U.S. Department of ENERGY

Carbon Dioxide Removal Multi-Year Program Plan

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1. Overview

1.1 Introduction and Background

The Working Group III Report of the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) states that the deployment of carbon dioxide removal (CDR) is necessary to achieve net-zero greenhouse gas emissions globally.[1] CDR can counterbalance emissions from hard-to-abate sectors, like agriculture and aviation, where emissions reductions may be overly expensive or impractical, and it could allow society to address overshoot of climate targets through enabling net-negative emissions. While the specific extent of CDR required is highly contingent upon the realized difficulty of eliminating hard-to-abate emissions and the pace of overall emissions reductions, the IPCC finds that hundreds of billions of tonnes of carbon dioxide (CO_2) may need to be removed by 2100 to achieve climate targets. The Energy Modeling Forum 37 study, coordinated by researchers from Stanford University, combines insights from 16 climate modeling teams and estimates that the United States alone may require between one and three billion tonnes of CO_2 removal per year in 2050 to achieve net zero.[2]

Due to scalability limitations for any individual approach, CDR deployment plans generally include a diverse mix of both conventional approaches, such as reforestation and afforestation, and novel approaches, such as biomass-based removal and direct air capture (DAC). With novel or "engineered" CDR currently removing fewer than two million tonnes per year globally,[3] there is a significant need to invest in the rapid development, responsible maturation and commercial deployment of novel CDR technologies to achieve U.S. and global climate targets.

The U.S. Department of Energy's (DOE) Office of Fossil Energy and Carbon Management (FECM) and National Energy Technology Laboratory (NETL) have been conducting applied research, development, and demonstration (RD&D) of transformational carbon capture, utilization, and storage technologies since 1999 with the goal of decreasing cost and improving process efficiency. The Carbon Dioxide Removal Program, established in 2022, is leveraging expertise in materials, equipment, and process development to advance

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1 IPCC, 2022: Summary for Policymakers [P.R. Shukla, J. Skea, A. Reisinger, R. Slade, R. Fradera, M. Pathak, A. Al Khourdajie, M. Belkacemi, R. van Diemen, A. Hasija, G. Lisboa, S. Luz, J. Malley, D. McCollum, S. Some, P. Vyas, (eds.)]. In: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.001.

2 Browning, M., McFarland, J., Bistline, J., Boyd, G., Muratori, M., Binsted, M., ... & Weyant, J. (2023). Net-zero CO_2 by 2050 scenarios for the United States in the energy modeling forum 37 study. *Energy and Climate Change*, 4, 100104.

3 Smith, S. M., Geden, O., Gidden, M. J., Lamb, W. F., Nemet, G. F., Minx, J. C., Buck, H., Burke, J., Cox, E., Edwards, M. R., Fuss, S., Johnstone, I., Müller-Hansen, F., Pongratz, J., Probst, B. S., Roe, S., Schenuit, F., Schulte, I., Vaughan, N. E. (eds.) The State of Carbon Dioxide Removal 2024 - 2nd Edition. DOI 10.17605/OSF.IO/F85QJ (2024)

a diverse suite of CDR solutions that will assist DOE in achieving the Carbon Negative Shot™ objectives and stated climate goal of a net-zero emissions U.S. economy by 2050 through investments in relevant, innovative technologies capable of gigaton-scale removal in a just and equitable way. Announced on November 5, 2021, the Carbon Negative Shot™ is the U.S. government's first major effort in CDR and is a Department-wide call for crosscutting innovation in and commercialization of a wide range of CDR pathways. The Carbon Negative Shot™ sets a 2032 goal of less than $100 per net metric ton of CO_2-equivalent ($/t$CO_2$e) removed across CDR pathways with gigaton-scale potential and inclusive of measurement, monitoring, reporting, and verification (MMRV), robust carbon accounting through cradle-to-grave life cycle analysis (LCA), and secure storage.

Negative emissions are achieved when more emissions are removed from the atmosphere than are generated in a given process. CDR can achieve negative emissions using technologies, practices, and approaches that capture atmospheric CO_2 and securely store it in geological, terrestrial, or ocean reservoirs or in long-lived products. Novel or "engineered" CDR technologies include DAC, biomass carbon removal and storage (BiCRS), enhanced mineralization, and marine CDR (mCDR). These pathways can provide longer-term and more secure storage relative to conventional or "nature-based" pathways, such as afforestation and soil carbon sequestration, making them a vital part of the CDR portfolio.

Novel CDR approaches[4] that minimize removal reversibility and maximize storage duration are the primary focus of the CDR Program's work and have intersections with all aspects of carbon management, requiring close collaboration and coordination with FECM's Point Source Carbon Capture, Carbon Dioxide Conversion, Carbon Transport and Storage, and Hydrogen with Carbon Management Programs, as well as other DOE Program Offices and Federal agencies. Sustained interagency coordination with other Federal agencies is particularly important given the complex policy, legal, and regulatory considerations for CDR projects. The CDR Program is continually working to build and maintain these interagency relationships, share technical information and expertise, and work with other departments on both CDR and other climate change mitigation efforts. These efforts include, but are not limited, to Federal RD&D; permitting and siting; analysis of the benefits and potential impacts of climate mitigation technologies and policies; and public outreach, education, and engagement. To incorporate more perspectives and build a robust CDR ecosystem, the CDR Program also engages with industry, state and municipal governments, nonprofits, academia, consultancies, and other stakeholders involved in advancing CDR goals. As directed by Congress in the Consolidated Appropriation Act of 2021, DOE has coordinated an interagency CDR task force to prepare a report on the status, scalability, and policy support needs of a portfolio of CDR approaches.[5]

DOE pursues the achievement of low-cost and commercially feasible, environmentally and socially responsible, and scalable CDR through investments in RD&D aimed at: (a) decreasing CDR costs and identifying opportunities for valuable co-products or other economic benefits; (b) improving life cycle emissions performance; (c) reducing land, energy, and water requirements and mitigating other potential environmental impacts; (d) accelerating

[4] "Novel CDR approaches" refers to CDR pathways that are technologically and commercially less mature, relative to biological pathways in natural and working lands (such as improved forest management or afforestation). Novel CDR pathways included in this MYPP include direct air capture (DAC), marine CDR (mCDR), enhanced mineralization, and biomass carbon removal and storage (BiCRS).

[5] Consolidated Appropriations Act, 2021, Pub. L. No. 116-260, § 5002, 134 Stat. 1182, 2550-52 (2020). https://www.congress.gov/bill/116th-congress/house-bill/133/text.

kinetics and enhancing other influential technical parameters; (e) ensuring long-lived and resilient materials and process stability; (f) integrating new technologies with existing markets and supply chains; (g) developing data-driven modeling capabilities; and (h) implementing effective MMRV protocols to ensure sufficient confidence in the results and impacts of CDR.

To make progress toward these goals, DOE plans to design and release a series of multi-topic, multi-year funding opportunities soliciting RD&D that will be coordinated across DOE Program Offices to achieve Carbon Negative Shot™ objectives across CDR pathways. These funding opportunities are expected to focus on several topics responsive to both Departmental annual CDR programmatic priorities and several CDR Bipartisan Infrastructure Law (BIL)-related activities. These opportunities will incorporate Community Benefits Plan (CBP) requirements where applicable to ensure projects support workforce development and environmental protection and minimize and mitigate potential adverse impacts.

This Multi-Year Program Plan (MYPP) summarizes the DOE CDR Program's efforts to support achievement of the Carbon Negative Shot™ target and net-zero U.S. emissions by 2050. The activities included in this plan are funded either from annual base appropriations or funding provided by the BIL. The document also explains, where applicable, how planned base program activities complement BIL efforts and how the combined base program and BIL efforts contribute to meet the Administration's decarbonization goals. The MYPP is intended to be a living document that will be refined based on learnings across the CDR technology portfolio.

1.2 Alignment with DOE and FECM Plans

The CDR MYPP is aligned with current DOE strategy, Administration policies, Congressional legislation, and international CDR efforts, as detailed below.

DOE FECM Strategic Vision – This MYPP is a direct outgrowth of the FECM Strategic Vision published in 2022, which highlights seven strategic RD&D pathways associated with advancing carbon management approaches toward deep decarbonization and maturing technologies that lead to sustainable energy resources and industrial processes.[6] While each is distinct in its own way, these seven pathways interact and integrate with each other to fulfill FECM's contribution to a just and commercially viable decarbonization. FECM is highly focused on RD&D for CDR. Work at different technology readiness levels (TRLs) and on diverse CDR approaches is intended to provide optionality for the country's net-zero goals. Also important is FECM's role in de-risking technologies, improving transparency around costs and performance, and leveraging expertise to evaluate potentially transformative CDR pathways. FECM's strategy includes the advancement of a diverse portfolio of CDR approaches that will aid in gigaton-scale CO_2 removal by 2050 and support multiple aspects of DOE's Energy Earthshots Initiative through CO_2 removal and reactive capture and conversion to long-lived products.[7]

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[6] U.S. Department of Energy- Office of Fossil Energy and Carbon Management. (2022). *Strategic Vision: The Role of FECM in Achieving Net-Zero Greenhouse Gas Emissions*. https://www.energy.gov/sites/default/files/2022-04/2022-Strategic-Vision-The-Role-of-Fossil-Energy-and-Carbon-Management-in-Achieving-Net-Zero-Greenhouse-Gas-Emissions.pdf

[7] https://www.energy.gov/energy-earthshots-initiative

DOE Energy Earthshots Initiative – a series of quantifiable goals across different technology pathways to drive innovation breakthroughs for reaching net-zero carbon emissions by 2050 and for creating new clean energy and industrial jobs. The CDR Program will benefit from the achievements of all the Earthshots—Long Duration Storage, Geothermal, Floating Offshore Wind, Industrial Heat, and Hydrogen—but the technologies and capabilities developed by the Program and outcomes of future CDR RD&D efforts are essential to the Carbon Negative Shot™ and to support the Clean Fuels and Products Shot™.

Announced on May 24, 2023, the Clean Fuels and Products Shot™ aims to decarbonize the fuel and chemical industry through alternative, more sustainable sources of carbon. The CDR Program provides support through co-funding of reactive capture and conversion projects with the Carbon Conversion Program.

In addition to the Earthshots, DOE's Office of Clean Energy Demonstrations (OCED) has a primary objective to accelerate market adoption and deployment of decarbonized energy systems by supporting at-scale clean energy demonstration projects. OCED's portfolio includes the Regional DAC Hubs. The goal of this BIL initiative is to responsibly catalyze a commercial DAC industry in the U.S. and establish the U.S. as the global leader in developing and demonstrating the commercial viability of this critical climate technology.

Administration Budget Priorities – The FY25 President's Budget Request for CDR is $90.2 million to support continued activities to advance novel DAC and mCDR materials and processes to help optimize and reduce the cost, front-end engineering and design studies for BiCRS, and novel approaches that can leverage industrial waste minerals and naturally occurring minerals to capture atmospheric CO_2.[8]

Congressional Direction – In addition to funding activities as directed by annual appropriations bills, the CDR Program advances projects that are aligned with other pieces of Congressional legislation. The 2021 Infrastructure Investment and Jobs Act or the IIJA (Public Law 117-58; also known as the Bipartisan Infrastructure Law or the BIL) appropriates $3.5 billion for development of four domestic Regional DAC Hubs (BIL Section 40308) to accelerate commercialization of, and demonstrate the processing, transport, geologic storage, and/or conversion of, CO_2 captured from the atmosphere. FECM and NETL manage the Regional DAC Hubs in tandem with OCED. BIL also authorized and appropriated a total of up to $115 million for the development and execution of DAC-related prize competitions, which includes up to $15 million for the Pre-Commercial Prize (BIL Section 41005a) and up to $100 million for the Commercial Prize (BIL Section 41005b). These prizes will catalyze rapid DAC and CDR technology advancement while incorporating community benefits planning, stakeholder engagement, and workforce development.

In August 2022, Congress enacted the Inflation Reduction Act (IRA) (Public Law 117-169), the largest piece of climate legislation in U.S. history.[9] Building on BIL, IRA establishes a comprehensive set of clean energy incentives, largely through multi-year tax credits for a wide range of efforts including clean hydrogen (45V), sustainable aviation fuel (45Z), and carbon management (45Q). This law significantly enhanced the Section 45Q

[8] U.S. Office of Management and Budget. (2024). *Budget of the U.S. Government: Fiscal Year 2025*. https://www.whitehouse.gov/wp-content/uploads/2024/03/budget_fy2025.pdf

[9] H.R. 812 (IH) - Inflation Reduction Act of 2023. https://www.govinfo.gov/app/details/BILLS-118hr812ih

tax credit by (a) increasing its value to $180/ton for DAC projects with secure geologic storage that also satisfy prevailing wage and apprenticeship requirements; (b) reducing the minimum scale threshold for DAC to 1,000 tonnes per year; and (c) extending the deadline to commence construction to January 1, 2033. Projects are also now eligible to claim the credit as a direct payment for the first five years after the equipment is placed in service (12 years for nonprofits and co-ops).

Mission Innovation – Mission Innovation is a global initiative of over 20 nations aiming to promote investment in RD&D towards the Paris Agreement goals and pathways to net zero by making clean energy affordable, attractive, and accessible for all. Mission Innovation has stated a goal for enabling CDR technologies to achieve a net worldwide reduction of 100 million tonnes of CO_2 annually by 2030. Led by the United States, Canada and the Kingdom of Saudi Arabia, the Mission Innovation CDR Mission is aiming to foster a public-private approach that will ensure accuracy in large-scale CO_2 removal measurement, analyze and mitigate potential environmental impacts, and improve performance while lowering the cost of CDR. The focus is on three CDR technological approaches—DAC, BiCRS, and enhanced mineralization—as well as advancing best practices for LCA, techno-economic analysis (TEA) and MMRV. The Mission Innovation CDR Mission recently developed and plans to maintain a CDR demonstration and deployment map to give up-to-date progress of CDR testing and implementation worldwide. Finally, Mission Innovation leads the CDR Launchpad, which is a coalition of governments including the U.S. working together on large demonstration projects and sharing data and experiences to accelerate the pace of CDR technology development. The Mission Innovation CDR team has published a report highlighting the CDR technology gaps and opportunities and an associated action plan summarizing the expected workflow.[10, 11]

1.3 Overarching Goals and Desired Benefits of Research, Development, and Demonstration Investments

All CDR Program efforts are structured to support the Department's Carbon Negative Shot™ 2032 goal of a portfolio-wide average cost of less than $100/t$CO_2$e removed across CDR pathways with gigaton-scale potential, inclusive of MMRV, robust carbon accounting through cradle-to-grave LCA, and secure storage.

- By 2028, achieve a portfolio-wide average cost of less than $200/t$CO_2$e removed[12] across CDR pathways with gigaton-scale potential
- By 2030, achieve a portfolio-wide average cost of less than $150/t$CO_2$e removed across CDR pathways with gigaton-scale potential

The CDR Program will also provide demand-side support to CDR technology developers through prize competitions and potentially other mechanisms with the goal of purchasing high-quality net carbon removals.

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[10] Mission Innovation: CDR Mission. (2022). Carbon Dioxide Removal Technology Roadmap: Innovation Gaps and Landscape Analysis, 1st Edition. https://explore.mission-innovation.net/wp-content/uploads/2022/09/Carbon-Dioxide-Removal-Mission-Roadmap-Sept-22.pdf

[11] Mission Innovation: CDR Mission. (2022). Carbon Dioxide Removal Mission Action Plan 2022-26, 1st Edition. http://mission-innovation.net/wp-content/uploads/2022/09/Attachment-2-Public-Facing-CDR-Mission-Action-Plan-Sept-2022.pdf

[12] DOE will use cost data reported by pilots projects (greater than 1kta CO_2e net removed), weighted on total removal capacity to inform the average cost of the CDR program portfolio.

DOE intends to purchase CDR credit from a portfolio of novel CDR approaches and technologies at relatively small, but growing volumes. Federal procurement of CDR credits, even at modest volumes, will help to establish quality criteria, advance MMRV, and encourage additional private purchases to scale the market. It is anticipated the CDR program will purchase credits from several projects including multiple CDR pathways with secure storage, cumulatively totaling:

- 5,000 tonnes from commercial-scale activities by 2026
- 15,000 tonnes from commercial-scale activities by 2028
- 25,000 tonnes from commercial-scale activities by 2030
- 50,000 tonnes from commercial-scale activities by 2032
- 80,000 tonnes from commercial-scale activities by 2034

2. Carbon Dioxide Removal Programs

The FECM CDR Program is structured around four main programs that represent the following novel or "engineered" CDR technology pathways from the Carbon Negative Shot™. Importantly, the Carbon Negative Shot™ also includes biological approaches, such as soil carbon sequestration and afforestation. FECM supports research and development (R&D) programming directly related to quantification and modeling of biological carbon removal approaches such as reforestation and soil carbon sequestration, as outlined in the Carbon Negative Shot™. Additionally, the four technology program areas summarized below provide crosscutting benefits that support terrestrial biological approaches, such as MMRV improvements and siting considerations that advance the scale-up and cost effectiveness of biological approaches.

Direct Air Capture

Direct air capture (DAC) involves the extraction of CO_2 directly from ambient air in either motive/active (fan-powered) or passive (wind-driven) air contacting devices connected to broader systems that generally cycle through capture and regeneration stages to release concentrated CO_2 for conditioning and secure geologic storage or utilization. The CDR Program is maturing existing (Gen-1) and next-generation (Gen-2+) DAC processes, that are often classified as solid sorbent, aqueous solvent, mineral looping, electrochemical, and/or membrane-based technologies. A subset of DAC technologies falls under the category of reactive carbon capture, which integrates capture and conversion into a useful product without the production of an intermediate stream of pure CO_2. Reactive carbon capture approaches will be matured in collaboration with the Carbon Conversion Program.

Biomass Carbon Removal and Storage

Biomass carbon removal and storage (BiCRS) involves the capture of CO_2 from the atmosphere through the growth of sustainably sourced biomass.[13] After growing, the sustainable biomass is collected and processed for energy, material, or carbon storage applications in a manner resulting in the stable storage of the biogenic carbon initially taken up during growth. BiCRS methods include, but are not limited to, bioenergy with carbon capture and storage (BECCS), biochar, biomass burial, long-lived bioproducts, and bio-oil storage.

Enhanced Mineralization

Enhanced mineralization routes accelerate the geologic processes that remove CO_2 from the atmosphere through the reaction of alkali minerals with air and water to form stable solid carbonate compounds that can be stored geologically or in long-lived products (e.g., building materials). The CDR Program is leveraging ongoing efforts by the Carbon Transport and Storage Program, primarily on in-situ methods, to further advance ex-situ and surficial pathways. Ex-situ mineralization occurs within controlled environments (i.e.,

[13] https://www.energy.gov/sites/default/files/2024-03/beto-2023-billion-ton-report_2.pdf

reactors or other engineered systems like DAC) at an industrial facility or dedicated carbonation plant typically removed from natural mineral sites. Surficial mineralization occurs at or near the ground surface in an open system. Approaches include enhanced rock weathering, which involves the spreading of crushed alkali minerals on agricultural lands to form intermediate bicarbonate ions which can drain into waterways and precipitate into carbon minerals as part of the ocean carbon cycle.

Marine Carbon Dioxide Removal

Marine carbon dioxide removal (mCDR) solutions remove CO_2 from the atmosphere or upper hydrosphere and securely store it either in marine or geological reservoirs or long-lived products. The CDR Program seeks to support mCDR strategies that pose the least amount of potential environmental risks to the aquatic environment local to the activity and maximizes potential co-benefits, such as addressing ocean acidification. mCDR approaches span a wide range of biotic (e.g., seaweed and microalgae cultivation, artificial upwelling and downwelling) and abiotic (e.g., electrochemical engineering processes and ocean alkalinity enhancement) pathways.

For each CDR pathway, this Technical Plan includes a description of the underlying technology class, existing challenges to deployment and operation, corresponding program goals, technical research activities, demonstration and market-building activities, and LCA/TEA/MMRV activities. Milestones are listed for each pathway to provide specific metrics for tracking progress toward the Program and country's high-level CDR goals.

Each CDR technology has a unique set of requirements and impacts. FECM and NETL work to advance all CDR pathways across multiple domains, driving toward scalability, low costs, minimal environmental impacts, minor resource requirements, ample co-benefits, and social, economic, and environmental benefits for communities. The CDR approaches and technologies represented in FECM's portfolio have distinct supply-chain, permitting, resource requirement, and business model considerations that need to be accounted for. FECM and NETL programs aim to identify and address these market and commercialization consideration, while also addressing technology challenges. All Program efforts are structured to support the Department's Carbon Negative Shot™ goals of gigaton-scale CDR with secure storage and robust accounting of life cycle emissions at a portfolio-wide average cost of less than $100/net metric ton CO_2e. Given the complex, multi-objective, and interdisciplinary nature of CDR, all funded project teams are expected to approach their work as holistically as possible by delivering a technology maturation plan and conducting technoeconomic, life cycle, technology gap, and environmental, health, and safety analyses, and consider the wide-ranging implications of decisions early in the RD&D process.

To ensure progress across the portfolio, the CDR Program leverages multiple crosscutting enabling capabilities that facilitate flexibility and knowledge transfer. These capabilities and resources include access to computational resources enabling process design, materials discovery, optimization, uncertainty assessment, material degradation, and siting; CDR testbed facilities at the NETL DAC Center, National Carbon Capture Center (NCCC), and DAC Pre-Commercial EPIC Prize incubators; and LCA and TEA expertise.

As part of the funding for pre-commercial and commercial DAC prize competitions provided by BIL, FECM launched the $35 million CDR Purchase Pilot Prize, which will be the first instance in history of federal procurement of CDR credits. FECM has announced 24 semifinalists for the first round of the prize competition that intend to collectively provide 196,558 tonnes of removal credits generated via CDR (i.e., DAC, BiCRS, enhanced mineralization, and other planned and managed sinks in terrestrial ecosystems and the upper hydrosphere) over the course of the competition if selected.[14] This initial round of purchases marks a key milestone and precedent for the future of the DAC market and is a critical initial step for testing business cases for CDR deployment. The program has also received funding from base appropriations to continue CDR purchasing, which may be continued via a prize competition or an alternative mechanism.

To supplement this initiative, FECM announced the Voluntary CDR Purchasing Challenge that will call on external organizations to join DOE in purchasing CDR credits.[15] This unique effort will send an important signal to the market and funnel much-needed funds toward CDR technology providers seeking to secure financing. Google was the first to respond by announcing a pledge of at least $35 million of CDR credit purchases over the next 12 months, and Meta has since announced a matching $35 million pledge[15, 16]

2.1 Direct Air Capture (DAC)

2.1.1 Technology Description and Approaches

Direct air capture (DAC) separates CO_2 from ambient air using mechanical equipment that leverages chemical or physical phenomena. Originally proposed for use as a climate technology by Lackner et al. in 1999,[17] the technology is an adaptation of point-source carbon capture, which separates CO_2 from more concentrated flue gas streams at industrial facilities and power plants. Due to the low concentration of CO_2 in ambient air relative to flue gas, DAC requires more energy per unit of CO_2 captured than point-source carbon capture. While it may seem counterintuitive to expend energy on DAC while society is still emitting CO_2 from point sources and access to sufficient energy is still limited in areas of the world, it is critical for DAC technologies to operate and mature in tandem with and as a complement to the deployment of point-source carbon capture. DAC can overcome some of the limitations inherent to point-source carbon capture, such as through its abilities to: (a) compensate for distributed emissions sources and for those power or industrial facilities for which carbon capture retrofits would be costly or impractical; (b) be sited flexibly, allowing for streamlined co-location with storage and conversion; (c) contribute to net-negative emissions once net-zero emissions are achieved; and (d) produce a stream of circular, atmospheric carbon suitable for net zero-aligned use in production of short-lived chemicals and fuels. DAC programming is closely coordinated with other FECM technology areas. DAC RD&D efforts are coordinated with expertise and programming within the Point Source Carbon Capture Program to address common technical and commercial challenges, while Regional DAC Hubs efforts are coordinated with the Carbon Transport and Storage Program to ensure enabling infrastructure is effectively leveraged. Coordination with the Carbon Conversion Program focuses on reactive capture approaches and integration of DAC technologies with CO_2 conversion pathways that may provide reliable offtake and revenue sources for DAC operations.

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[14] White House Fact Sheet: Biden-Harris Administration Announces New Principles for High-Integrity Voluntary Carbon Markets. https://www.whitehouse.gov/briefing-room/statements-releases/2024/05/28/fact-sheet-biden-harris-administration-announces-new-principles-for-high-integrity-voluntary-carbon-markets/

[15] https://blog.google/outreach-initiatives/sustainability/pledge-to-support-carbon-removal-solutions/

[16] https://sustainability.atmeta.com/blog/2024/10/11/growing-our-commitment-to-carbon-removal-with-the-u-s-department-of-energy/

[17] Lackner, K., Ziock, H. J., & Grimes, P. (1999). *Carbon dioxide extraction from air: is it an option?* (No. LA-UR-99-583). Los Alamos National Lab.(LANL), Los Alamos, NM (United States).

In 2020, the Point Source Carbon Capture Program initiated a DAC RD&D approach focused on cost reduction and with an understanding that a few DAC technologies are more mature (denoted Gen-1), while most others (Gen-2+) are more nascent. The dichotomy between Gen-1 and Gen-2+ has since been supported by request for information responses[18] and an informal, yet thorough, survey conducted by NETL's Research and Innovation Center of the most pressing RD&D challenges faced by DAC entrepreneurs and the required testing and analytical capabilities to accelerate technology maturation. The CDR Program continues to explore and invest in multiple RD&D opportunities across DAC TRLs to ensure that as many approaches as possible will be able to scale up successfully and leverage advances in areas such as process intensification, modularization, and advanced manufacturing.

Relatively mature Gen-1 DAC processes usually involve active movement of air through air contactors, high-capacity factors, and fixed plant locations. These processes also generally feature (a) temperature–vacuum swing adsorption using amine-based solid sorbents and low-temperature regeneration; or (b) absorption using hydroxide-based aqueous solvents and high-temperature regeneration. Newer Gen-2+ DAC processes can include a variety of innovative approaches such as (a) passive (as opposed to active or "motive") capture; (b) intermittent operation to synchronize with corresponding renewable energy resources; (c) distributed operation such as through heating, ventilation, and air conditioning (HVAC) systems; (d) high-temperature mineral looping; (e) electrochemical regeneration; (f) regeneration or "swings" using conditions other than temperature and pressure like humidity, pH, and light; or (g) other emerging material and process innovations. Typically, however, DAC processes can be categorized as one of the following two high-level categories:

Solid Sorbent-Based Processes

Solid sorbent-based processes employ solid capture media with a high affinity for CO_2 molecules to selectively adsorb CO_2 from ambient air. The sorbent material usually involves an amine on a high-surface area support (e.g., resins, alumina, silica, activated carbon, cellulose, covalent organic frameworks, and metal–organic frameworks), a hydroxide, an alkali carbonate, and/or zeolites. Once carbonated, a "swing" of some condition or combination of conditions—such as temperature, pressure, or humidity—is applied to the sorbent to release higher-purity CO_2 in a controlled fashion for subsequent storage or conversion. Desorption regenerates the sorbent allowing for the sorbent material to be continuously recycled in the DAC process.

Aqueous Solvent-Based Processes

Aqueous solvent-based processes employ aqueous capture media with a high affinity for CO_2 molecules for selective absorption from the air. The solvent typically contains aqueous hydroxide or amine solutions that selectively react with CO_2 as air is passed through air contactors. Once carbonated, the solvent can be processed in a variety of ways that regenerate the solvent and result in a release of higher-purity CO_2 in a controlled fashion for subsequent storage or conversion, similar to sorbent-based processes.

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[18] U.S. Department of Energy Request for Information (DE-FOA-0002660) *Deployment and Demonstration Opportunities for Carbon Reduction and Removal Technologies.*

Atmospheric Reactive Carbon Capture

A subset of DAC technologies of interest to NETL and FECM are classified as reactive carbon capture, which is a technology category that involves simultaneous capture and conversion of CO_2 from ambient air.[19] Reactive carbon capture generally makes use of dual-functional materials that can selectively separate CO_2 from ambient air and convert it into a valuable product upon regeneration of the sorbent or solvent. By integrating capture and conversion rather than engaging in these processes sequentially, reactive carbon capture can leverage process synergies to reduce capital and operating costs. Reactive carbon capture outputs may include chemical products such as methanol, methane, and carbon monoxide,[20] but any outputs must be further processed into relatively long-lived products rather than combustible ones to enable carbon removal as opposed to mere emissions reduction. Given the overlap with carbon utilization and the potential for reactive carbon capture to be applied to point-source CO_2 streams, the CDR Program collaborates with both the Carbon Conversion and Point Source Carbon Capture Programs on reactive carbon capture.

2.1.2 Challenges and Program Goals

DAC, when paired with permanent storage, provides a high-certainty and direct mechanism for removing CO_2 from the atmosphere, but its primary challenge and trade-off relative to other CDR and even emissions reduction methods is its high cost. This high cost is driven by a number of technical and economic barriers.

As sorbents and solvents are frequently a core cost driver, DAC benefits from capture materials that are cheap, have high capture capacities, are resistant to degradation, minimize pressure drop, are configurable into effective form factors, enable fast kinetics, are selective toward CO_2, and integrate well with the rest of the system. Ideally, these capture materials also feature low manufacturing emissions, low toxicity, sizable and diverse supply chains, and simple replacement procedures at end-of-life. Optimizing across all attributes is difficult, and the tolerability of trade-offs may ultimately depend on technological and geographical considerations specific to each technology and operator.

Energy is another key cost driver for DAC as a significant amount of energy is required to power capture, regeneration, and subsequent conditioning and compression. The dilute concentration of CO_2 in ambient air of around 425 parts per million necessitates processing a massive volume of air for a modest amount of CO_2 separation. For active DAC systems involving fans or blowers, energy must be expended to overcome the pressure drop and move ample quantities of fresh air through the system. The vast majority of energy for DAC is usually required as part of the regeneration step given the need for elevated temperatures or changes in other conditions (e.g., pressure, electric current, moisture) required to induce desorption. Additional energy is required for ancillary processes, compression, CO_2 transportation, and CO_2 storage. Aggregated energy requirements pose both a direct financial cost to the system, as well as an indirect cost through the emissions from the generation of that energy, which increase the gross amount of CO_2 that must be removed and therefore cost for net atmospheric removal.

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[19] Reactive carbon capture could also theoretically be applied to CO_2 streams from biomass combustion or direct ocean capture, implying a potential overlap with BiCRS or mCDR.

[20] Jeong-Potter, C., Arellano-Treviño, M. A., McNeary, W. W., Hill, A. J., Ruddy, D. A., & To, A. T. (2024). Modified Cu–Zn–Al mixed oxide dual function materials enable reactive carbon capture to methanol. EES Catalysis, 2(1), 253-261.

Finally, capital costs are another significant driver of high DAC costs. Current DAC systems are largely produced at small scales and in small volumes, preventing developers from taking advantage of economies of scale. High costs for custom-engineered equipment drive higher system-level costs. Additional capital cost drivers include other industrial necessities such as land; site preparation; equipment installation; piping; instrumentation and controls; electrical components; civil work; engineering, procurement, and construction fees; design and engineering; contingencies; and all other pieces of ancillary equipment. There may also be trade-offs between capital costs and other important facility attributes, such as capacity factors, material degradation, and energy consumption, complicating cost optimization for DAC plants.

To holistically optimize DAC performance to maximize cost reduction and environmental benefits, the CDR Program is particularly interested in funding the development of DAC projects that pursue at least several of the below goals.

Project Approach

- Leverage comprehensive and cohesive experimental and computational RD&D coupled with iterative TEA and LCA refinements to ensure rapid, responsible and sustainable progress toward Carbon Negative Shot™ goals
- Develop creative strategies to explore and optimize across interdependent system parameters in pursuit of effective cost and environmental impact reduction
- Engage with EPC firms and other experienced entities in the chemical and process industries to develop robust designs for implementation at scale

Materials

- Discover and develop advanced, novel sorbents or solvent-based working solutions, novel concepts, and hybrid systems with improved long-term stability towards mechanical, oxidative, and hydrothermal degradation under relevant DAC environments and rejuvenation/recyclability potential to reduce costs and environmental impacts from material production
- Minimize or eliminate degradation co-products that could be released into the surrounding environment or necessitate further conditioning to enable CO_2 transport
- Leverage advances from or contribute to advances in other academic and technology areas such as nanotechnology, polymer science, gas separation, and catalysis

Energy

- Reduce capture energy requirements by utilizing novel, low-pressure drop air contacting methods, passive DAC systems with efficient air-contacting mechanisms, or other innovations
- Utilize novel regeneration process designs, such as sorbent transportation or Joule heating, to lower regeneration energy requirements and/or make use of low-grade waste heat
- Integrate renewable energy resources and industrial facilities equipped with point-source carbon capture in a way that minimizes net removal costs and reduces competition for limited low-carbon energy resources
- Minimize energy related to water sorption and/or employ novel strategies to minimize water co-adsorption, such as through the use of a desiccant for feed air pre-conditioning or hydrophobic sorbents

Equipment

- Prepare systems to tolerate the significant extent of environmental and climatic variability of feed air (e.g., deriving from variable temperature, humidity, pressure, wind speed, particulate matter, other pollutants, precipitation, weather patterns, etc.)
- Employ advanced design geometries and fabrication techniques to deliver low-pressure drop air contactors that holistically reduce system costs
- Consider and develop strategies to minimize costs of producing input materials, air contactors, and other necessary equipment at industrial scales through either existing manufacturing and supply chains or advanced manufacturing methods
- Maximize CO_2 capture volumetric productivity (e.g., working capacity and/or adsorption/desorption kinetics) of DAC components to reduce size, capital costs, land requirements, and the environmental footprint of the facility

System

- Develop full process designs considering factors such as heat integration, CO_2 conditioning, and impurity management
- Produce valuable co-products, such as potable water or low-carbon hydrogen
- Minimize complexity, residence times, and conditioning and purification costs
- Enable and promote inherent safety for DAC materials and facilities with an emphasis on both plant operators and surrounding communities
- Investigate energy savings from production of low-purity CO_2 paired with suitable storage methods
- Balance trade-offs between modular and centralized system designs to pursue cost reduction through both learning-by-deployment and economies of scale
- Consolidate or efficiently integrate multiple unit processes/operations to achieve cost reduction and improvements to carbon removal efficiency

Reactive Carbon Capture

- Develop dual-functional materials for reactive carbon capture approaches that simultaneously capture CO_2 from ambient air and catalytically convert it into valuable chemicals amenable to use in long-lived products
- Ensure adequate capture and conversion rates for reactive carbon capture approaches relative to competing DAC and conversion processes

Figure 1. Projected funding opportunities for DAC technologies.

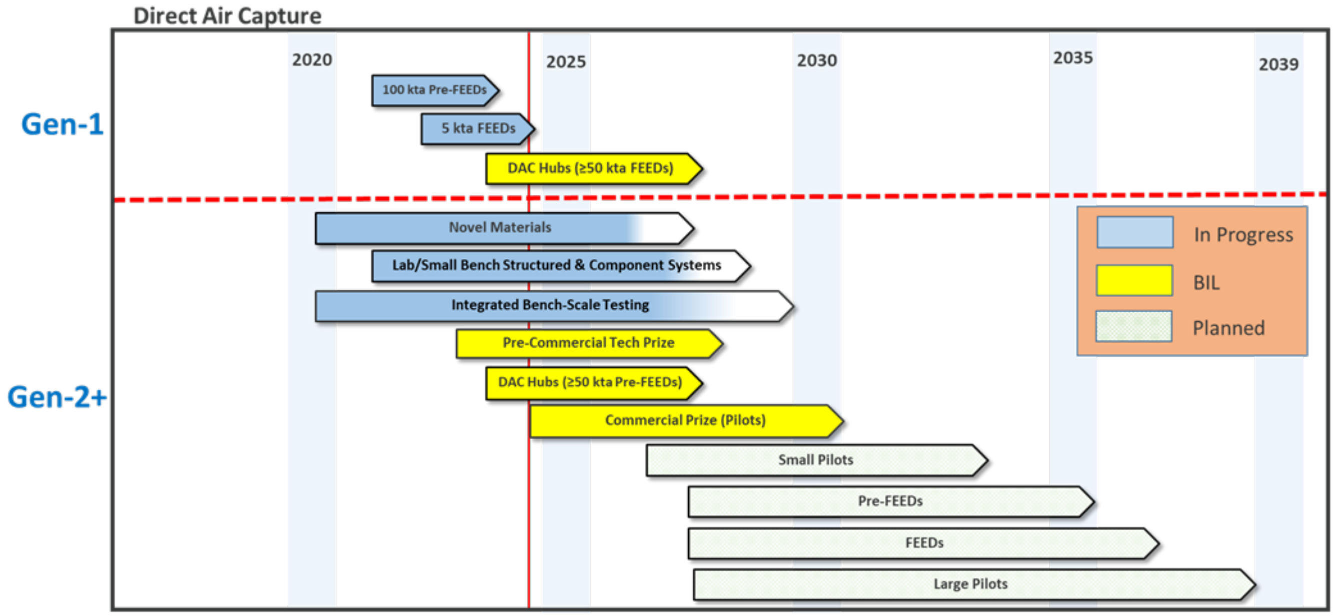
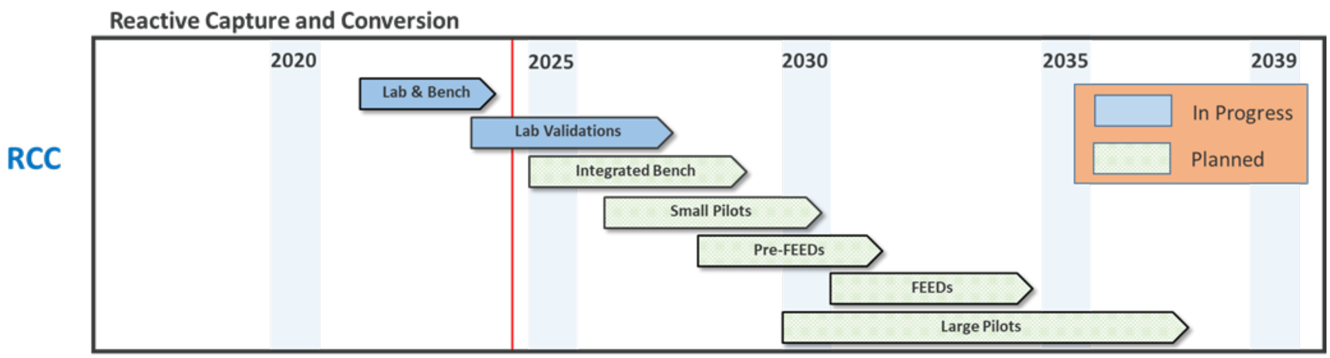


Figure 2. Projected funding opportunities for reactive carbon capture technologies.



2.1.3 Technical Research Activities

As organizations within the Office of the Under Secretary for Science and Innovation, FECM and NETL are committed to funding scientific work that advances DAC. Across CDR and DOE more generally, this work is often funded using funding opportunity announcements (FOAs)/notices of funding opportunity (NOFOs), Small Business Innovation Research (SBIR)/Small Business Technology Transfer (STTR) awards, prize competitions, field work proposals with DOE national labs, and Technology Commercialization Fund awards to DOE national labs.

Numerous lab- and bench-scale projects have been completed or are in progress to advance next-generation (Gen-2+) DAC functional media including polyamines, alkali salts and hydroxides, amino acids, metal organic frameworks, minerals, dendrimers, and aerogels; structured material systems including monoliths, laminates, electrodes, and membrane fibers and bundles; component designs including electrochemical cells and coated air contactors that involve 3D-printing, heat exchangers, sheets, and plates; and intensified process cycles including moisture-, concentration-, alkalinity-, and electro-swings and electric and microwave heating. Not as much dedicated work has been performed on DAC with reactive carbon capture, but more is expected in the coming years.

Specifically, the program includes R&D focused on development of new materials for DAC systems. Developing advanced and high-quality materials for DAC is a vital starting point, as most if not all subsequent technology development steps and operational parameters derive from the utilized core materials. Over a dozen projects are currently underway to advance early-stage research into a multitude of creative and potentially impactful new approaches to DAC with a focus on addressing key process chemistry challenges related to reaction kinetics, selectivity, and equilibrium constraints.

More advanced bench-scale testing for DAC is also being funded. Four projects are currently testing structured material systems and component design for optimized DAC systems.[21] Five projects are testing integrated DAC systems demonstrating both capture and regeneration steps. Bench-scale testing of a range of novel air contactor approaches and geometries to enhance DAC performance is also underway.[22]

Prize competitions offer an alternative means to FOAs for promoting and incentivizing early-stage DAC innovation. As of November 2024, seven semifinalist DAC teams have been awarded cash prizes and technical assistance vouchers under the BIL-funded Direct Air Capture Pre-Commercial Technology Prize based on their plans to address industry gaps with novel DAC technology designs. Teams are advancing their approaches throughout the competition and will construct integrated, bench-scale prototypes of their technology that are expected to operate across a range of environmental conditions for at least 500 hours. To progress in the competition, teams must also develop technology maturation plans describing the next phase of integrated testing.

FECM and NETL are funding Oak Ridge National Laboratory to investigate the use of DAC with building air-handling equipment and potential integration into HVAC systems. This project includes sorbent synthesis, integrated testing with an HVAC unit and mobile greenhouse, techno-economic and life cycle analysis, and development of a broader system integration strategy.

FECM and NETL also support the selection of various early-stage DAC technologies for Phase I and II funding through SBIR/STTR. Over the past few years, over a dozen companies have utilized different phases of SBIR funding to advance early-stage DAC concepts ranging from metal–organic frameworks to acid–base ion exchange to dual-functional materials and beyond.

Technologies enabling DAC via reactive carbon capture are currently low in technological maturity with ample research being conducted at the lab and component scales. Numerous CO_2-derived products can

[21] See DE-FOA-0002614 AOI-2A: AOI-2A – Carbon Dioxide Removal R&D: Bench-Scale Testing of Structured Material Systems, or Component Designs for Optimized Direct Air Capture. Project Selections for FOA 2614: Carbon Management (Round 1)

[22] See DE-FOA-0002614 AOI-2B Carbon Dioxide Removal R&D: Bench-Scale Testing of Optimized Direct Air Capture Integrated Processes. Project Selections for FOA 2614: Carbon Management (Round 1)

be produced through reactive carbon capture, translating to the possibility of various unique reactor designs and processes, each with their own benefits and drawbacks. However, there are overarching challenges that reactive carbon capture processes must all overcome; namely, they all must be able to handle dilute CO_2 streams while also achieving high product yield and conversion efficiency. Researchers must take steps with reactive carbon capture systems to address common issues such as catalyst poisoning and poor thermal management. To advance research into early-stage reactive carbon capture systems and launch the technology on a cost reduction trajectory, FECM and NETL issued a reactive carbon capture lab call in 2021[23] and selected a few teams developing reactive carbon capture pathways through the SBIR program. Future FOAs may provide additional opportunities for funding reactive carbon capture research.

As shown in Figures 1 and 2, continued technical research activities focused on novel materials, new structured material systems, novel component designs, and integrated bench-scale testing are expected to continue for up to the next decade as DAC technologies continue to mature. Funded projects will support the program goals outlined in this document and new areas of technical interest as they emerge. Early-stage research funding will occur in parallel with further development, piloting, front-end engineering and design (FEED) studies, and market-building activities to ensure continued innovation and support a diverse and robust DAC technology ecosystem.

2.1.4 Development and Market-Building Activities

While learning-by-researching is a key means for driving technology optimization and early cost reduction, learning-by-deployment and economies of scale enable continued cost reduction as technologies mature.[24] To support continued innovation and cost reduction, FECM and NETL are committed to supporting DAC technologies as they progress from the lab to the piloting stage and beyond. This is partially accomplished through funding for field testing, pre-FEED studies, and FEED studies, but also through broader ecosystem-level support with the DAC Hubs program, NETL DAC Test Center, and credit procurement support. These efforts are critical for promoting DAC scaling and leveraging it to accomplish Carbon Negative Shot™ and climate targets. DAC in particular stands to learn significantly from pilot facilities given the environmental and climatic variability that affects ambient air fed into the systems.

The Regional DAC Hubs program, funded by the Bipartisan Infrastructure Law and co-managed with the Office of Clean Energy Demonstrations (OCED), provides up to $3.5 billion to establish four megaton-scale DAC Hubs throughout the United States. Regional DAC Hubs are networks of DAC projects, CO_2 utilizers, transport systems, subsurface resources, and sequestration resources, all located within the same region to leverage shared infrastructure and learning to drive cost reduction. NETL and FECM have selected 14 project teams seeking to conduct initial feasibility studies and five project teams seeking to conduct FEED studies on potential DAC Hub locations throughout the United States. Two additional teams, overseen by OCED, have been selected for more advanced project development of facilities ultimately capable of removing 1 million metric tons of CO_2 per year. Work continues on implementing the selected DAC Hub projects, and future

[23] https://netl.doe.gov/sites/default/files/netl-file/21CMOG_PSC_Kumar.pdf

[24] Elia, A., Kamidelivand, M., Rogan, F., & Gallachóir, B. Ó. (2021). Impacts of innovation on renewable energy technology cost reductions. *Renewable and Sustainable Energy Reviews*, 138, 110488.

DAC Hub funding opportunities will focus on accomplishing the Congressional directive for the Hubs and continuing to holistically develop the United States' DAC ecosystem.

Pilot-scale/field testing is a key part of technology development as it provides data not always available at the laboratory/bench scale. This may include insights into material stability and process emissions over thousands of cycles in a real-world field installation. Results can be used to drive FEED studies, inform efficient and responsible process maturation, and accelerate technology deployment. Long-duration pilot tests are also essential to the identification of potential degradation products released into the environment by solvents and sorbents. NETL and FECM are highly interested in furthering DAC field testing with a particular focus on operation in real-world climatic conditions. Four teams have been funded under Area of Interest-2 of FOA 2188 and an additional five teams are being funded under Area of Interest-2B of FOA 2614, which are focused specifically on field testing integrated DAC systems. Studying degradation and managing corresponding co-pollutants is also a primary goal of FECM and NETL's Multi-Year Research Plan, in collaboration with FECM and NETL's work on point-source carbon capture.

Pre-FEED and FEED studies help establish site-specific process designs and involve composition of various engineering packages required for industrial implementation. These studies are a key step toward construction and operation, and completion is required to have a thorough understanding of facility requirements and considerations before breaking ground. FEED studies in particular prompt developers to work through staffing needs, resource access, permitting, plot plans, hazard and operability analysis, structural engineering, instrumentation engineering, and integrated project scheduling, all of which are vital for successful projects. Three teams have completed pre-FEED studies for DAC facilities removing at least 100,000 tonnes per year (tpa) in three distinct climates to investigate the impact of climatic variability. FOA 2560 funded three advanced FEED studies for DAC facilities intending to remove at least 5,000 tpa leveraging low-carbon sources of heat including nuclear, geothermal, and waste heat from industrial facilities. As DAC technologies continue to mature, it is expected that a higher proportion of funding will go toward completing pre-FEED and FEED studies to support continued commercialization.

Under the BIL-funded CDR Purchase Pilot Prize, FECM has announced 24 semifinalists for the first round of the prize competition that includes nine DAC teams intending to collectively provide 33,824 tonnes of removal credits generated via DAC over the course of the competition if selected.

To ensure continued robust development of DAC startups to eventually supply credits for these programs, FECM is also funding several DAC-focused startup accelerators through the DAC Pre-Commercial Energy Program for Innovation Clusters (EPIC) Prize. These organizations support DAC entrepreneurs to refine and commercialize their innovations. A separate Commercial DAC Pilot Prize has also been announced. This prize will support early-stage DAC startups as they design and construct their first pilot facilities capturing at least 500 tpa and prepare for further technological maturation.

For reactive carbon capture, development work conducted through FY28 will lead into the selection of pilot-scale and subsequent engineering design studies using future funding opportunities. Based on current development, Pre-FEEDs and FEED studies for reactive carbon capture technologies are expected to be performed from FY28 through FY30. Work beyond this scale will focus on maturing technologies at the large-pilot scale and accelerating full-scale commercialization.

Building on lessons learned, the CDR Program will continue DAC development and market-building across a range of approaches and TRLs both intramurally and extramurally to reduce costs and assist the technology's path to commercialization and scale. This will require continued efforts in novel material and process development; integrated testing at the bench, pilot, and demonstration scales; engineering design studies; and carbon removal credit procurement through various funding mechanisms, including grants, cooperative agreements, and prize competitions.

2.1.5 Life Cycle Analysis, Techno-Economic Analysis, and Measurement, Monitoring, Reporting and Verification Activities

Life cycle analysis and techno-economic analysis are required aspects of DOE's DAC projects. Project teams are generally expected to include these assessments and to iteratively conduct studies to inform parallel RD&D efforts. In addition, the Strategic Systems Analysis and Engineering group within NETL's Research and Innovation Center is refining baseline TEA and LCA case studies on solid sorbent,[25] aqueous solvent,[26] and mineral looping DAC to serve as benchmarks for comparative purposes. This work is a primary goal in NETL and FECM's Multi-Year Research Plan. To ensure rigor and consistency with past work, these studies will, where possible, utilize vendor quotes, EPC discussions, and assessment techniques applied in past NETL evaluations of point-source carbon capture systems.

MMRV for DAC is often simpler compared to other CDR pathways as it usually involves geologic storage of CO_2 captured directly from the atmosphere and can leverage decades of existing work on carbon storage from point-source carbon capture and storage. However, there are still open questions in DAC MMRV surrounding topics such as reversal risk and carbon accounting for different low-carbon energy procurement strategies. FECM and NETL are engaging with internal experts, industry stakeholders, academics, and others to better understand current issues and solutions in these domains. As part of the CDR Purchase Pilot Prize, competitors must submit and comply with suitable MMRV plans for their credit proposal. Several DAC companies have been selected as semifinalists, and FECM and NETL will ensure that all protocols, providers, and approaches are scientifically robust and defensible for carbon removal credit generation.

Coordination with the Carbon Conversion Program is ongoing for pathways involving DAC and carbon conversion, including reactive carbon capture. These coordination activities include advancement of LCA guidance and models for DAC processes with a conversion coproducts and development and demonstration of DAC technologies integrated with conversion or reactive carbon capture processes. MMRV can be complicated for this pathway due to the difficulty of tracking commodity chemicals throughout their diverse and vast supply chains and wide variability and lack of standards surrounding carbon storage in polymer products. To advance reactive carbon capture as a potential means of quality, defensible CDR, development of effective MMRV and LCA protocols and guidance is critical. Such work may also play a key role in determining the applicability of certain technologies for tax credits, government CDR purchasing, or a number

[25] J. Valentine, A. Zoelle, "Direct Air Capture Case Studies: Sorbent System," National Energy Technology Laboratory, Pittsburgh, PA, July 8, 2022.

[26] J. Valentine, and A. Zoelle, "Direct Air Capture Case Studies: Solvent System," National Energy Technology Laboratory, Pittsburgh, PA, August 31, 2022.

of other funding opportunities. MMRV development must be done in tandem with technology development to ensure any developed guidance is fair and applicable. Further behavioral or industrial changes outside of the scope of the CDR Program, such as improvements to plastics recycling, may be required to fully realize plans for production of carbon-negative materials using DAC CO_2.

2.1.6 Milestones

The below milestones are a means of quantitatively tracking progress toward the program goals as outlined in this MYPP.

Technology Development:

- Enable the continued development of DAC in the United States by successful completion of at least four (4) DAC Hubs FEED studies with a minimum initial capacity of at least 50 kta by 2026
- Design and implement techniques and infrastructure for trace pollutant quantification at the DAC Center by 2026
- Measure trace emissions from at least five DAC technologies conducting DAC Center testing by 2027
- Design and install a cyber physical testing interface at the DAC Center by 2027
- Field testing of at least three (3) 500 tpa Gen 2+ DAC technology small pilots by 2028
- Propose at least one accelerated aging protocol for predicting the long-term degradation of capture materials and initiate extended validation testing by 2028
- Deploy a 500 tpa small reactive carbon capture pilot by 2029 and initiate several 1,000 tpa large pilot field studies by 2030

Analysis:

- Develop case studies of DAC technologies into a viable baseline study that can serve as the basis/ benchmarks for protocol development by 2026
- Finalize computational fluid dynamics cost and performance, and LCA evaluation of passive DAC systems by 2026
- Finalize and deploy detailed models of base DAC systems that allow for the evaluation of technologies at a variety of ambient conditions covering differing climates and diurnal variations by 2027
- Create draft case studies for joint development and commercialization of at least three DAC materials/ processes by 2028
- Finalize market, TEA, and LCA evaluations of the most promising novel DAC technologies evaluated under this goal by 2028
- Costs have a defensible and credible pathway to decreasing below <$200 per net tonne CO_2e removed for both Gen 1 and Gen 2+ DAC technologies by 2030

Purchasing, Collaborations, and Broader Goals:

- Purchase thousands of tonnes of high-quality carbon removal credits from commercial-scale DAC activities by 2027
- Conclude joint development agreements with at least three partners for materials/processes at TRL varying from 2 to 5 by 2027
- Support technology maturation to ensure that as many DAC facilities as possible will commence construction by January 1, 2033, to be eligible for the 45Q tax credit

2.2 Marine Carbon Dioxide Removal (mCDR)

2.2.1 Technology Description and Approaches

Marine carbon dioxide removal (mCDR) pathways are potential CDR methods that utilize the ocean to draw down atmospheric carbon dioxide, and the U.S. Department of Energy is supporting research and development in the mCDR field in collaboration with other agencies such as the U.S. Department of Commerce's National Oceanic and Atmospheric Agency (NOAA) and the U.S. Army Corps of Engineers. Enhancing the ocean's ability to draw down CO_2 from the atmosphere, thereby durably removing it from the atmosphere for extended periods of time (hundreds to thousands of years), shows promise as a highly scalable and effective CDR method. More research needs to be done, not only into the foundational science behind these pathways, but also challenges remain around societal acceptance, governance, and MMRV.

In response to Congressional direction in the FY22 budget, the CDR Program initiated R&D activities related to the drawdown of CO_2 from the atmosphere into ocean waters.[27] mCDR solutions remove CO_2 from the atmosphere and upper hydrosphere and securely store the excess carbon, either in marine or geological reservoirs or long-lived products. In addition to CO_2 drawdown, some mCDR approaches could offer other societal and ecological co-benefits. Among these are development of a new coastal blue carbon economic sector, ecosystem restoration, and ocean acidification mitigation.[28] The 2022 National Academies of Sciences, Engineering, and Medicine report titled, "A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration" discusses the benefits, risks, and potential of mCDR generally, as well as the pathways identified as most promising. As shown in Figure 3, the approaches span a wide range of biotic and abiotic methodologies.[29]

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[27] "The agreement provides $5,000,000 for research, development, and demonstration activities related to the indirect sequestration of carbon dioxide from ocean waters." 168 Cong. Rec. H1709, 2184 (Mar. 9, 2022) (joint explanatory statement of Consolidated Appropriations Act, 2022). https://www.govinfo.gov/content/pkg/CREC-2022-03-09/pdf/CREC-2022-03-09-pt3-PgH1709.pdf.

[28] Cross, J.N., Sweeney, C., Jewett, E.B., Feely, R.A., McElhany, P., Carter, B., Stein, T., Kitch, G.D., and Gledhill, D.K., 2023. Strategy for NOAA Carbon Dioxide Removal Research: A white paper documenting a potential NOAA CDR Science Strategy as an element of NOAA's Climate Interventions Portfolio. NOAA Special Report. NOAA, Washington DC. DOI: 10.25923/gzke-8730.

[29] National Academies of Science, Engineering, and Medicine. (2022) A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration. https://nap.nationalacademies.org/catalog/26278/a-research-strategy-for-ocean-based-carbon-dioxide-removal-and-sequestration

Biotic:

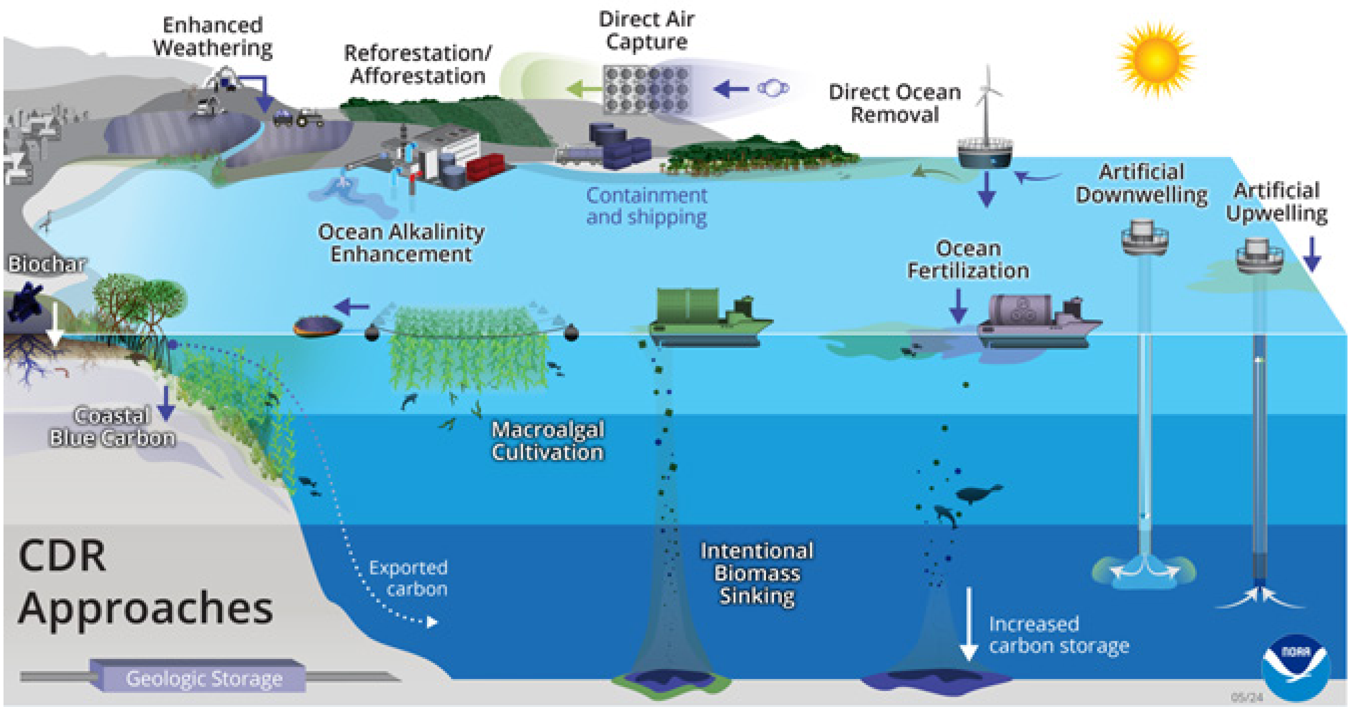
- **Nutrient fertilization**: Adding micronutrients (e.g., iron) or macronutrients (e.g. phosphorus or nitrogen) with the purpose of enhancing photosynthetic activity of marine phytoplankton, thereby increasing the amount of carbon dioxide taken up in the surface ocean and converted into biomass. Some of this biomass will sink to the deeper ocean, durably storing carbon dioxide away from the atmosphere.
- **Artificial upwelling and downwelling**: Artificial upwelling is the process of bringing deep water, which is more nutrient and CO_2 rich than surface waters, to the surface with the purpose of enhancing surface productivity. Artificial downwelling is the process of transporting surface water to the deeper ocean to increase ventilation in the deeper ocean to ease downward carbon flux.
- **Macroalgal cultivation**: Growing macroalgae takes up CO_2 from the atmosphere and converts it into biomass. Macroalgae is then intentionally sunk to the deep ocean, thereby storing carbon dioxide away from the atmosphere.

Abiotic:

- **Electrochemical approaches**: Electrochemical approaches refer to the direct removal of CO_2 from the ocean, or enhancement of ocean storage capacity of CO_2, by passage of a current through seawater. This changes CO_2 concentration and/or capacity by exploiting the pH-dependency solubility of CO_2 .
- **Ocean alkalinity enhancement**: Ocean alkalinity enhancement processes enhance the alkalinity of seawater, thereby increasing the amount of CO_2 that the ocean takes up from the atmosphere in order to re-establish equilibrium. This can be done in various ways, including direct liquid or mineral addition of alkaline substances to seawater, enhanced mineral weathering, and combined electrochemical or thermal approaches.

Combinations or hybrids of multiple mCDR approaches can be applied as well to make oceans more amenable to CO_2 uptake from the atmosphere through either the removal of CO_2 or the addition of alkaline materials to lower its pH. The net result is aimed at providing a way to utilize the ocean as a resource for drawing down CO_2 from the atmosphere, minimizing potential harm and maximizing potential co-benefits, such as decreased ocean acidity, increase photosynthesis by marine phytoplankton, transfer of carbon into the deep ocean and marine sediments, reduced eutrophication and hypoxia in coastal regions, and fishery enhancements.

Figure 3. Approaches to mCDR from NOAA's State of the Science Fact Sheet.[30]



2.2.2 Challenges and Program Goals

While many mCDR approaches conceptually show promise in scalability and effectiveness, many challenges remain before mCDR is a meaningful part of a gigaton-scale CDR portfolio. DOE is actively working to address those challenges with various R&D activities and through productive collaborations with partners. Challenges to the field, and how DOE is actively working to meet them, include:

- **Improving the overall effectiveness and durability of mCDR approaches, balanced with protecting ecosystems and invested communities from potential harm, and maximizing potential co-benefits.** In any type of research performed that can affect the makeup of the oceans, it is critical that activities minimize harm to the environment – balanced with the ongoing harm of climate change – and that oceanic activities adhere to domestic and international agreements.
    - **DOE is financially supporting research into mCDR** pathways through work in our national labs, various funding calls (e.g., eight mCDR Phase 1 projects funded through FOA 2614: Field Validation of Abiotic Ocean-Based Carbon Removal), and two mCDR projects funded through the NOAA-managed National Oceanographic Partnership Program[31] focused on foundational mCDR research. DOE will continue to invest in a broad portfolio of mCDR approaches to address key technical challenges and to meet the needs of the growing field and increase market interest.

[30] U.S. Department of Commerce. *State of the Science Fact Sheet- Carbon Dioxide Removal*. National Oceanic and Atmospheric Administration. https://sciencecouncil.noaa.gov/wp-content/uploads/2024/07/CDR-fact-sheet_final_-19July2024-1.pdf

[31] National Oceanic and Atmospheric Administration. (2023, September 7). *Announcing $24.3M Investment Advancing Marine Carbon Dioxide Removal Research*. NOAA Ocean Acidification Program. https://oceanacidification.noaa.gov/fy23-nopp-mcdr-awards/

  - **DOE is partnering with NOAA, the Federal government's expert in oceanographic and mCDR, through a Memorandum of Agreement** to collaborate to advance mCDR R&D over a five-year period through at least 2029, leveraging the capacities and strengths of each agency to meet the challenges of the field.[32]
- **Ensuring that mCDR activities are carried out in a manner that suits the local environment and communities, with robust life cycle analyses that ensure net-negative CO_2e and responsible material procurement and disposal**. RD&D efforts will be conducted in a manner that considers various stakeholder engagement to address critical issues, such as permitting and local economic and environmental benefits or impacts.
  - **DOE is a member of the White House Fast Track Action Committee on Marine Carbon Dioxide Removal (MCDR-FTAC)**, collaborating with other relevant agencies to craft a Federal Research Plan for mCDR.[33] As part of this effort, DOE is contributing expertise from lessons learned from other CDR pathways and the marine energy field on social responsibility and acceptance, driving down costs, and reliable LCA and TEA frameworks. This activity lays the groundwork for productive future collaboration and coordination to advance the science of mCDR and support responsible technology deployments.
  - **DOE plans to investigate opportunities for mCDR testbeds**, a need widely identified in the mCDR community. As seen in the marine energy field, test sites are a mechanism by which research can potentially be expedited, costs can be driven down, potential environmental impacts can be minimized, and community relationships can be built. Based on prior experience, DOE is a natural leader to fill this community need.
- **Confirming that if a future carbon credit market includes mCDR, there is robust measurement, monitoring, reporting, and verification of CO_2e**. Standardized and scientifically rigorous MMRV is needed to track that removal is effective and accurately accounted for when considering tax credits or incentives that make CDR economically viable.
  - **DOE is investing $35 million into development of next-generation MMRV technologies** through ARPA-E's Sensing Exports of Anthropogenic Carbon through Ocean Observation (SEA-CO_2) program.[34] While partner agencies such as NOAA maintain and expand their robust observational and monitoring capabilities for the global carbon cycle, DOE is complementing these activities by investigating next-generation mCDR monitoring technology. This work will need to continue with additional future support from DOE.
  - **DOE is holding funding recipients in the Purchase Pilot Prize to rigorous MMRV standards**, setting expectations of such standards throughout the market. The three mCDR competitors named as semifinalists from the BIL-funded CDR Purchase Pilot Prize intend to collectively provide 12,521

[32] U.S. Department of Energy. (2024, June 6) NOAA, DOE Sign Agreement to Advance Marine Carbon Dioxide Removal. Office of Fossil Energy and Carbon Management. https://www.energy.gov/fecm/articles/noaa-doe-sign-agreement-advance-marine-carbon-dioxide-removal

[33] United States, National Science and Technology Council. *Charter of the Marine Carbon Dioxide Removal Fast Track Action Committee of the Subcommittee on Ocean Science and Technology*. 19 September 2023, https://www.noaa.gov/sites/default/files/2023-10/mCDR_FTAC_charter_2023_09_19_approved.pdf

[34] U.S. Department of Energy. *Sensing Exports of Anthropogenic Carbon through Ocean Observation*. Advanced Research Projects Agency–Energy. https://arpa-e.energy.gov/technologies/programs/sea-co2

tonnes of removal credits generated via mCDR over the course of the competition, if selected, and must present robust MMRV plans.[35] Their selection as semifinalists in the Purchase Pilot Prize not only helps push the mCDR field to high MMRV standards, but also signals to potential private investors that the mCDR field is capable of producing high-quality carbon credits. DOE has allocated additional funding to continue purchasing activities.

2.2.3 Technical Research Activities

The CDR Program is funding eight abiotic mCDR conceptual design studies to assess the current state of technology readiness and better inform future R&D needed to achieve the Carbon Negative Shot™ target of $100/net tCO_2e removed. These studies will be followed by down-selected field validations to assess real-world performance, cost, and environmental impacts. Building on lessons learned, the CDR Program will continue these foundational efforts both intramurally and extramurally in collaboration with the Office of Science, ARPA-E, and NOAA to reduce both the capital and operating costs while ensuring responsible environmental stewardship. The CDR Program is particularly interested in abiotic mCDR technologies that feature one or more of the following capabilities:

- Incorporation of processes and/or materials that maximize durability or permanence of the carbon removed from air and stored in the ocean;
- Operation under a wide range of environmental conditions;
- Adoption of transformational mCDR materials, novel concepts, or hybrid systems that mitigate environmental risks to the local aquatic environment;
- Maximize CO_2 capture volumetric productivity (net removal efficiency on a unit material and energy basis) of mCDR components to reduce size, capital costs, and environmental footprint of integrated systems;
- Integration with existing or new infrastructure (marine energy technologies, desalination facilities, wastewater treatment, beach nourishment etc.) for deployment of solids or solutions into seawater to reduce capital costs;
- Ability to reduce auxiliary power by utilizing novel equipment, component designs, and/or process schemes that allow heat integration; and
- Development and evaluation of mCDR carbon accounting and MMRV models, approaches and sensor technologies to continuously monitor carbon removal permanence.

Future funding opportunities will expand on the current foundational research portfolio (i.e., NOAA National Oceanographic Partnership Program (NOPP) program and FOA 2614), and current carbon market activities. The CDR Program is interested in continued R&D of advanced mCDR technologies, integrated pilot-scale testing in relevant environments, and the design of commercial-scale mCDR systems through pre-FEED and FEED studies. Further work may be aimed toward demonstrating matured technologies at large pilot scale or at developing next generation mCDR technologies starting at lab and component scales. During this time, additional technology development will occur through SBIR/STTR funding to continue to innovate mCDR technology advancement by small businesses.

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[35] U.S. Department of Energy. *DOE Announces $1.2 Million To Accelerate America's Carbon Dioxide Removal Industry.* https://www.energy.gov/articles/doe-announces-12-million-accelerate-americas-carbon-dioxide-removal-industry

2.2.4 Development and Market-Building Activities

Markets for mCDR, and CDR broadly, are emerging independent of government validation or regulated commercial deployment. There remain many open questions on regulatory compliance for commercial mCDR developments and engagement with international protocols and treaties (London Convention and London Protocol, High Seas Treaty, etc.). In recognition of these challenges, and to lay the groundwork for a field moving towards possible commercialization, DOE has selected semifinalists for the CDR Purchase Pilot Prize and is reviewing the technical merits of their proposals.

2.2.5 Life Cycle Analysis, Techno-Economic Analysis, and Measurement, Monitoring, Reporting, and Verification Activities

NETL is finalizing a comprehensive report on LCA and TEA for mCDR. This report will investigate various needs, challenges to be met, and responsibilities to uphold throughout the life cycle of various mCDR pathways. A critical challenge to the success of mCDR, and many CDR pathways broadly, is responsible disposition and identification of alternative uses for byproducts (e.g., H^+, CO_2 stripped from seawater). Another challenge to be addressed throughout the life cycle of a project is energy needs. To maximize the net CO_2e removed from an activity, zero-carbon energy that is not used from a pre-existing limited energy supply is preferred. Potential synergies in this area exist with the Office of Energy Efficiency and Renewable Energy's Water Power Technologies Office (WPTO). To help ensure that mCDR is carried out in an energy-efficient and responsible manner, WPTO has invested in activities and infrastructure related to mCDR at DOE's Pacific Northwest National Laboratory and is involved in the White House MCDR-FTAC Research Plan drafting process.

Critical components of LCA and TEA activities are ensuring the net-negative CO_2e of mCDR activities. Here, the CDR Program recognizes ARPA-E's work in their SEA-CO_2 program and plans to issue funding opportunities for MMRV R&D. Robust MMRV will be critical for the development of a responsible carbon credit market, and ocean systems pose unique challenges to accurate MMRV. In recognition of the importance of MMRV, the CDR Program is holding the Purchase Pilot Prize semifinalists to high MMRV standards.

2.2.6 Milestones

Recognizing the promise that mCDR holds as a scalable and effective CDR solutions mix, the presence of mCDR in the CDR Program's portfolio has increased over the past few years. The DOE's involvement in fruitful collaboration with NOAA and other government partners through a Memorandum of Agreement and the White House Fast Track Action Committee are evidence of this growing focus on mCDR, respectively. Multiple mCDR research projects have been funded through the NOAA NOPP funding call supported by DOE, FOA 2614, the SBIR program, ARPA-E's SEA-CO_2 program, and the Purchase Pilot Prize. LCA and TEA studies are currently underway at NETL. Continuing to grow activity in the mCDR space in the coming years is a priority for the CDR Program, in line with the following milestones.

Technology Development:

- Field testing of at least two 1 tpa mCDR small pilots by 2027
- Collaborate with other federal agencies, leveraging existing agreements and developing new partnerships, to establish and operate a network of coordinated test centers and laboratory facilities for mCDR R&D across the U.S., inclusive of bench-scale operations, small pilot and prototype testing capabilities, mesocosm and raceway[36] facilities, and appropriately permitted field test sites by 2028
- Complete at least three mCDR FEED studies by 2029
- Develop at least two large scale (not less than 1000 tpa) mCDR pilots by 2029

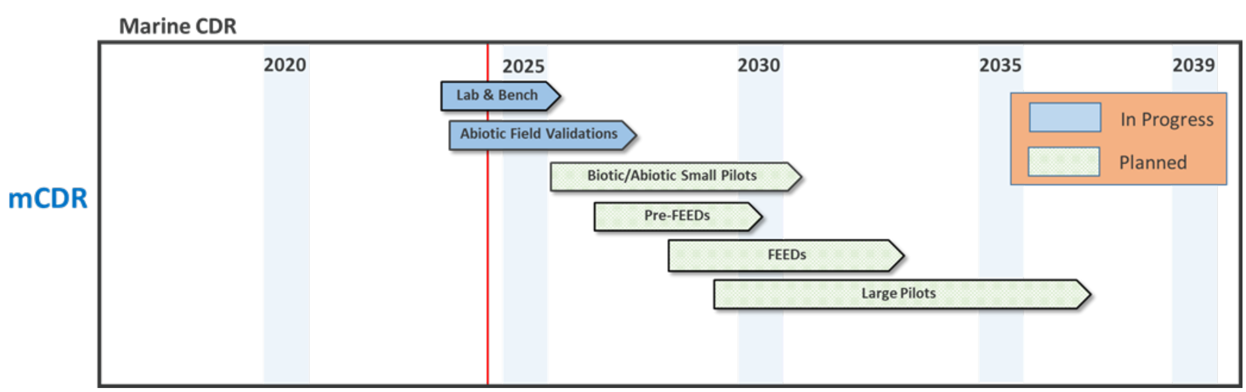
Analysis:

- Complete LCA and TEA case study for at least one mCDR approach by 2025
- Develop LCA best practices for mCDR approaches by 2027, including best practice guidelines around responsible procurement of resources (including energy), and disposal of byproducts
- Finalize market and LCA evaluations of the most promising novel mCDR technologies evaluated under this goal by 2028

Collaborations and Broader Goals:

- Ongoing participation in the White House Marine Carbon Dioxide Removal Fast Track Action Committee report(s) including participation in and associated interagency working groups
- Through at least 2029 (5-year period of the current Memorandum of Agreement), collaborate with NOAA on a variety of mutually agreed-upon mCDR research and development activities, including cost-sharing activities and national lab participation
- Costs have a defensible and credible pathway to decrease below <$200 per net tonne CO_2e removed for mCDR technologies by 2030

Figure 4. Projected funding opportunities for mCDR technologies.



[36] Mesocosms are experimental systems, typically tanks, that enable monitoring and assessment of representative natural systems within a controlled environment.
Raceways are shallow artificial ponds, typically in a rectangular or oval configuration with perturbation or water flow to enable the growth of algae in concentrated systems.

2.3 Biomass Carbon Removal and Storage (BiCRS)

2.3.1 Technology Description and Approaches

Biomass carbon removal and storage (BiCRS) refers to the broader suite of biomass-based CDR approaches beyond those that produce energy or employ point source carbon capture and storage technologies (biomass energy with carbon capture and storage, or BECCS).[37] As introduced in the 2020 Innovation for Cool Earth Forum Roadmap, BiCRS refers to processes that a) use biomass to remove CO_2 from the atmosphere, b) store CO_2 or carbon in the subsurface or in long-lived products, and c) does not damage, and ideally promotes, food security, rural livelihoods, biodiversity conservation, and other important values (e.g. culturally significant sites and resources).

BiCRS pathways are wide ranging and can leverage many sustainably-sourced biomass feedstocks (e.g. woody biomass, algae, agricultural cover crops and residues, perennial grasses, etc.), conversion processes (hydrothermal liquefaction, combustion, pyrolysis, torrefaction, gasification, etc.), and terminal storage mechanisms (long-lived bioproducts, geological storage, biochar, bio-oil, etc.) to remove CO_2 from the atmosphere. Biomass feedstocks can also produce a variety of products and coproducts that may displace more carbon intensive incumbent products, reducing emissions alongside carbon removal.

DOE has historically focused on BiCRS technologies that require dedicated point-source carbon capture technologies. In the context of BiCRS pathways, the Point Source Carbon Capture Program focused almost exclusively on BECCS technologies over the last 20 years, but the CDR Program is broadening R&D efforts to include all BiCRS approaches since biomass can act as an efficient CO_2 removal medium without the additional requirement of energy production. Additionally, the BiCRS terminology focuses on the biomass's inherent carbon value, or ability to remove CO_2, rather than its energy capacity. With this shift in evaluation, different feedstocks can provide different benefits under varying scenarios. For example, one recent study illustrated that at carbon prices below \$200/tCO_2 (which are currently available in U.S. public and private markets), it becomes more valuable to use municipal solid waste and forestry residue for carbon removal through a BiCRS process than to use the wastes for bioenergy alone.[38]

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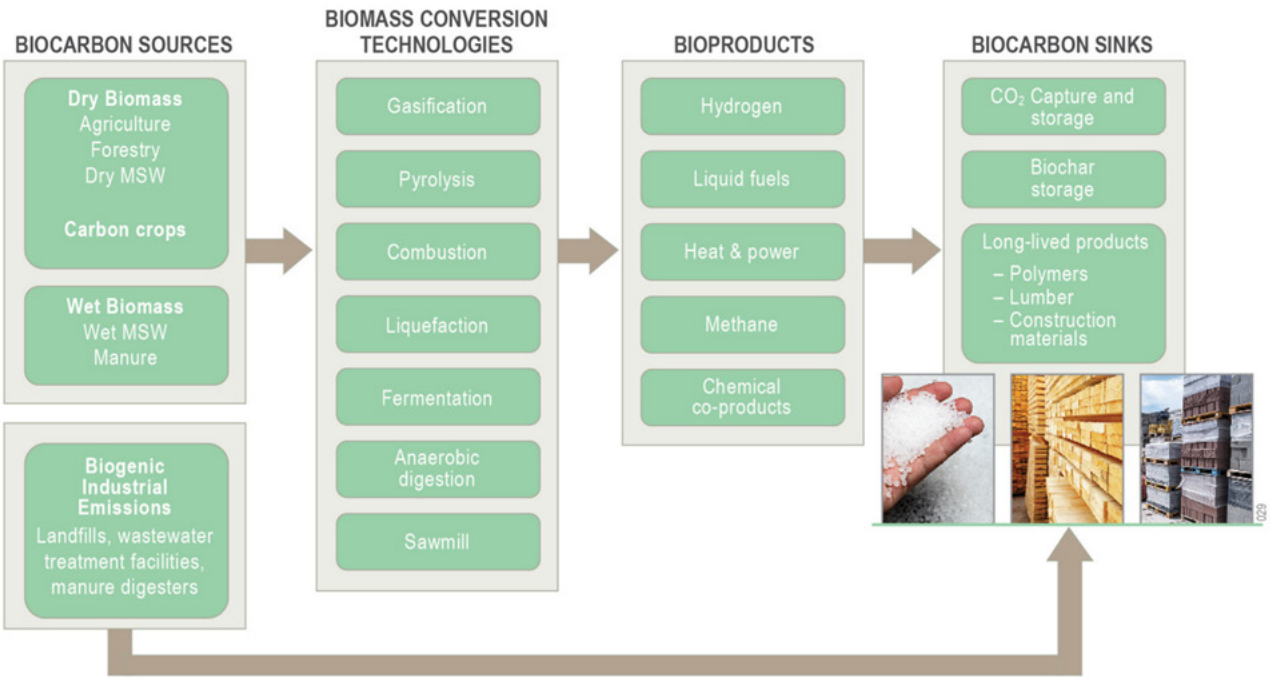
[37] Sandalow, David, Aines, Roger, Friedmann, Julio, McCormick, Colin, and Sanchez, Daniel L. *Biomass Carbon Removal and Storage* (BiRCS) Roadmap. United States: N. p., 2021. Web. doi:10.2172/1763937.

[38] Woodall CM and McCormick CF (2022). Assessing the optimal uses of biomass: Carbon and energy price conditions for the Aines Principle to apply. Front. Clim. 4:993230. doi: 10.3389/fclim.2022.993230

Figure 5. BiCRS feedstocks, conversion technologies, products, and storage mechanisms. (Roads to Removal, 2023, Figure 6-20).[39]



Moreover, the regionality, temporal availability, and preexisting markets for biomass feedstocks require that proposed conversion approaches and storage methods align with proximate resources or that low-cost and low-emissions transportation opportunities exist. The landscape of BiCRS pathways is rapidly evolving, as a commercial emphasis on net carbon removal potential, in lieu of energy production, has redirected RD&D efforts toward pathways that can most effectively and sustainably remove CO_2 from the atmosphere without disrupting ecosystem integrity, food systems, and other social and environmental considerations.[40]

Commercial production or collection of biomass feedstocks, such as woody biomass, dedicated crops, and algae, requires significant agricultural inputs with potential adverse impacts on ecosystems, food production, and biodiversity. Responsible and science-based management of natural and working lands, including forestry and land management, optimal water usage, and environmentally safe agricultural practices are necessary to maximize the overall sustainability and application of BiCRS. Cultivating, transporting, and processing biomass at large scales has introduced numerous challenges in ensuring sustainable land management and high carbon efficiency. Because BiCRS technologies have not been developed on a substantial scale, additional challenges remain unresolved including the environmental impacts and energy demand of biomass processing. Additionally, evaluating the CDR impact of these technologies for efficiency calculations and carbon incentives presents challenges for all BiCRS technologies in terms of tailored MMRV protocols.

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[39] Pett-Ridge, J., Kuebbing, S., Mayer, A. C., Hovorka, S., Pilorgé, H., Baker, S. E., ... & Zhang, Y. (2023). *Roads to removal: options for carbon dioxide removal in the United States* (No. LLNL-TR-852901). Lawrence Livermore National Laboratory (LLNL), Livermore, CA (United States).

[40] Pett-Ridge, Jennifer, Slessarev, Eric W., Schmidt, Briana M., Peridas, George, Pang, Simon H., and Baker, Sarah E. *Initial Considerations for Large-Scale Carbon Removal in the United States.* United States: N. p., 2022. Web. doi:10.2172/1867535.

DOE has committed to a multifaceted approach for the deployment of BiCRS technologies, which prioritizes food security, rural livelihoods, biodiversity conservation, and other important values related to just and responsible deployment. The CDR Program is funding two BiCRS pre-FEED studies to assess the current state of technology readiness, support private-sector efforts to receive 45Q tax credits for initial deployments, and better inform future R&D needed to achieve the Carbon Negative Shot™ target of $100/net t$CO_2$e.

DOE and FECM RD&D programs address a range of challenges across the bioeconomy. The scope of BiCRS RD&D activities within the CDR Program is constrained to processes that demonstrate alignment with DOE's Carbon Negative Shot, meaning potential to contribute to a portfolio of approach to achieve $100 per net tonne of CO_2 removed, with robust MMRV and sustained storage of at least 100 years. Optimizing the use of biomass resources for CDR applications must be balanced with alternative ecosystem, economic, and energy needs, and the RD&D activities outlined in this MYPP attempt to identify BiCRS pathways that are most likely to scale cost-effectively, while balancing other social and environmental objectives. Figure 5 provides an illustrative diagram of BiCRS pathways, indicating the extensive permutations of feedstocks, conversion process, and storage mechanisms.

The landscape of BiCRS technologies and pathways introduces multiple topics with overlaps in other DOE Offices and FECM programs. BiCRS pathways may be used to produce energy products, such as hydrogen (Hydrogen Fuel Cell Technology Office and FECM's Hydrogen with Carbon Management Program) or sustainable aviation and transportation fuels (Bioenergy Technologies Office). BiCRS pathways also may require transport and storage infrastructure (FECM's Carbon Transport and Storage Program), include conversion of carbon oxides and biogenic feedstocks into value-added products (FECM's Carbon Conversion Program), or leverage carbon capture technologies (FECM's Point Source Carbon Capture Program). Accordingly, this MYPP accounts for and aligns with the programming and objectives of other DOE offices and FECM programs, leveraging collaboration opportunities and avoiding duplication of efforts.

2.3.2 Challenges and Program Goals

BiCRS pathways and technologies face a variety of challenges for commercialization, including improving the efficiency of conversion processes for both net-removal potential and economics, streamlining and advancing biomass collection, cultivation, transportation and preprocessing, and improving MMRV tools and frameworks.

LCA is expected to serve a crucial role in the BiCRS pathway, as the net-negativity or CDR efficiency of a technology or process is contingent on the lifecycle boundaries and assumptions used to calculate total greenhouse gas flows on a unit basis.[36] Standardization of LCA practices and guidance for the emissions accounting of biomass-based pathways will differentiate processes with the potential to remove CO_2 from the atmosphere with secure storage from processes that may provide emissions reductions or avoidances. The objectives outlined in this section focus on the workstreams needed to improve LCA tools and practices and advance pathways likely to deliver scalable CDR. Specifically, many BiCRS processes involve interventions within existing biomass-based processes, such as pulp and paper operations or biofuel production. Important considerations regarding the additionality and attribution of emissions benefits from process alterations need to be addressed to determine whether a given pathway can be considered BiCRS. Moreover, given the limited availability of biomass feedstocks and competing alternate use cases, responsibly scaling BiCRS pathways within the broader bioeconomy will require strategic and intentional allocation of resources toward the highest value application.[37] This MYPP does not assign or provide a framework to assess the relative value of competing biomass uses, however, the RD&D activities described in subsequent sections are expected to yield key performance metrics, scalability and sustainability criteria, and technology development and demonstration milestones to help identify, vet, and develop effective and sustainable BiCRS approaches.

2.3.3 Technical Research Activities

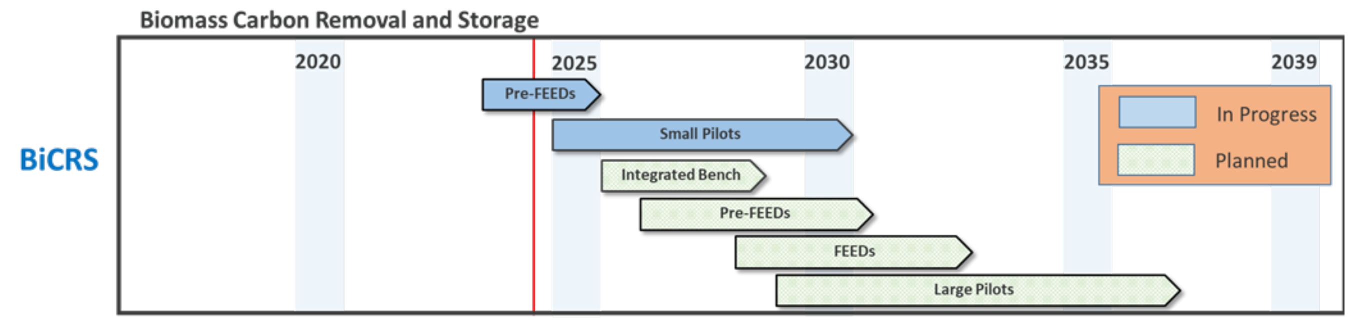
The objective of the CDR Program is to research, identify, develop, demonstrate, commercialize, and scale BiCRS pathways. The CDR Program is particularly interested in advanced BiCRS technologies that feature one or more of the following capabilities:

- Account for the diverse combinations of factors that influence BiCRS processes, including the selection and preparation of sustainably sourced biomass (e.g., composition, harvesting, pre-treatment steps, feeding) and the influence of the environment (e.g., temperature, humidity) to reduce costs
- Maximize BiCRS durability and permanence of carbon removal
- Optimize net CO_2 removal efficiency to reduce material requirements, capital costs, land requirements, and environmental footprint
- Consolidation of two or more unit processes/unit operations to potentially achieve the desired reductions in carbon removal capital cost and improvements in carbon removal efficiency
- Reduce auxiliary power by utilizing novel equipment, component designs, and/or process schemes that allow heat integration
- Identify, characterize, and address ecosystem and public health benefits associated with collection and conversion of hazardous biomass and other biogenic feedstocks for BiCRS applications
- Develop and implement BiCRS carbon accounting and MMRV approaches and technologies
- Deploy advanced detection tools to collect the needed data, define baselines, and develop automated analysis capabilities to monitor real-time CO_2 uptake rates and quantities achieved through BiCRS implementation

Future funding opportunities will expand on the current efforts in BiCRS. From FY25 through FY28, DOE will fund small pilots capable of removing at least 1 kta.[41] In FY26-FY27, an additional round of funding of commercial-scale pre-FEED and FEED studies is projected. Finally, large pilot studies are envisioned for FY28 through FY30. During this time, additional technology development will occur through SBIR/STTR funding to continue to innovate BiCRS technology advancement by small businesses.

[41] DOE Invests $58 Million to Tackle Climate Change by Removing Carbon From the Atmosphere | Department of Energy

Figure 6. Projected funding opportunities for BiCRS technologies.



2.3.4 Development and Market-Building Activities

To support continued innovation and cost reduction, FECM and NETL are committed to supporting BiCRS technologies as they progress from the lab to the piloting stage and beyond. This is partially accomplished through funding for field testing, pre-FEED studies, and FEED studies, but also through broader ecosystem-level support with credit procurement support. These efforts are critical for promoting BiCRS scaling and leveraging it to accomplish Carbon Negative Shot™ and climate targets.

Pilot-scale/field testing is a key part of technology development as it provides data not always available at the laboratory/bench scale. This may include insights into material stability and process emissions over thousands of hours of operation under variable environmental conditions in a real-world field installation. Results can be used to drive FEED studies, inform efficient and responsible process maturation, and accelerate technology deployment. NETL and FECM are highly interested in furthering BiCRS pilot testing with a particular focus on operation in real-world climatic conditions. Studying degradation and corresponding co-pollutants is also a primary goal of FECM and NETL's Multi-Year Research Plan.[42]

Pre-FEED and FEED studies help establish site-specific process designs and involve composition of various engineering packages required for industrial implementation. These studies are a key step toward construction and operation, and completion is required to have a thorough understanding of facility requirements and considerations before breaking ground. FEED studies in particular prompt developers to work through staffing needs, resource access, permitting, plot plans, hazard and operability analysis, structural engineering, instrumentation engineering, and integrated project scheduling, all of which are vital for successful projects. Under FOA 2614, the CDR Program is funding two BiCRS pre-FEED studies to assess the current state of technology readiness for CO_2 removal in electric power generation and industrial applications, support private-sector efforts to receive 45Q tax credits for initial deployments, and better inform future R&D needed to achieve the Carbon Negative Shot™ target of $100/net tCO_2e. As BiCRS technologies continue to mature, it is expected that a higher proportion of funding will go toward completing pre-FEED and FEED studies to support continued commercialization.

[42] In contrast to Muti-Year Program Plans, which provide a high-level public overview of anticipated FECM programming, Multi-Year Research Plans summarize specific intramural tasks that are performed and managed by the National Energy Technology Laboratory's Research and Innovation Center.

As part of the funding for pre-commercial and commercial DAC prize competitions provided by BIL, FECM launched the $35 million CDR Purchase Pilot Prize, which will be the first instance in history of federal procurement of CDR credits. As of November 2024, FECM has announced 24 semifinalists for the first round of the prize competition that includes seven BiCRS teams intending to collectively provide 112,035 tonnes of carbon removal credits over the course of the competition, if selected. To supplement this initiative, FECM also announced the Voluntary CDR Purchasing Challenge that will call on external organizations to join DOE in purchasing CDR credits. This unique effort will send an important signal to the market and funnel much-needed funds toward BiCRS providers seeking to secure financing.

Building on lessons learned, the CDR Program will continue BiCRS development and market-building across a range of approaches and TRLs both intramurally and extramurally to reduce costs and assist the technology's path to commercialization and scale. This will require continued efforts in novel material and process development; integrated testing at the bench, pilot, and demonstration scales; engineering design studies; and carbon removal credit procurement through various funding mechanisms, including grants, cooperative agreements, and prize competitions.

2.3.5 Life Cycle Analysis, Techno-Economic Analysis, and Measurement, Monitoring, Reporting, and Verification Activities

Life cycle analysis and techno-economic analysis are required deliverables of DOE's awarded BiCRS projects. Project teams are generally expected to include these assessments and to iteratively conduct studies to inform parallel RD&D efforts. In addition, the Strategic Systems Analysis and Engineering group within NETL's Research and Innovation Center is developing baseline TEA and LCA case studies for BiCRS approaches to serve as benchmarks for comparative purposes. This work is a primary goal in NETL and FECM's Multi-Year Research Plan. To ensure rigor and consistency with past work, these studies will, where possible, utilize vendor quotes, EPC discussions, and assessment techniques applied in past NETL evaluations of point-source carbon capture systems.

To ensure credibility and transparency, reliable MMRV methods, which are essential to ensure the stability and permanence of captured CO_2, are necessary. The effectiveness of current measurement methods themselves can vary widely depending on the BiCRS approach. Furthermore, a number of variables and operational decisions in a given system configuration make standardization difficult. Standardized protocols to accurately measure and report carbon sequestration are still in development, adding complexity to the process, especially in open systems. Ultimately, these challenges lead to an increase in overall costs. Specifically, to address the full lifecycle of emissions for a BiCRS pathway, there is a need to characterize the impact of feedstock cultivation and harvesting on soil carbon sequestration. Accordingly, FECM has supported research and development to study these plant-soil interactions as well as novel tools to more accurately and cost-effectively measure soil carbon stocks and fluxes.[43]

[43] Office of Fossil Energy and Carbon Management. (2023). DOE Announces Over $5 Million Toward Four Lab-led Energy Projects Supporting Carbon Management and Resource Sustainability. Department of Energy. Washington, DC. DOE Announces Over $5 Million Toward Four Lab-led Energy Projects Supporting Carbon Management and Resource Sustainability

The CDR Program plans to expand on initial TEA efforts that have identified MMRV as a challenge to large-scale BiCRS deployment, as well as continue to support the development of a framework for MMRV through the national laboratories to level-set and harmonize across protocols under development by non-governmental organizations and the private sector. As a companion to these efforts, the CDR Program also plans to develop and publish a set of LCA best practices to assist stakeholders across the supply chain with their ability to pursue the most promising methods developed.

2.3.6 Milestones

Technology Development

- Field testing of at least three 1,000 tpa BiCRS small pilots by 2028
- Complete at least three BiCRS FEED studies by 2029

Analysis

- Develop LCA best practices document for BiCRS by 2027
- Finalize market and LCA evaluations of the most promising novel BiCRS technologies evaluated under this goal by 2028

Broader Goals

- Reduce costs of BiCRS technologies to meet Carbon Negative Shot™ goals of achieving <$100 per net tonne CO_2e across the portfolio of CDR approaches

2.4 Enhanced Mineralization

2.4.1 Technology Description and Approaches

Rocks containing alkali minerals[44] remove CO_2 from the atmosphere by chemically reacting with air and water to form stable solid carbonate compounds as part of the natural carbon cycle. This process provides a thermodynamically favorable form of permanent carbon storage (see Equation 1). Mineral carbonates represent the largest resource for long-term CO_2 sequestration (i.e., one million years) with a storage capacity of greater than one million gigatons (quadrillion) globally.[45] Silicate minerals such as olivine (i.e., Mg_2SiO_4), non-silicate minerals including hydroxides (e.g., brucite $Mg(OH)_2$, lime $Ca(OH)_2$) as well as carbonates (e.g., calcite $CaCO_3$) themselves can mineralize to form carbonates.

$$MO + CO_2 \rightarrow MCO_3 + heat \quad (1)$$

[44] Most commonly calcium- and magnesium-rich silicates.

[45] Kelemen, P., Benson, S.M., Pilorgé, H., Psarras, P., and Wilcox, J. (2019) An Overview of the Status and Challenges of CO_2 Storage in Minerals and Geological Formations. Front. Clim. 1:9. DOI: 10.3389/fclim.2019.00009

Enhanced mineralization routes accelerate these reaction rates, which normally occur over geologic timescales (i.e. millennia), to align with the timelines necessary for the use of atmospheric CO_2 sourced directly from the air or atmospheric CO_2 rich solutions to contribute to climate goals (i.e., years to decades).[46] Research into carbon mineralization was spearheaded in the 1990s, including Walter Seifritz's investigation into accelerating the natural weathering processes for olivine and serpentine (i.e., $Mg_3Si2O_5(OH)_4$) to demonstrate the theoretical and practical feasibility of using abundant minerals to sequester CO_2 on a large scale,[47] as well as Klaus Lackner and his team's work on mineralization processes for the conversion of atmospheric CO_2 captured from DAC into stable carbonates.[48]

The three main methods of enhanced mineralization are in-situ, ex-situ, and surficial. In-situ approaches, or reactions that occur underground in geologic formations by injection of concentrated CO_2 streams that mineralize in the pores of the rocks, are covered in the Carbon Transport and Storage (CTS) Program's MYPP. The CDR Program, as described here, is focused on advancing methods of above ground mineralization, which are more nascent in their development efforts. These two approaches are differentiated by their location and set-up, as well as process control, scalability, and speed.

- **Ex-situ mineralization** occurs in controlled environments (i.e. reactors or other engineered systems like DAC) at an industrial facility or dedicated carbonation plant typically removed from natural mineral sites. This allows for greater control and optimization of reaction conditions, but at the expense of larger energy and resource requirements.
- **Surficial mineralization** takes place at or near the ground surface and with less direct intervention for enhancement (e.g., spreading fine mineral particles over large areas to increase surface area available for reacting), thus potentially lowering energy and resource requirements.

Carbon captured via these methods may be permanently stored in natural systems or materials in the form of value-add products (e.g., concrete). Enhanced rock weathering is a type of surficial approach that occurs when intermediate bicarbonate ions form at the ground surface through natural weathering and either result in soil carbonate minerals or drain away and precipitate as carbonate minerals upon entry into the ocean carbon cycle. As such, enhanced rock weathering is typically used to describe methods where fine mineral particles are applied to agricultural lands and coastlines as opposed to industrial and waste management sites.[49] A number of studies have been published to demonstrate the potential of enhanced rock weathering,

[46] White, S.K., Spane, F.A., Schaef, H.T., Miller, Q.R.S., White, M.D., Horner, J.A., McGrail, B.P. Quantification of CO_2 Mineralization at the Wallula Basalt Pilot Project. *Environ Sci Technol.* 2020 Nov 17; 54(22): 14609-14616. doi: 10.1021/acs.est.0c05142.

[47] Seifritz, W. 1990. CO_2 Disposal by means of silicates. Nature 345(6275):486. DOI: 10.1038/345486b0.

[48] Lackner, K.S., C.H. Wendt, D.P. Butt, E.L. Joyce, and D.H. Sharp. 1995. Carbon-dioxide disposal in carbonate minerals. Energy 20(11):1153-1170. DOI: 10.106/0360-5442(95)00071-N.

[49] Schuiling, R.D., Krijgsman, P. Enhanced Weathering: An Effective and Cheap Tool to Sequester CO_2. Climatic Change 74, 349–354 (2006). https://doi.org/10.1007/s10584-005-3485-y

resulting in increased interest in its further investigation and application.[50, 51, 52, 53] This approach can also contribute to enhancing ocean alkalinity and slowing ocean acidification,[54] which are covered in more detail in the mCDR technology section.

The Department's investigation of carbon mineralization as a promising method for permanent CO_2 storage dates to the early 2000s through field studies and simulations to gain insight into the reaction and separation mechanisms and the effects of geological conditions.[55, 56] These initial efforts included identifying suitable minerals, such as olivine and serpentine, as well as optimizing the conditions under which industrial by-products could be used for sequestration. Since then, FECM and NETL have funded numerous research projects aimed at better understanding and accelerating mineral carbonation. These efforts have largely focused on in-situ approaches with significant applied R&D activities pursued through the CTS Program, as well as the Point Source Carbon Capture Program in the reaction of point source CO_2. Enhanced mineralization, for example, is a key focus for the CTS Program's CarbonSAFE initiative, established in 2015 and aimed at developing large-scale, safe, and permanent CO_2 storage sites. Several CarbonSAFE projects have explored the feasibility of using different mineral substrates for ex-situ carbonation. Pilot projects and field demonstrations aimed at validating the effectiveness of enhanced mineralization in real-world conditions, have bridged the gap between laboratory research and large-scale implementation. More details on the history of these activities and plans for future efforts for in-situ mineralization methods more specifically are described in the CTS Program's MYPP. The CDR Program, established in 2021, now seeks to leverage the established understanding of carbon mineralization reactions to further scale above ground mineralization, including enhanced rock weathering, due to the near-term potential to help achieve the Carbon Negative Shot™ goal.

Alkali minerals from mafic (e.g., basalt) and ultramafic igneous rocks (e.g., dunite, peridotite), known for their high magnesium and iron content along with moderate to low silica content, are found in natural geologic formations, particularly in the Pacific Northwest and Southeast within the continental United States (see Figure 7). Alkaline feedstocks can also be sourced from minerals found in mine tailings from both operating and closed mines, as well as by-products from industrial facilities (e.g., cement kiln dust, steel slag) as a means of avoiding new mining efforts. These reactive mineral-containing materials can also lower the energy required for mineralization due to their non-crystalline nature which enhances the material dissolution rate.

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[50] Beerling, D.J.; Kantzas, E.P.; Lomas, M.R.; Wade, P.; Eufrasio, R. M.; Renforth, P.; Sarkar, B.; Andrews, M.G.; James, R.H.; Pearce, C. R.; Mercure, J.-F.; Pollitt, H.; Holden, P. B.; Edwards, N.R.; Khanna, M.; Koh, L.; Quegan, S.; Pidgeon, N.F.; Janssens, I.A.; Hansen, J.; Banwart, S.A. Potential for Large-Scale CO_2 Removal via Enhanced Rock Weathering with Croplands. *Nature* **2020**, 583 (7815), 242-248.

[51] Almaraz, M,; Bingham, N.L.; Holzer, I.O.; Geoghegan, E. K.; Goertzen, H.; Sohng, J.; Houlton, B.Z.; Methods for Determining the CO_2 Removal Capacity of Enhanced Weathering in Agronomic Settings. *Frontiers in Climate* **2022**, 4, 1.

[52] Knapp, W.J.; Stevenson, E. I.; Renforth, P.; Ascough, P. L.; Knight, A.C.G.; Bridgestock, L.; Bickle, M.J.; Lin, Y.; riley, A.L.; Mayes, W.M.; tipper, E.T. Quantifying CO_2 Removal at Enhanced Weathering Sites: A Multiproxy Approach. *Environ. Sci. Technol.* **2023**, 57(26), 9854-9864.

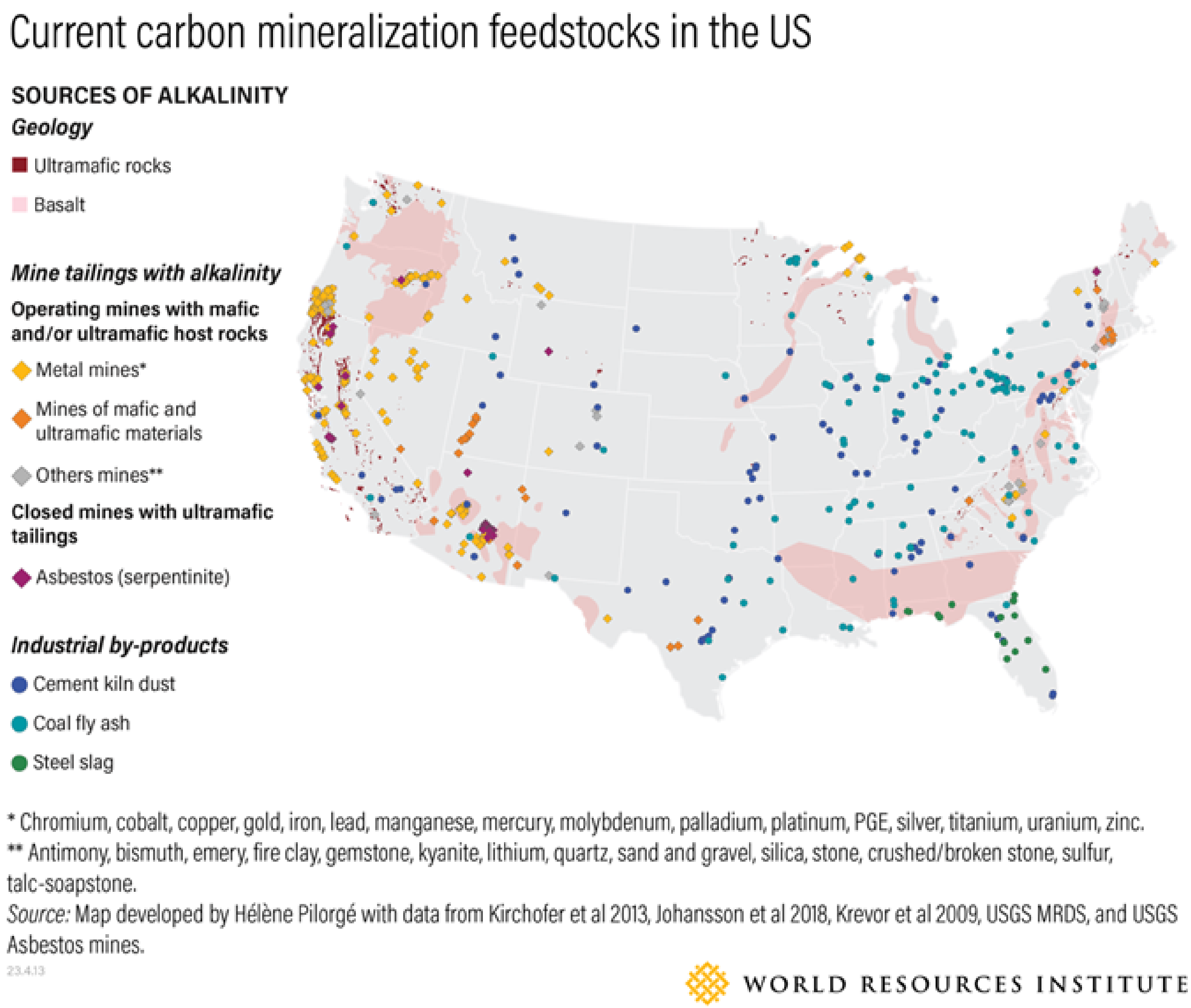
[53] Daniel Goll, et al., Potential CO_2 removal from enhanced weathering by ecosystem responses to powdered rock. Nature Geoscience, 2021. 14: p. 1-5, 10.1038/s41561-021-00798-x.

[54] Phil Renforth and Gideon Henderson, Assessing ocean alkalinity for carbon sequestration. Reviews of Geophysics, 2017. 55(3): p. 636-674, https://doi.org/10.1002/2016RG000533.

[55] Xu, T., Apps, J.A., Pruess, K. Numerical Simulation of CO_2 Disposal by Mineral Trapping in Deep Aquifers, *Applied Geochemistry*, Volume 19, Issue 6, 2004, 917-936, ISSN 0883-2927, https://doi.org/10.1016/j.apgeochem.2003.11.003.

[56] Klara, S.M., Srivastava, R.D., McIlvried, H.G. Integrated Collaborative Technology Development Program for CO_2 Sequestration in Geologic Formations––United States Department of Energy R&D, Energy Conversion and Management, Volume 44, Issue 17, 2003, 2699-2712, ISSN 0196-8904, https://doi.org/10.1016/S0196-8904(03)00042-6.

Figure 7. Carbon mineralization feedstocks in the U.S.[57]



Enhanced mineralization can contribute to carbon removal targets in the near term by utilizing existing physical infrastructure (e.g., mining and agricultural equipment) and technologies without the need for significant, upfront capital investments. Initial simulations of enhanced rock weathering, for example, indicate that up to 215 gigatons could be removed over the next 75 years, if applied across all arable lands globally.[58] Enhanced mineralization and weathering approaches have begun to gain traction in recent years with offtake agreements in the voluntary carbon market that include an emphasis on generating field data to support the improved measurement necessary to further scale these deployments.

57 Image reproduced from Riedl et al., WRI, 2023. "What is Carbon Mineralization? | World Resources Institute"

58 Baek, S. H., Kanzaki, Y., Lora, J. M., Planavsky, N., Reinhard, C. T., & Zhang, S. (2023). Impact of climate on the global capacity for enhanced rock weathering on croplands. Earth's Future, 11, e2023EF003698. https://doi.org/10.1029/2023EF003698

Co-benefits beyond CDR are also possible. The utilization of mine tailings, for example, can help stabilize and permanently store waste for certain industries or extract critical minerals for use in clean energy applications (e.g., batteries). Depending on the composition, minerals can also serve as soil amendments in enhanced rock weathering approaches to replace lime in agricultural and potentially provide other agronomic benefits by preventing soil erosion and raising soil pH levels.[59] These potential co-benefits, however, need to be better quantified through continued research.[60]

Within the FECM's Office of Carbon Management, the CDR Program coordinates with the CTS Program's efforts on in-situ mineralization to leverage ongoing resource assessments on analyzing potential feedstocks that can be utilized for ex-situ and surficial mineralization routes. Collaboration also exists on the results obtained from the investigation of novel, proof-of-principle processes and fundamental research (e.g., kinetics, rock mechanics). Carbonated minerals are investigated further in the conversion to value-added materials by the Carbon Conversion Program and broader industrial decarbonization efforts across the Department. Moving forward, collaboration with FECM's Mineral Sustainability Program will explore opportunities to co-optimize carbon mineralization alongside the extraction of critical minerals when utilizing mine tailings and industrial by-products, building from the ARPA-E Mining Innovations for Negative Emissions Resources program.

The CDR Program also seeks to expand on opportunities for collaboration with United States Geology Survey (USGS), United States Department of Agriculture (USDA), National Institute of Standards and Technology (NIST) and the U.S. Environmental Protection Agency (EPA). Finally, Mission Innovation's CDR Mineralization technical track includes efforts around resource mapping that the CDR Program seeks to both leverage and inform to realize the full domestic and global potential for enhanced carbon mineralization.

2.4.2 Technology Challenges and Program Goals

While the CDR Program's efforts in enhanced carbon mineralization are nascent, the growing number of project developer companies formed in recent years coupled with increased demand-side interest from buyers in the voluntary carbon market, offers an opportunity to establish a foundation for sourcing vast quantities of suitable minerals and optimizing across supply chains to achieve the full potential of these technologies in a timely and cost-effective manner. To do so, the CDR Program will address the following key challenges that will arise as more promising laboratory approaches transition to and are replicated for small-scale pilot projects and full-scale commercial operations.

- **High-grade energy inputs to accelerate the kinetics of mineralization:** The technical intervention required (e.g., grinding minerals into smaller grain sizes to increase their surface area for surficial weathering or high temperature and pressure operation for ex-situ processes) to speed up mineralization for efficient CO_2 capture also increases the energy and associated requirements. Overall, energy-intensive processes (i.e., mining, processing, and transporting minerals) across chosen system configurations need to be further reduced when scaling to larger volumes to reduce overall costs.

[59] Beerling, D.J.; Epihov D.Z.; Kantola, I.B.; Masters, M.D.; Banwart, S.A. Enhanced Weathering in the US Corn Belt Delivers Carbon Removal with Agronomic Benefits. *Proc. Natl. Acad. Sci. U.S.A.* 2024, 121, 9.

[60] *Environ. Sci. Technol.* 2024, 58, 39, 17215–17226 https://doi.org/10.1021/acs.est.4c02368

- **Optimizing for variability in process conditions within and across systems and approaches**: A diverse combination of factors influence individual mineralization and weathering pathways, including the selection and preparation of rocks and minerals (e.g., mineralogy, particle size, reactive surface area, mineral pre-treatment steps) and environmental conditions (e.g., temperature, humidity, soil properties, plant-mineral interactions). Modeling real-world mineralization rates and permanence as a function of process design and environmental conditions need to be further developed. Measuring baseline and enhanced mineralization rates and kinetics across different mineral types, reaction fronts, and environmental conditions will also assist. Reliable and efficient supply chains for optimal sourcing, processing, and distributing minerals to appropriate application sites are also necessary as these networks grow.
- **Difficulty with accurately assessing baselines and quantifying atmospheric CO_2 removal**: To ensure credibility and transparency, reliable MMRV methods are necessary to ensure the stability and permanence of captured CO_2. The effectiveness of current measurement methods themselves can vary widely. Furthermore, a number of variables and operational decisions in a given system configuration makes standardization difficult. Up to four orders of magnitude in variability have been recently reported across published enhanced rock weathering techniques.[61] Advanced detection tools (e.g., ideal sensor types for gas flux, solid carbonate precipitates, aqueous bicarbonates and carbonates in soil pore waters) and standardized protocols to accurately measure and report carbon sequestration are in development to address these complexities, especially in open systems. The intersection of the carbon cycle and weathering need to also be better understood. Ultimately, these challenges lead to an increase in overall costs.
- **Complexity in assessing long-term environmental impacts and benefits**: While the environmental impacts of sourcing minerals are well known, characterizing and quantifying co-benefits (e.g., waste remediation, soil pH amendment, improved crop yield and quality, stimulated biogenic CO_2 uptake, reduced fertilizer usage, reduced nitrous oxide and ammonia emissions), as well as potential adverse effects (e.g., introduction and migration of particulate matter, fate of trace metals) is still limited for mineral application and complicated in terms of existing methods of measurement. Large scale application must also ensure sustainable mining practices and not interfere with existing land uses and ecosystems.
- **Lack of specific regulatory frameworks**: The regulatory landscape is still evolving since methods of enhanced mineralization and weathering remain relatively new. Adapting and navigating existing legal frameworks are necessary while standards and best practices are in development based on continued R&D. Environmental and mining regulations can also vary significantly by region.

Addressing these challenges will increase trust and support for the viability of enhanced mineralization methods to promote adoption and align with consistent and effective purchases through the voluntary carbon market. As such, a better understanding of and transparent communication about the benefits, risks, and safeguards of enhanced mineralization methods is critical.

The goal of the CDR Program is to maximize the CO_2 removal volume productivity across mineralization methods and feedstocks to increase overall capacity to at least tens of megatons and up to hundreds of megatons, while reducing the overall cost across pathways.

61 "Does Enhanced Weathering Work? We Are Still Learning," https://carbonplan.org/research/enhanced-weathering-fluxes March 18, 2024.

2.4.3 Technical Research Activities

The CDR Program is designed to accelerate widespread implementation of more established mineralization methods while further developing emerging approaches to achieve desired capacity levels and cost targets. A portfolio approach will be pursued in terms of both the types of pathways (e.g., mineralization methods, feedstocks, application sites) investigated and funding mechanisms pursued to support these pathways (e.g., FOAs, SBIR, lab calls, prizes). In addition to developing cross-cutting capabilities that can collectively advance all mineralization methods, the CDR Program is interested in pursuing the specific challenges of individual pathways that can contribute to overall capacity and cost targets. These outputs will also inform where follow-on investments should be made for the most promising methods. For example, the CDR Program is funding a project with Lawrence Livermore National Laboratory that is exploring the surficial mineralization of serpentinite rocks containing chrysotile and brucite at a legacy asbestos mine in San Benito County, California.[62] Based on initial baseline measurements to characterize the site and confirm optimal location, field testing is now underway to investigate multiple approaches to accelerate mineralization from these rocks in a tightly controlled environment to determine whether these large ultramafic deposits, mostly in California, represent a promising regional solution for larger-scale implementation. Field trials such as these are crucial to advancing the field.

To achieve the Carbon Negative Shot™ goal, the CDR Program will focus on four key strategies related to technology development, piloting and field validation, and external partnerships. These will address the R&D and market-related challenges identified above. From FY25 through FY28, DOE will fund small pilots capable of removing at least 1 kta.[63] The activities outlined below are necessary to fully realize the cost-effective CO_2 removal through enhanced mineralization methods. Each strategy is comprised of planned activities and associated targets between now and 2032.

Strategy #1: Improve the characterization of the resource potential of enhanced mineralization pathways across supply chains.

Despite the potential for scalability and overall carbon storage capacity, additional characterization, including for the geologic formations containing basalt and other mafic rocks, will enable mineralization methods to achieve their full potential. The USGS recently published a feasibility assessment of in-situ and ex-situ storage at a regional level, along with the proximity to potential mineral sources.[64] The 2023 Roads to Removal Report, however, did not evaluate mineralization methods, including enhanced rock weathering, in terms of their capacity for CO_2 removal and cost in the nation-wide assessment of CDR approaches due to lack of comprehensive high-resolution data at the time the analysis commenced in 2021.[65] A growing number of field studies have since been conducted. Researchers at Yale University have started an open-source database of enhanced rock weathering literature for the community to contribute to and utilize.[66] More experiments, including ones that collect region-specific data and verify modeled estimates, will enable a comprehensive assessment of mineralization methods both at a regional level.

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[62] https://netl.doe.gov/project-information?p=FWP-FEW0278

[63] DOE Invests $58 Million to Tackle Climate Change by Removing Carbon From the Atmosphere | Department of Energy

[64] Blondes, M.S., Merrill, M.D., Anderson, S.T., and DeVera, C.A., 2019, Carbon dioxide mineralization feasibility in the United States: U.S. Geological Survey Scientific Investigations Report 2018–5079, 29 p., https://doi.org/10.3133/sir20185079.

[65] Pett-Ridge, J., Kuebbing, S., Mayer, A. C., Hovorka, S., Pilorgé, H., Baker, S. E., ... & Zhang, Y. (2023). *Roads to removal: options for carbon dioxide removal in the United States* (No. LLNL-TR-852901). Lawrence Livermore National Laboratory (LLNL), Livermore, CA (United States).

[66] https://docs.google.com/spreadsheets/d/1Il3M6sVInMWxqaH_XpOokxKIJlz5H_MqoHqCODMUWos/edit?gid=1950141395#gid=1950141395

Previous and ongoing resource assessments (see CTS Program's MYPP) at specific project sites for in-situ mineralization have included identifying and analyzing calcium- and magnesium-enriched deposits; defining source characteristics of materials (e.g., location, accessibility, volume, concentration, reaction rates); and analyzing carbon mineralization with various materials at various relevant conditions. As noted, ex-situ and surficial mineralization methods, including enhanced rock weathering, introduce additional variables and complexity, especially in open systems and when by-products are used for other end uses.

The CDR Program will explore where additional accuracy and granularity of data is feasible and necessary across supply chains for different system configurations to enable a more efficient transportation, distribution, and application of available alkali mineral feedstocks along with optimization of reaction conditions for chosen pathways. This level of characterization across mineralization pathways in partnership with complementary interagency efforts (e.g., USGS and USDA) and stakeholders across the supply chain (i.e. technology developers, distributors, agricultural land and mine owners, and buyers) should further assist in achieving the theoretical potential for carbon sequestration from these technologies within an acceptable time horizon.

Strategy #2: Scale promising mineralization methods by transitioning laboratory experiments to pilot-scale testing and field trials.

While small field trials have commenced, most work to-date in enhanced mineralization has focused on laboratory/bench-scale experiments. Accelerating larger-scale field trials or pilots is necessary. As such, FECM launched the Carbon Negative Shot™ Pilot funding opportunity in 2024 with an area of interest dedicated to ex-situ and surficial mineralization methods, including enhanced rock weathering. Projects selected through this funding opportunity will integrate pilot-scale testing in relevant environments at capacity levels of at least one kta removed and tests for at least one thousand hours of continuous operation.

These three-year pilot-scale tests, due to commence in early 2025, will complement private sector efforts by providing data that can be used to drive FEED studies for applicable systems. Furthermore, data collection and reporting across systems in the relevant real-world environment with natural variations in ambient conditions will provide valuable information to better understand and validate the diverse combination of factors that influence mineralization processes. This includes mineral selection and sourcing (e.g., mineralogy, particle size, reactive surface area, mineral pre-treatment steps). Environmental impacts, including temperature, rainfall, humidity, plant-mineral interactions, and soil properties (e.g., pH, clay content, organic matter, carbonate content), on mineralization rates will also be validated. Outputs from these pilot-scale tests will inform larger pilot studies (10 kta removal and greater) over the next five years.

Strategy #3: Build partnerships with stakeholders across the supply chain to strengthen the feedback loop between field testing and commercial deployment.

The CDR Program plans to investigate opportunities to partner with academia and the national laboratories, along with agricultural and mining industries, to establish regional field-scale test facilities. This will allow technology developers to optimize conditions for their individual mineralization pathways and tighten the feedback loop of incorporating new findings into their R&D processes. One potential model is the CTS Program's CarbonSTORE initiative.[67]

[67] https://www.energy.gov/fecm/request-information-carbon-storage-technology-operations-research-carbonstore

Shared testing resources can also help reduce the cost burden of critical data collection in the field and accelerate the timeline to larger-scale implementation, while also providing additional confidence in the effectiveness of a chosen pathway. For open systems, in particular, additional R&D is necessary in the development of more accurate and cost-effective sensing and measurement. Field measurements like these will also be useful for validating models and toolsets for MMRV of total carbon sequestration and permanence that will help lower overall costs by reducing the reliance on additional experimental data.

Strategy #4: Harmonize MMRV frameworks and LCA best practices.

The CDR Program plans to expand on initial TEA efforts that have identified MMRV as a significant cost barrier to large-scale mineralization deployment, continue to support the development of a framework for MMRV through the national laboratories to level-set and harmonize across methodologies, and collaborate with non-governmental organizations and the private sector on supporting data collection methods, where applicable. These efforts, described in section 2.4.5, will drive further R&D to improve methods for MMRV, especially in open systems.

2.4.4 Development and Market-Building Activities

Activities within the strategies listed in section 2.4.3 are intended to support both the R&D and market challenges currently facing enhanced mineralization. To complement these efforts, along with demand-side commitments already made by buyers, the FECM CDR Purchase Pilot Prize includes an enhanced mineralization track. This prize represents the first-ever instance of federal procurement of CDR credits and has a goal of developing and fulfilling innovative, technically robust, validated and commercial-scale CDR purchases. The 24 semifinalists announced in spring 2024 for the first round of the prize competition include five teams, including companies already selling credits commercially, that intend to collectively provide 38,178 tonnes of removal credits in mineralization approaches over the course of the competition, if selected. These outcomes will inform additional rounds, including addressing mineralization-specific challenges that are identified over the course of the competition.

2.4.5 Life Cycle Analysis, Techno-Economic Analysis, Measurement, Monitoring, Reporting, and Verification Activities

The MMRV challenges associated with mineralization approaches will be addressed through the activities in section 2.4.3 to support the harmonization of MMRV frameworks and associated techniques. As a companion to these efforts, the CDR Program also plans to develop and publish a set of LCA best practices to assist stakeholders across the supply chain with their ability to pursue the most promising methods developed. These will be used to further refine R&D priorities and metrics for the program. Costs for mineralization pathways vary by the rock composition and method used. In 2018, for example, cost estimates were between $60 for dunite and $200 for basalt per tonne of CO_2.[68] Due to this variability, a specific cost target has not been set for the program, so as not to bias in the near term against specific methods with promising carbonation potential and reactivity in the long term. As such, funded projects will be consistently evaluated

[68] Strefler, J., et al. 2018, "Potential and Costs of Carbon Dioxide Removal by Enhanced Weathering of Rocks." Environmental Research Letters 13: 034010. doi 10.1088/1748-9326/aaa9c4

against their TEA to demonstrate a sufficient reduction in cost for their selected pathway. Supply chain mapping efforts will also help provide additional fidelity to current costs and opportunities to drive down further through technological innovation and supply chain optimization.

2.4.6 Milestones

The following interim 2028 milestones will enable the achievement of the overall CDR Program goal of deployment of cost-effective, megaton-scale sequestration through above ground mineralization methods (i.e. ex-situ and surficial) by 2032. Progress towards these milestones will be used to inform subsequent funding opportunities and follow-on activities by the CDR Program.

- Kiloton-scale pilots at field sites successfully completed
- MMRV framework and LCA best practice guidelines established across mineralization pathways for use by the project developers, demand-side buyers, and researchers
- Hundreds of thousands of tonnes of removal purchases certified across mineralization pathways

Appendix A: Funding Opportunities

Direct Air Capture

From 2020 to present, DOE has issued funding opportunity announcements (FOA) for DAC in the amounts of $10 million (DE-FOA-0002188), $15 million (DE-FOA-0002402), $19.5 million (DE-FOA-0002560), $18 million (DE-FOA-0002614), and $1.236 billion (DE-FOA-0002735) to capture CO_2 directly from the air. DE-FOA-0002188, issued by FECM on March 30, 2020, included the following two areas of interest (AOIs) for novel materials development and integrated bench-scale testing:

- **AOI-1: Development of Novel Materials for Direct Air Capture of CO_2**. The objective is to fund research to develop carbon capture materials specifically tailored for DAC processes.
- **AOI-2: Field Testing of Direct Air Capture**. The objective is to conduct applied R&D to decrease the cost of DAC through the testing of existing DAC materials in integrated field units that capture CO_2 and produce a concentrated CO_2.

DE-FOA-0002402, issued by FECM on January 15, 2021, includes two AOIs for component systems development and commercial-scale pre-FEED studies at three distinct locations:

- **AOI-1: Bench-Scale Testing of Structured Material Systems or Component Designs (TRL 3) for Optimized Direct Air Capture**. The objective is to advance promising structured material systems or component designs for DAC to a sufficient maturity level that can justify their scale-up in a subsequent program.
- **AOI-2: Initial Engineering Design of Carbon Capture Utilization and Storage Systems (TRL 6) for Direct Air Capture**. The objective is to complete an initial design of a commercial-scale, carbon capture, utilization, and storage-DAC system that separates, and stores or utilizes, a minimum of 100 KTA net CO_2 from air.

DE-FOA-0002560, issued by FECM on October 26, 2021, focuses on developing lower cost, scalable DAC technologies using existing low-carbon energy sources or industrial waste heat through three AOIs:

- **AOI-1: Front-End Engineering Design Studies for Direct Air Capture Systems at Existing (retrofit) Domestic Nuclear Power Plants**. The objective is to execute and complete FEED studies of advanced DAC systems capable of removing a minimum of 5 KTA net CO_2 from air based on LCA, suitable for long duration carbon storage (i.e., geological storage or subsurface mineralization) and co-located with an operational nuclear power plant facility.

- **AOI-2: Front-End Engineering Design Studies for Direct Air Capture Systems at Existing (retrofit) Domestic Geothermal Resources**. The objective is to execute and complete FEED studies of advanced DAC systems capable of removing a minimum of 5 KTA net CO_2 from air based on LCA, suitable for long duration carbon storage (i.e., geological storage or subsurface mineralization) and co-located with a geothermal resource.
- **AOI-3: Front-End Engineering Design Studies for Direct Air Capture Systems Using Waste Heat at Existing (retrofit) Domestic Industrial Plants Coupled with CO_2 Conversion Producing Low Carbon Intensity Products.** The objective is to execute and complete FEED studies of an advanced DAC system capable of removing a minimum of 5 KTA net CO_2 from air based on LCA, co-located with an industrial plant facility, and coupled with a carbon conversion technology to convert CO_2 into low carbon intensity products (e.g., synthetic aggregates, concrete, and low carbon synthetic fuels and chemicals).

The FEED studies under this FOA will enable DOE to better understand DAC system costs, performance, as well as business case options, thereby enabling DOE to better focus its DAC R&D Program to accelerate development of this climate-critical technology.

DE-FOA-0002614, issued by FECM on May 5, 2022 (Release 1) and September 30, 2022 (Release 2), focuses on bench-scale testing of advanced DAC component systems and integrated technologies through two AOIs:

- **AOI-2A: Carbon Dioxide Removal R&D: Bench-Scale Testing of Structured Material Systems, or Components Designs for Optimized Direct Air Capture.** The objective is to advance promising structured material systems and component designs for DAC.
- **AOI-2B: Carbon Dioxide Removal R&D: Bench-Scale Testing of Optimized Direct Air Capture Integrated Processes.** The objective is to develop and bench-scale test an integrated, continuous CO_2 capture and release process for DAC.

BIL: Direct Air Capture Hubs

DE-FOA-0002735, issued by FECM and OCED on December 13, 2022, initiates the process of conceptualizing, designing, planning, constructing, and operating the Regional DAC Hubs through three Topic Areas (TAs), with additional funding opportunities expected to follow in the coming years.

- **TA-1: Feasibility (Phase 0)** is designed to support earlier-stage efforts to explore the feasibility of a potential DAC Hub's location, ownership structure, business model, CO_2 storage/utilization option(s), and technology partner(s) during Phase 0.
- **TA-2: Design (Phase 1)** is designed for DAC Hub projects ready to pursue a FEED study for a Hub's initial capture capacity and supporting infrastructure during Phase 1. To be eligible for TA-2, applicants must: (1) be ready to design a DAC Hub that captures at least 50,000 tonnes of CO_2 per year (50 KTA), (2) provide evidence from prior operations to support that scale-up, and (3) present a DAC Hub Capacity Build-Out Plan to eventually reach the goal of at least 1 million tonnes of CO_2 per year (1 MTA), among other requirements.
- **TA-3: Build (Phases 2-4)** is designed for DAC Hub projects that have already completed a FEED study and are seeking support for project development for a potential Hub. To be eligible for TA-3, applicants must: (1) be ready to perform a detailed design, and build a DAC Hub that captures at least 50 KTA CO_2, (2) provide evidence from prior operations to support that scale-up, and (3) present a DAC Hub Capacity Build-Out Plan to eventually reach the goal of at least 1 MTA CO_2, among other requirements.

BIL: Direct Air Capture Prizes

The DAC Pre-Commercial Prize offers up to $15 million in prizes and support and is currently split between two competitions: the DAC Pre-Commercial Energy Program for Innovation Clusters (EPIC) Prize and the DAC Pre-Commercial Technology Prize. The American-Made DAC Pre-Commercial Prizes are a suite of prizes that work together in concert to advance DAC technologies and the incubators that make the technology innovation and development process possible.

The DAC Pre-Commercial EPIC Prize, offering up to $3.7 million in cash prizes, is open to incubator teams that submit creative and impactful plans to support DAC innovators and create meaningful mentorship, education, and training opportunities while initiating meaningful community engagement. As shown in Figure 8, competitors will win increasingly larger cash prizes as they successfully meet technology milestones established for the three escalating phases: Think It, Move It, and Prove It.

Figure 8. DAC Pre-Commercial EPIC Prize Structure.

The DAC Pre-Commercial Technology Prize, offering up to $4 million in cash prizes and technical assistance vouchers, is open to DAC technology developers that identify a critical need in the DAC industry, develop a solution to address this gap, and test the idea to a degree of scale. The purpose of the prize is to deliver scalable DAC technologies that will help develop into a sustainable DAC industry and to maximize the benefits of the clean energy transition in the United States. As shown in Figure 9, competitors will win increasingly larger prizes, in the form of cash and technical assistance vouchers, as they successfully meet technology milestones established for the three escalating phases: Develop, Design, and Deploy.

Figure 9. DAC Pre-Commercial Technology Prize Structure.

The Commercial DAC Prize offers up to $100 million in prizes and support to be split among two competition tracks: the Commercial DAC Pilot Prize and the Commercial CDR Purchase Pilot Prize. The Commercial CDR Purchase Pilot Prize offers up to $35 million in cash awards and purchase agreements and is the first U.S. government initiative to establish direct purchases for CDR (including, but not limited to DAC technologies) from domestic providers. To win these prizes, teams must successfully integrate a reliable supply of CDR offerings, purchase agreements with offtake partners, and delivery commitments. As shown in Figure 10, competitors will win increasingly larger cash prizes as they successfully meet technology milestones established for the three escalating phases that compel competitors to draft and execute CDR Credit Purchase Agreements and Community Benefits Plans.

Figure 10. Commercial CDR Purchase Pilot Prize Structure.

The Commercial DAC Pilot Prize offers up to $52.5 million in cash awards to construct transformational DAC pilot facilities with the capacity to capture over 500 tonnes of CO_2 from the atmosphere per year. As shown in Figure 11, competitors will win increasingly larger cash prizes as they successfully meet technology milestones established for the four escalating phases: Concept, Engineer, Permit, and Operate.

Figure 11. Commercial DAC Pilot Prize Structure

In terms of reactive carbon capture, DOE initiated a lab call (FY2021-006-Lab Call) to accelerate the advancement of process intensification and integration of R&D for reactive carbon capture. Through this joint investment in reactive carbon capture, projects from several national labs, including the Pacific Northwest National Laboratory, Oak Ridge National Laboratory, Lawrence Livermore National Laboratory, and National Renewable Energy Laboratory, began in 2021 and will finish at the end of FY24.

DOE also recently announced up to $20 million in funding for reactive carbon capture development through FOA 2614 AOI-2G. Selected reactive carbon capture projects will conduct concept studies followed by lab validation studies of promising reactive carbon capture approaches with a goal to establish a pathway to reach DOE's Carbon Negative Shot™ target of less than $100/t$CO_2$e removed.

Marine Carbon Dioxide Removal

DOE recently announced up to $10 million in R&D funding for marine carbon dioxide removal (mCDR) field validations through FOA 2614 AOI-2F. Selected mCDR projects will complete conceptual design studies followed by field validations of cost-effective processes for abiotic ocean-based capture to make significant progress towards reaching DOE's Carbon Negative Shot™ target of less than $100/net t$CO_2$e removed. Projects have been reviewed and selected with public announcements made in late 2023.[69]

Additionally, the U.S. Department of Commerce's National Oceanic and Atmospheric Administration (NOAA) put out a Notice of Funding Opportunity (NOFO) calling for relevant mCDR projects, for which FECM has also signed on as a contributing partner, providing $4 million out of a total $30 million. This NOFO is focused on expanding understanding of various aspects of mCDR to reduce uncertainty about extent of carbon removal, associated co-benefits and contribute to regulatory frameworks needed for both testing and scaling up of approaches.

Biomass Carbon Removal and Storage

Biomass carbon removal and storage (BiCRS) projects have been supported extensively by the DOE, including BECCS projects in bioethanol production. The Illinois Industrial CCS Project, funded by DOE, has been capturing CO_2 for permanent storage in a deep geological formation since 2016. It remains the largest BECCS projects globally with a biogenic carbon capture rate of 0.5 to 1 MTA. Other projects, including the Arkalon Ethanol Plant and the Bonanza Ethanol Plant, project carbon capture rates on the order of 0.1-0.3 MTA, with enhanced oil recovery applications. Approximately, 2 MTA of biogenic carbon is captured globally with 90% sourced from bioethanol BECCS projects.[70]

DOE selected two pre-FEED studies through FOA 2614. Under AOI-2C, the Filer City BiCRS Net-Negative Study ($1.4 million DOE share) will be led by CMS Enterprises. This project aims to develop engineering design studies for a 100% sustainably sourced biomass fired power plant with CO_2 capture technology in Filer City,

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[69] Office of Fossil Energy and Carbon Management. (2023). Project Selections for FOA 2614: Carbon Management (Round 2). Department of Energy. Washington, DC. https://www.energy.gov/fecm/project-selections-foa-2614-carbon-management-round-2

[70] International Energy Agency. "Bioenergy with Carbon Capture and Storage - Energy System." IEA, www.iea.org/energy-system/carbon-capture-utilisation-and-storage/bioenergy-with-carbon-capture-and-storage. Accessed 27 July 2023.

Michigan. Under AOI-2E, Electricore was awarded a $1.5 million DOE funded Net-Zero Lime Kiln and Carbon Removal Facility project to complete the initial design of a commercial-scale, advanced carbon capture system that separates CO_2 with at least 95% capture efficiency from process streams at the Carmeuse's lime production facility in Butler, Kentucky. The retrofit of this lime plant will use sustainably sourced biomass alone or in combination with natural gas, and/or coal as an energy source to mitigate emissions. Additional federal funding, totaling $16.5 million, has been awarded to various R&D efforts to increase the CO_2 capture ability of algal systems while lowering the cost of traditional algal technologies.

DE-FOA-0003082, issued by FECM on February 12, 2024, includes:

- **AOI-1: Small Biomass Carbon Removal and Storage (BiCRS) Pilots**. The objective of AOI-1 is to support integrated pilot-scale testing (≥1,000 tonne CO_2e/yr) of BiCRS or conversion with appropriate MRV.
- **AOI-3: Multi-Pathways CDR Testbed Facilities**. The objective of AOI-3 is to support CDR testbed facilities suitable for evaluating, developing, and integrating multiple CDR pathways across different ecosystems, climates, and communities.

Enhanced Mineralization

The CDR Program currently supports Lawrence Livermore National Laboratory's investigation (FWP-FEW0278) of the mineralization capabilities of serpentinite rocks and tailings from a local asbestos mine. This project has demonstrated that gas flux and carbonate detection methods can be suitable for detecting carbon removal of hundreds of tonnes per year across an area smaller than a square kilometer, demonstrating the tractability of mineralization MMRV. As discussed previously, more research efforts and funding are required to develop the technology to a level where a pilot-scale system (or larger) can be successfully demonstrated.

DE-FOA-0003082, issued by FECM on February 12, 2024, includes:

- **AOI-2: Small Mineralization Pilots**. The objective of AOI-2 is to support integrated pilot-scale testing (≥1,000 tonne CO_2e/yr) of enhanced mineralization technologies with appropriate MRV from enacted authorities and appropriations.
- **AOI-3: Multi-Pathways CDR Testbed Facilities**. The objective of AOI-3 is to support CDR testbed facilities suitable for evaluating, developing, and integrating multiple CDR pathways across different ecosystems, climates, and communities.

FECM's Carbon Transport and Storage Program recently selected seven resource assessments of natural materials and industrial wastes that could be used to store large amounts of CO_2 via in-situ and ex-situ mineralization through FOA 2614 AOI-4.

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