture is essential for decarbonizing existing hydrogen production. Today, hydrogen has use cases that include ammonia fertilizer production. While ammonia is primarily used for fertilizer, its potential as a hydrogen carrier for decarbonizing hard-to-abate industries like shipping (alongside other fuels like methanol produced from clean hydrogen) has become a focus of research in recent years—suggesting the importance of decarbonizing its production will only grow. As with all emerging clean energy technologies, responsible deployment should include additional research and analysis to ensure negative impacts to environmental and human health are avoided.

With the 45Q tax credit, carbon capture for ammonia production from natural gas is already economically viable, and some producers have already launched commercial-scale projects. This is because ammonia's unique production process using natural gas and nitrogen is emissions-intensive, and the purity of the emissions streams is high and the cost of capture relatively low.

Given the strong economics of this use case today, DOE's investment in the development of carbon capture for ammonia production has focused primarily on developing storage resources nearby these capture projects, such as the Wabash Valley Resources ammonia production site in Indiana. There are currently no ammonia projects in DOE's funded portfolio, but there are a number of ammonia projects undergoing the review process with LPO, which funds more commercially ready projects.

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[82] Potential chemical products include one-carbon (C1) (e.g. methanol, formic acid), two-carbon (C2) (e.g. ethylene), multi- carbon (C2+) hydrocarbons (carboxylates), polymers, and polymer precursors. Potential conversion technologies include electrochemical, thermochemical, and biological pathways.

Grid Decarbonization

Necessary: Newest fossil power retrofits: The U.S. mid-century strategy forecasts that fossil fuels with carbon capture are likely important in 2050, depending on the scaling of other clean energy sources. While the 2050 picture is not yet clear, it is particularly important to develop carbon capture for the newer natural gas power units in the United States fleet as a source of reliable, clean firm electricity as other clean alternatives scale.

In addition, there is significant new coal power capacity around the world that may not be feasible to abate without carbon management as quickly as is needed to meet climate goals. Developing coal power carbon capture retrofits here in the U.S. will help the technology become more feasible to deploy in places where replacement with other clean energy sources proves infeasible.

At the same time, there is global ambition to work towards the phaseout of unabated fossil fuels power generation, so a strategic focus in this sector is to ensure that carbon capture does not lock in older fossil infrastructure that might otherwise be phased out in favor of other clean alternatives—some of which are emerging as cheaper and healthier for some communities, especially those that have born disproportionate pollution from existing fossil fuel power generation.

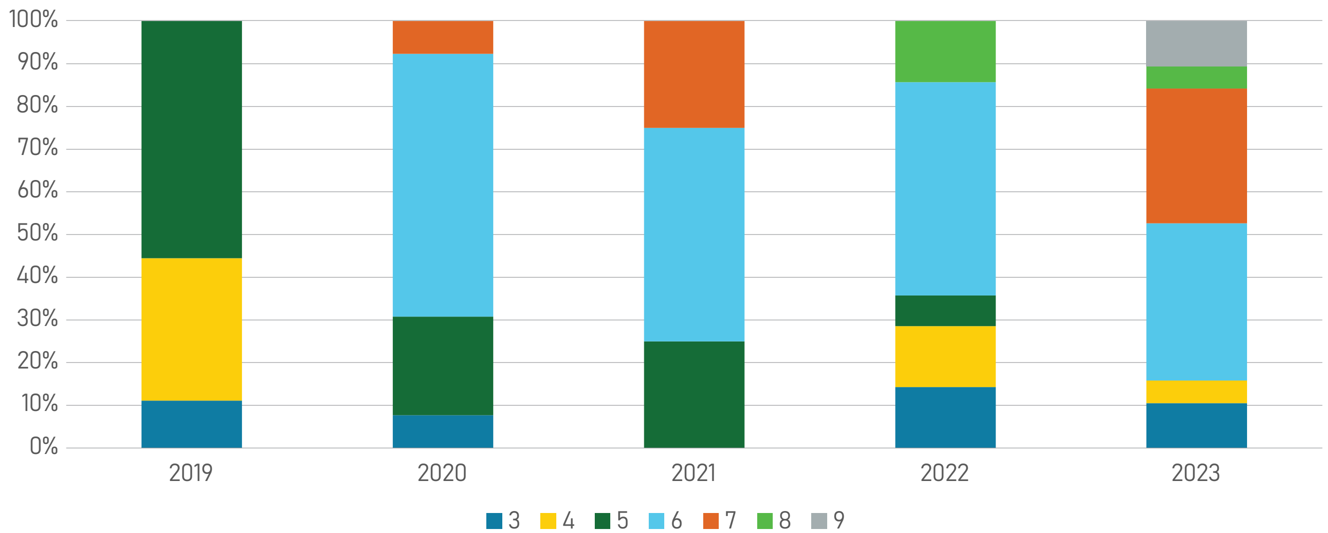
DOE's strategic focus for deployment of carbon capture in this sector is therefore newer fossil generation infrastructure, with the greatest ability to provide clean, dispatchable decarbonized power in the near-term, and with applicability in a global context. Carbon capture retrofits on newer fossil power plants are considered an important step toward both reducing emissions and developing a diverse portfolio of reliable, domestically produced, low-carbon energy sources, which is important for national energy security.

Budget and Funding Trends

In line with the priorities outlined in this Strategy, as well as the mandates of Congressional provisions, the following shifts have occurred in DOE's allocation of funding over the last several years.

Shift to funding more mature carbon capture projects: In 2021-2024, DOE's funding has shifted toward funding technologies considered to be at a higher "technology readiness level".[83] This shift is the result of progress in readying lab-scale technologies, such as direct air capture and point-source capture for cement, for pilot and demonstration at larger scales. It is also the result of Bipartisan Infrastructure Law provisions that made funding available for cost-sharing cooperative agreements and loan guarantees for larger scale project development.

Figure 18: DOE carbon management funded projects by technology readiness level, 2019-2023



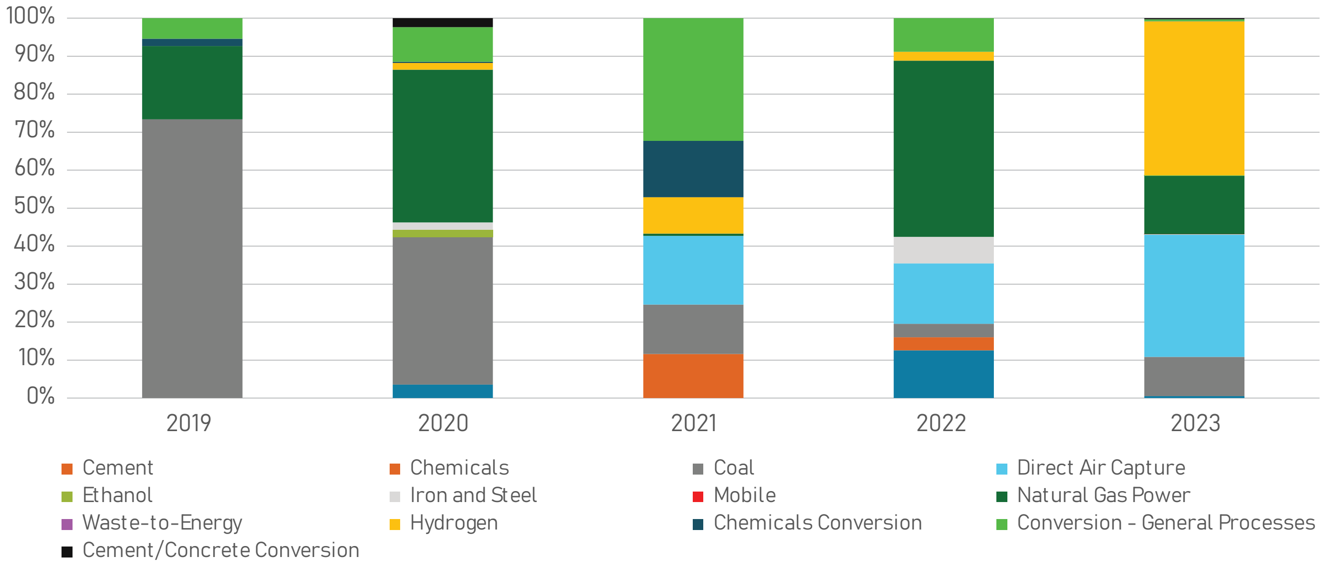
Note: Assumes OCED selected projects are awarded

Shift toward carbon capture projects on lower-concentration emissions sources: One of the primary cost-drivers of carbon capture technologies is the concentration of CO_2 in the flue gas. A number of industrial processes yield such high-purity streams of CO_2 that technologies need to only add basic filtration and compression before transporting and storing the carbon; other processes, such as cement production, yield much lower-concentration emissions streams and require much more energy and equipment to capture the CO_2.

Decades of DOE investments in carbon capture for these higher-purity streams led to improved performance and costs for those cases—such that with the revision of the 45Q tax credit, many of these high-purity capture opportunities became economically viable for the first time. While some lower-purity emissions sources in industrial and power applications are economic with 45Q credits alone, many key use cases are not economic without additional innovation support. DOE's focus has shifted to these lower-purity emissions sources which require further support to become commercially viable.

[83] The Technology Readiness Level (TRL) Scale is a framework for evaluating technology maturity that was pioneered by the National Aeronautics and Space Administration (NASA) in the 1980s. TRL indicates the maturity of a given technology.

Figure 19: DOE carbon management funding commitments by industrial sector, 2019-2023



Note: Assumes OCED selected projects are awarded

Shift toward carbon dioxide removal: While DOE's carbon management research was historically focused on point-source carbon capture, it shifted to include carbon dioxide removal, which includes synthetic, biogenic, and geochemical pathways. Carbon dioxide removal has become a growing focus within the global climate community as it becomes evident that even the existing levels of CO_2 in the atmosphere are enough to cause significant damage.

Figure 20: DOE carbon management funding commitments by use case, 2019-2023

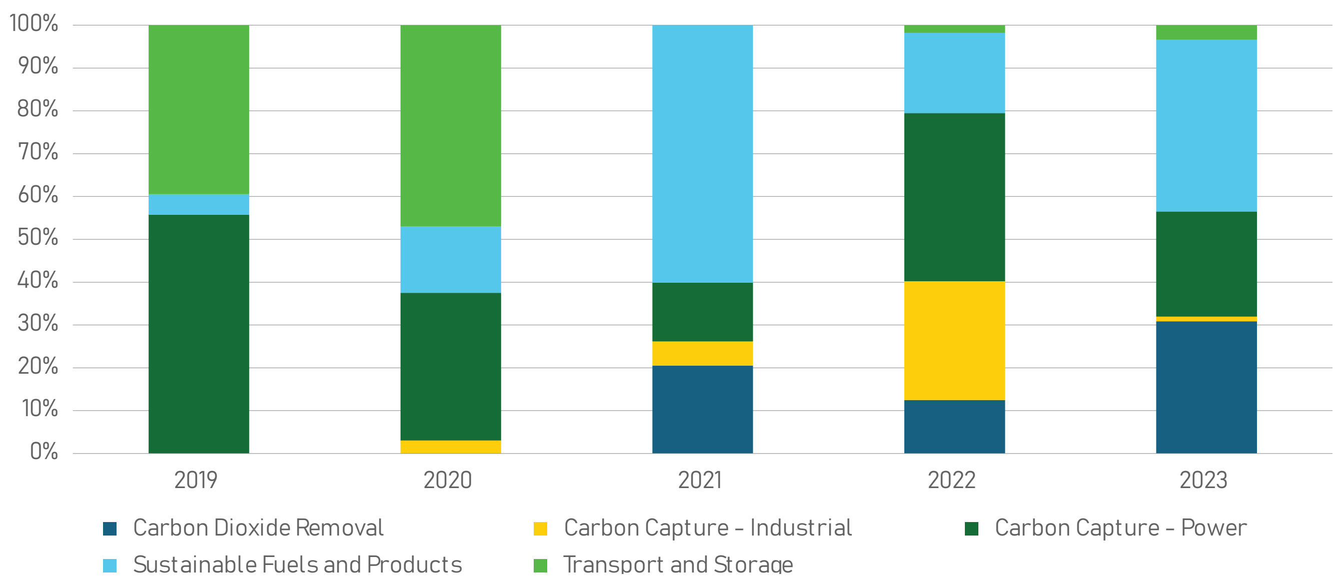


Figure 21: Number of DOE projects selected or awarded (January 2022-March 2024) and non-DOE funded projects

Number of DOE Projects Selected or Awarded 2022-March 2024									Non-DOE Funded Projects
Use-case	Sector/Source	Pre-FEED		FEED studies		Pilots		Demos	Commercial in U.S.
		Base (capture only)	BIL/IRA (inte-grated)	Base (capture only)	BIL/IRA (inte-grated)	Base (3kta or < 10 MW)	BIL/IRA (75+kta or 25+ MW)	BIL/IRA	Operational
1 Carbon Dioxide Removal	Direct Air Capture with Storage							2	1
	Biomass Carbon Removal								
	Enhanced Weathering								
	Marine Carbon Dioxide Removal								
2 Industrial Decarbonization	Cement	2		3	2	3		2	
	Hydrogen/Ammonia/Fertilizers	5		3		1		1	5
	Refining and Petrochemical						1		
	Aluminum								
	Glass					1			
	Lime								
	Pulp and Paper						1		
	Iron/Steel	1		1		2			
	Natural Gas Processing								5
	Liquefied Natural Gas								
3 Sustainable Fuels and Products	Ethanol								5
	CO_2 Conversion for Concrete								
	CO_2 Conversion for Chemicals							3	1
	CO_2 Conversion for Fuels								
4 Grid Decarbonization	Natural Gas Power	0		10	2	18	1	2	
	Coal Power	3		8	3	23	1	1	1
	Waste to Energy								

Case Study: Relevant Advanced Research Projects Agency-Energy (ARPA-E) Funding Programs

In 2019, ARPA-E launched the FLEXible Carbon Capture and Storage (FLECCS) program to develop point source carbon capture and storage technologies that enable power generators to be responsive to grid conditions in a high-variable renewable energy penetration environment. Phase 1 of the program awarded 12 projects a total of $11.5 million with six projects continuing into Phase 2 for a total of $33 million.

In addition, ARPA-E programs in CO_2 utilization from atmospheric sources have included:

- Harnessing Emissions into Structures Taking Inputs from the Atmosphere (HESTIA) to develop carbon-negative building materials using a wide-range of feedstocks and to transform residential and commercial buildings into net carbon storage structures. 17 projects were selected for a total of $39 million in addition to $5 million committed to support life-cycle analysis development for the program.
- Energy and Carbon Optimized Synthesis for the Bioeconomy (ECOSynBio), a $35 million program consisting of 15 projects to investigate using synthetic biology and renewable electricity to enable fully carbon-optimized renewable fuels and chemical syntheses with maximum carbon and resource efficiency.
- Mining Innovations for Negative Emissions Resources (MINER) to investigate CO_2 mineralization routes to improve mineral yield while decreasing the required energy, and subsequent emissions, to mine and extract energy-relevant minerals by investigating the potential of CO_2-reactive ores to unlock net-zero or net-negative emission technologies. 16 projects were selected for a total of $39 million.
- The Sensing Exports of Anthropogenic Carbon through Ocean Observation (SEA-CO_2), a $36 million program consisting of 11 projects to develop new chemical sensing and carbon flux modeling technologies to enable enhanced monitoring, reporting, and verification techniques necessary to establish the commercial value of ocean-based carbon dioxide removal.
- The OPEN 2021 program has funded a direct ocean CO_2 capture program from UCLA (Equatic), currently developing large scale demonstration units with private funding, and a program from UCSB on seaweed biomass sinking focused on basic science.
- ARPA-E's Exploratory Topic program has funded CAPTURA's direct ocean CO_2 capture program which is currently developing large scale demonstrations units with private funding

New funding for transport and storage infrastructure: As large-scale carbon capture projects come online, the need for transportation and storage infrastructure arises. The Bipartisan Infrastructure Law provisions gave DOE capacity to fund these commercial-scale projects for the first time. For transport, $2.1 billion was authorized for loans and grants, $100 million for front-end engineering design studies, and additional budget in annual base appropriations for pre-front-end engineering design studies for multimodal transport hubs. $2.5 billion of new funding became available for developing storage. In addition, DOE is continuing to evolve its base appropriations funding for CO_2 storage to support basin-scale management of geologic storage, which will become increasingly important as multiple geologic storage developers begin storing CO_2 in the same storage basin.

Life Cycle Assessment

Life cycle assessment is a methodology for holistically quantifying the environmental impacts of a product, service, or technology at each stage of its life, from raw material extraction to use and disposal. This analysis framework is core to the success of DOE carbon management programs because many of these technologies are themselves highly energy- and resource-intensive to build and operate. In some cases, the emissions associated with energy inputs used by the carbon management systems may result in a project yielding smaller reductions in "net" greenhouse gas emissions versus the baseline. Thus, projecting and tracking these net emissions is critical to identifying tradeoffs among various carbon management options (and between carbon management and alternative decarbonization approaches), comparing multiple applicants for funding, and ensuring all these projects are worthwhile.

DOE is committed to developing and maintaining industry-leading life cycle assessment methodologies to foster consistent application of the framework across the carbon management space, even as these methods continue to evolve rapidly with the development of new technologies. Not only are the methods of capturing and removing carbon evolving, but so are the technologies for measuring, reporting, and verifying their impacts —which in turn expands the data available as inputs to these models.

As part of this commitment, the multiple offices and national laboratories with life cycle assessment programs at DOE regularly coordinate both internally and externally, to ensure alignment with standards bodies, registries, and other agencies. DOE's life cycle assessment working group includes six national laboratories[84] and supports the life cycle assessment specialists with FECM along with LPO, OCED, Office of Energy Efficiency and Renewable Energy, and others.

Additionally, FECM is a founding member of the interagency Federal Life Cycle Assessments Commons, along with U.S. Department of Agriculture and EPA. The goals of the Commons are to advance life cycle assessment data and research, improve consistency in life cycle assessment methods, and enhance public and interagency access to life cycle inventory data.

Life cycle assessment requirements can vary for each of DOE's funding opportunity or loan guarantee, as well as for various clean energy tax credits administered by the Internal Revenue Service. This is because the expected environmental impacts of a project can vary by the maturity of the technology, the use case, and the region in which it may be deployed. In many cases, life cycle impacts for DOE-funded projects will likely be reduced once the carbon management industry is more mature for several reasons:

- Demonstration operating conditions and project sizes may be optimized for learning, not for the most efficient operation.
- Second, the amount of clean energy available in 2024 is very different from the amount of clean energy expected to be available by the time these carbon management projects are operating. This means that although many demonstrations may need to rely on higher greenhouse gas-intensity electricity at the start, thus increasing upstream emissions, they would be expected to transition to clean electricity over time, ultimately reaching net-zero emissions.

[84] Argonne National Laboratory, Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory, National Energy Technology Laboratory, National Renewable Energy Laboratory, and Pacific Northwest National Laboratory.

- Third, the current tax code for 45Q incentivizes deployment of carbon capture is based only upon total carbon captured and securely stored, and does not link the credit value received to life-cycle emissions directly, except for cases in which the captured CO_2 is converted for non-EOR purposes.[85] This is distinct from the tax guidance pertinent to other credits such as hydrogen and sustainable aviation fuel, where projects must prove their ability to meet specified life cycle greenhouse gas targets. Requirements for life-cycle impacts may expand as the industry matures.

As the industry matures, the net impacts of carbon management projects are expected to improve, as factors like operating efficiency, scale, availability of low-carbon energy, and life cycle assessment requirements advance. Even with those advancements, however, life cycle assessment must continue to be coupled with technoeconomic analysis to answer the question of whether a given carbon management project offers cost-effective net emissions reductions relative to alternative decarbonization pathways, such as replacing fossil infrastructure with renewables or adopting alternative chemistries in industrial production.

While life cycle assessment can assess the emissions of a project and compare it to the "business as usual" scenario (e.g., a plant continues operating without carbon capture), it does not typically assess emissions relative to alternative scenarios (e.g., phaseout of plant).[86] In order to answer these kinds of questions, more traditional attributional life cycle assessment must be expanded to more consequential type analyses, which are supplemented by other forms of technoeconomic and energy systems analysis, which in turn make a series of assumptions about variables, such as the maintenance costs of existing infrastructure, expected lifespan based on recent retrofits, cost and viability of alternatives, and macroeconomic models of energy prices, among others. These analyses inherently introduce uncertainty and may not be layered onto life cycle assessment results. Moving forward, it is a priority for DOE to continue to refine these analysis tools to be able to weigh these alternatives more rigorously.

Along the way, transparency about the life cycle assessment process is pivotal to ensuring these projects' impacts are well-understood by the public. DOE and its national laboratories regularly release guidance and analysis related to life cycle assessment—including best practices for life cycle assessment for direct air capture and detailed methodology for the recently-released 45V version of the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation model. DOE has collected public comments on life cycle assessments in the past and intends to continue expanding public-facing communications around this topic.

[85] However, the EPA's Greenhouse Gas Reporting Program regulations prescribe accounting methodologies that require facilities to quantify and report on amounts of CO_2 stored and any surface leakage. The EPA makes this information and related monitoring plans publicly available on its website. IRS 45Q regulations include reference to these EPA Greenhouse Gas Reporting Program requirements for demonstrating secure geological storage.

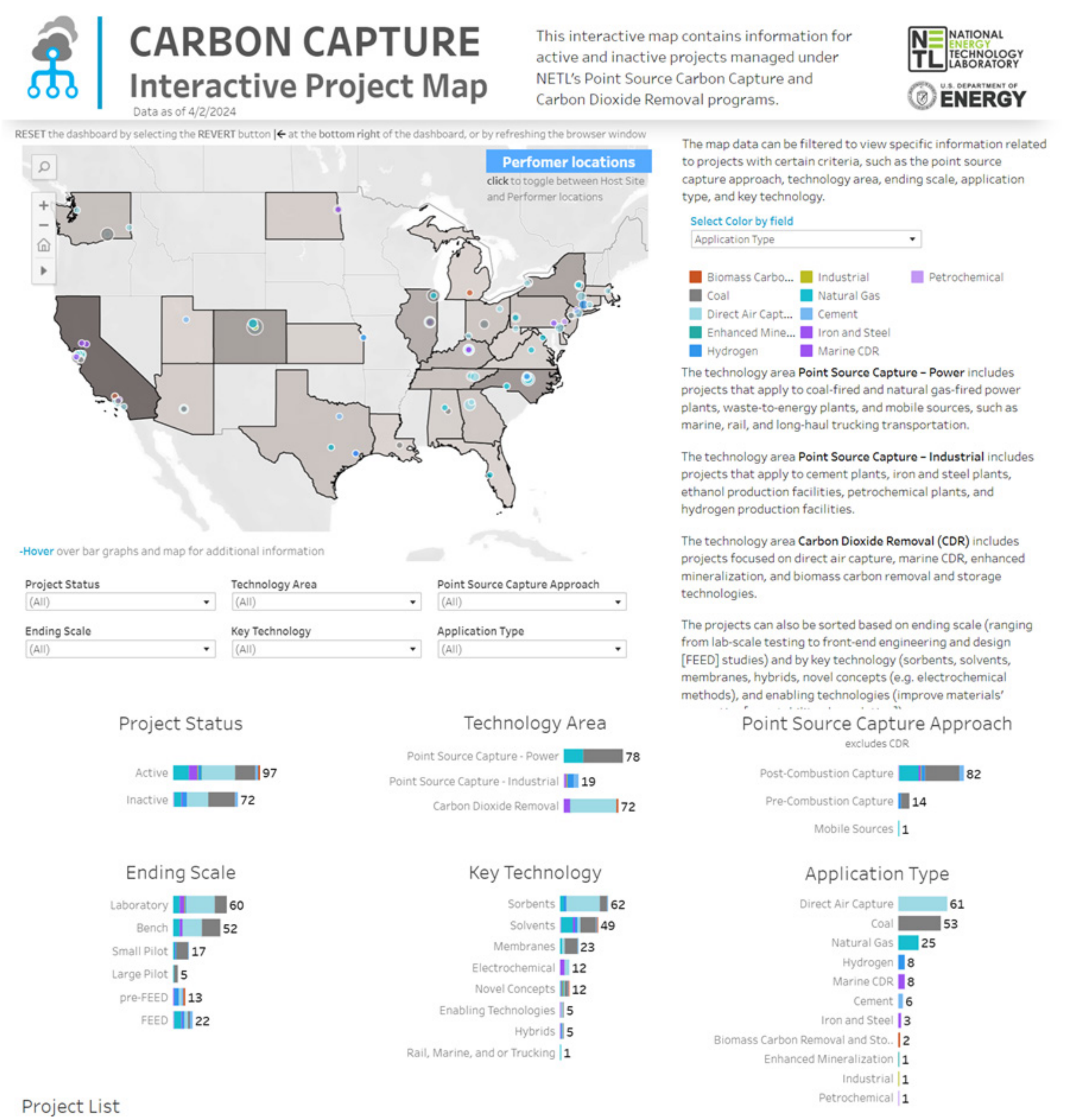
[86] When DOE requires projects to conduct life cycle assessments in fulfillment of the National Environmental Policy Act (NEPA), for example, the two scenarios compared are "action" and "no action"—there is not a third scenario that pairs "no action" with pursuing an alternative decarbonization pathway.

Additional Detail on DOE-Funded Point-Source Carbon Capture Projects

A full list of DOE-funded carbon management research and development projects is listed here: 0919-Carbon-Capture-Technology-Compendium-2022.pdf (doe.gov)

The National Energy Technology Lab also maintains a database of active point-source carbon capture projects Point Source Carbon Capture Project Map | netl.doe.gov.

Figure 22: Screenshot of NETL's database of active point-source carbon capture projects



OCED has selected a number of point-source carbon capture projects for front-end engineering design studies, pilot projects, and demonstration projects, as listed below in Figure 23. More projects with Bipartisan Infrastructure Law and Inflation Reduction Act funding will be announced in the future once additional funding is released and as negotiations progress on related provisions, such as hydrogen hubs.

Figure 23: Office of Clean Energy Demonstrations carbon management programs[87]

Program	Project Type	Topic Area	Project Title	Full Application Status	Emissions Source
Industrial Demonstrations	Demo	2	Novel CO_2 Utilization: Making EC and DMC for Electric Vehicle Batteries	Selected	Chemicals
Industrial Demonstrations	Demo	2	First Net Zero Cement Plant in California	Selected	Cement
Industrial Demonstrations	Demo	3	Decarbonization through Replacing Waste Stream Incinerators with Plasma Gasification to Produce Syngas	Selected	Chemicals
Industrial Demonstrations	Demo	2	ArcelorMittal Texas Holding – H_2 Ready DRI-CCS Demonstration	Selected	Iron & Steel
OCED Carbon Capture FEEDs	FEED	3.2	Foreman Cement Plant Carbon Capture and Storage FEED	Selected	Cement
OCED Carbon Capture FEEDs	FEED	1.1	Integrated Carbon Capture and Storage Project at Dry Fork Station	Selected	Coal Elec Gen
OCED Carbon Capture FEEDs	FEED	3.2	Mitchell Cement Plant Integrated CO_2 Capture Project	Selected	Cement
OCED Carbon Capture FEEDs	FEED	1.1	Edwardsport Flex Fuel Integrated Capture for Indiana's ENergy Transition (EFFICIENT)	Selected	Coal Elec Gen
OCED Carbon Capture FEEDs	FEED	1.1	Integrated Capture, Transport, and Geological Storage of CO_2 Emissions from Dallman Generating Station	Selected	Coal Elec Gen
OCED Carbon Capture FEEDs	FEED	2.1	Polk Power Station Integrated CO_2 Capture Project	Selected	Natural Gas Elec Gen
OCED Carbon Capture FEEDs	FEED	2.1	Entergy Lake Charles Power Station Integrated CO_2 Capture Project	Selected	Natural Gas Elec Gen
Carbon Capture Large Scale Pilot	Demo	2	Large-Scale Pilot Testing of Sorbent Based Post Combustion Carbon Capture System	Selected	Coal Elec Gen
Carbon Capture Demos	Demo	1	Project Tundra CCS Commercial Demonstration	Selected	Coal Elec Gen
Carbon Capture Demos	Demo	2	Baytown CCS	Selected	Natural Gas Elec Gen
Industrial Demonstrations	Demo	2	Mitchell Cement Plant Decarbonization Project	Selected	Cement
Carbon Capture Demos	Demo	2	Sutter Decarbonization Project	Selected	Natural Gas Elec Gen

87 https://www.energy.gov/oced/portfolio

Program	Project Type	Topic Area	Project Title	Full Application Status	Emissions Source
Industrial Demonstrations	Demo	1	Cross-cutting Decarbonization: Clean eMethanol Production Utilizing Biogenic CO_2 and Green H_2	Selected	Pulp and Paper
Carbon Capture Large Scale Pilot	Demo	1	Large-Scale Pilot Demonstration for Carbon Capture System at Delek's Big Spring Facility	Selected	Refining
Carbon Capture Large Scale Pilot	Demo	1	Carbon Capture from Pulp and Paper Industry (Vicksburg Containerboard Mill)	Selected	Pulp and Paper
Industrial Demonstrations	Demo	1	Sustainable Ethylene from CO_2 Utilization with Renewable Energy (SECURE)	Selected	Chemicals
Carbon Capture Large Scale Pilot	Demo	2	CO_2 Capture at NGCC Unit in Economically Distressed Area (Cane Run)	Selected	Natural Gas Elec Gen

Select National Laboratory Efforts on Carbon Management Appendix

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, Oregon, Morgantown, West Virginia, and Pittsburgh, Pennsylvania. As FECM's national laboratory and the only laboratory within the DOE complex dedicated to carbon management research, NETL has been integral to DOE's carbon management research, development, and demonstration endeavors.

NETL's competencies include 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 carbon management technologies, including the following:

1. **NETL CO_2-SCREEN Tool Provides Basis for Quantifying Storage Potential.** NETL researchers have developed the CO_2 Storage prospeCtive Resource Estimation Excel aNalysis (CO_2-SCREEN). The tool has been used to develop resource estimates published in NETL's Carbon Storage Atlases and is being leveraged globally by over 90 different organizations and over 20 countries to mature sequestration.
2. **NETL Developed Geochemically Informed Leak Detection (GLID) Model Facilitating Storage Deployment.** The GILD model, a combined and validated geostatistical method, has been successfully applied in collaboration with industry partners to evaluate expected geochemical responses to CO_2 leakage for the Gulf Coast, and is currently being applied towards other regions and is fully expected to reduce costs of widespread monitoring.
3. **Carbon Capture Technology Development Accelerated via CCSI2 Modeling and Simulation:** The CCSI Toolset has been leveraged in open carbon capture test campaigns at the National Carbon Capture Center and Test Centre Mongstad to collect relevant performance data in only weeks as compared to timelines of years using conventional testing approaches.

4. **NETL Studies Examine the Performance and Cost for Carbon Management Technology Development:** NETL techno-economic analyses of carbon management technologies used to broadly support DOE activities including FECM equities represented in the NREL Annual Technology Baseline (ATB), the EPA's 2023 proposed NSPS rule, DOE's Carbon Management Liftoff Report, the Energy Futures Initiative's Turning CCS Projects in Heavy Industry and Power into Blue Chip Financial Investments, and in DOE's 2023 Billion Ton Report.
5. **NETL Studies Detail Economics for CO_2 Transport and Storage:** NETL suite of tools for estimating the cost and financial performance of CO_2 transport by pipeline, onshore and offshore CO_2 storage in deep geologic formations, and onshore CO_2 storage using CO_2 enhanced oil recovery have widespread use, including LANL's I-WEST study, Princeton's net-zero America study, and the carbon capture, use and storage study performed by the National Petroleum Council for DOE, U.S. Energy Information Administration's National Energy Modeling System and National Renewable Energy Laboratory's Regional Energy Deployment System.
6. **NETL Leads Multi-Lab Effort Building Computational Tools to Manage Carbon Storage Risks.** Building on foundational work that earned the team a 2017 R&D 100 award, National Risk Assessment Partnership is now refining and deploying these tools to help stakeholders address questions on risk management, effective monitoring, estimating liability, and environmentally protective permitting of storage operations at the individual project and basin-scales.
7. **NETL Developed Metallic Materials to Improve the Reliability of Pipeline Transport.** NETL improved pipeline steel has a 31% increase in mechanical toughness (resistance to fracture) by micro-alloying with small amounts (57 to 263 parts per million) of cerium. Furthermore, coupling the alloy formulation with NETL's zinc-based, self-healing coating can manage internal corrosion.
8. **NETL Patent Pending Membrane Planning Field Test.** NETL's new membrane, with a CO_2 permeance exceeding 3000 GPU, 50% or more higher than commercial CO_2 capture membranes, has been upscaled for an upcoming field test for capturing CO_2 from the U.S. Steel's Edgar Thomson Plant in Braddock, Pennsylvania
9. **NETL Developed Record Setting Catalyst.** NETL's electrocatalyst, with improved maximum conversion rate of over 20% as compared to state-of-the-art commercial materials, is being patented and highlighted in the prestigious Applied Catalysis - Environment & Energy (IF~22).
10. **NETL Sensor Technologies for Enhancing the Reliability of CO_2 Capture, Storage, and Transportation.** NETL's fiber optic sensor and interrogation methods for monitoring pipeline integrity over large distances (greater than 100km), which can be used to monitor CO_2 transported in pipelines. This sensor is currently undergoing field testing in a buried pipeline operated by one the nation's largest pipeline operators.
11. **NETL Identifies Scenarios of Self-healing Cements for Carbon Sequestration.** Through a combination of laboratory research and numerical modeling, NETL has disseminated results illustrating reactions and conditions where wellbore cements can self-heal, which will ultimately lead to enhanced permanence of widespread carbon storage.
12. **NETL's Providing Robust Data Repository and AI/ML-Tools to Advanced Carbon Management Technologies.** Based on NETL's EDX platforms, NETL is providing a robust data repository by aggregating data across all FECM programmatic efforts and coupling the data with associated artificial intelligence and machine learning tools to accelerate the maturation and deployment of FECM technologies.

Additional National Laboratory Efforts on Carbon Management Appendix

Many other National Labs have significant capabilities related to carbon management. A non-exhaustive list of select National Labs efforts on carbon management are below.

National Lab	Description of Core Carbon Management Activities
Lawrence Berkeley National Lab	Berkeley Lab 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, Berkley Lab's strategic research efforts encompass multiple advanced carbon management technologies, such as geologic carbon storage at scale, carbon dioxide removal via direct air capture and carbon mineralization, nature-based carbon removal, carbon conversion and utilization, and methane monitoring and mitigation. Berkley Lab's advanced modeling and monitoring capabilities are laying the scientific groundwork for large-scale and secure geologic carbon dioxide 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. Several innovative carbon dioxide removal approaches are under development at Berkeley Lab, focusing for example on the discovery of new adsorbent materials and elucidating the fundamental chemical and physical processes of CO_2 adsorption. Berkeley Lab conducts a feasibility study for developing 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.
Lawrence Livermore National Lab (LLNL)	LLNL has a robust carbon management portfolio and workforce, developed via over 10 years of internal investment in the LLNL Carbon Initiative, encompassing: 1) industrial decarbonization, 2) carbon dioxide removal (direct air capture, biomass carbon removal and storage, soils); and 3) outreach and community engagement focused on carbon dioxide removal. For industrial decarbonization, LLNL has developed CO_2 conversion (electrochemical, reactive capture) and point source capture technologies and relies heavily on iterative design using advanced manufacturing and multi-scale modeling, guided by analysis, to drive technology performance improvements. Over the past three years, LLNL has developed approaches to accelerate the science of scale- up for carbon technology, including: mass manufacturable carbon capture packings with 30% higher mass transfer rates than standard packings, electrolyzers with record low cell voltages, and robust and fully validated electrochemical models to guide electrolyzer scale-up.

National Lab	Description of Core Carbon Management Activities
National Renewable Energy Laboratory (NREL)	Through our carbon management research and development, NREL seeks to enable socially-responsible and climate-beneficial CO_2 removal and CO_2 conversion at gigaton per year scale. Recognizing that the time to act is now, NREL's goal is to accelerate the rate of carbon dioxide removal and CO_2 conversion for hard-to-decarbonize sectors by supporting technology development, informed deployment, and robust accounting. NREL's carbon management work focuses on five key thrusts: (1) carbon dioxide removal and its integration with renewable energy, (2) CO_2 conversion, (3) comprehensive decision support, (4) biomass with carbon removal and storage, and (5) derisking integration and scale-up. NREL has a robust research and development portfolio on CO_2 conversion across EERE, Office of Science, FECM, and ARPA-E that directly supports DOE's Clean Fuels and Products Earthshot and Industrial Decarbonization strategies. NREL's portfolio spans technology-readiness levels and conversion approaches (e.g., biological, algal, thermocatalytic, electrochemical, and hybrid), targets a multitude of products from fuels and chemicals to building materials and proteins, and is a key pillar of NREL's Electrons-to-Molecules Critical Objective. A few specific examples of NREL's CO_2 conversion work include a field-deployable biological power-to-gas system, the CO_2 Reduction and Upgrading for e-Fuels Consortium, and development of reactive CO_2 capture technologies that have the potential to reduce energy intensity and capital expense for integrated CO_2 capture and conversion, such as for the production of methanol.
Oak Ridge National Lab	The science and technology of chemical separations, which are foundational to many carbon management and carbon dioxide reduction technologies, have been a key competency of the Oak Ridge National Laboratory (ORNL) since its establishment in 1943 as part of the Manhattan project. Today, ORNL leverages DOE's Office of Science 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 carbon dioxide removal. 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. 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 carbon dioxide removal and point source CO_2 capture, soil carbon storage, integrated and earth systems modeling of carbon dioxide removal 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 DOE's Fossil Energy and Carbon Management Program to continue advancing the development of these technologies.

National Lab	Description of Core Carbon Management Activities
Stanford Linear Accelerator Center (SLAC) National Accelerator Lab	SLAC's approach to carbon management and carbon dioxide removal 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. SLAC's 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'sworld 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. SLAC harnesses 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 carbon dioxide removal 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. SLAC and SRI International recently led a project for DOE-FECM on carbon dioxide removal innovation and produced a 75-page report that identified 15 emerging technologies having the potential to significantly impact the trajectory of carbon dioxide removal within the next decade. SLAC has additional carbon dioxide removal 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.

Other National Labs with carbon management activities include:

- Argonne National Lab: Carbon Management | Argonne National Laboratory (anl.gov)
- Los Alamos National Lab: Subsurface Energy | Applied Energy Programs (lanl.gov)
- Pacific Northwest National Lab: Carbon Management | PNNL
- Sandia National Lab: Coal & Carbon Management : Sandia Energy

Carbon Management Strategy, Working Group Contributors

This report was written with input from the following U.S. Department of Energy offices:

- Advanced Research Projects Agency–Energy
- Office of Energy Efficiency & Renewable Energy
- Office of Energy Justice and Equity
- Office of Fossil Energy and Carbon Management
- Loan Programs Office
- Office of Manufacturing and Energy Supply Chains
- Office of Clean Energy Demonstrations
- Office of Energy Jobs
- Office of Technology Transitions
- Office of Policy
- Office of Science

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