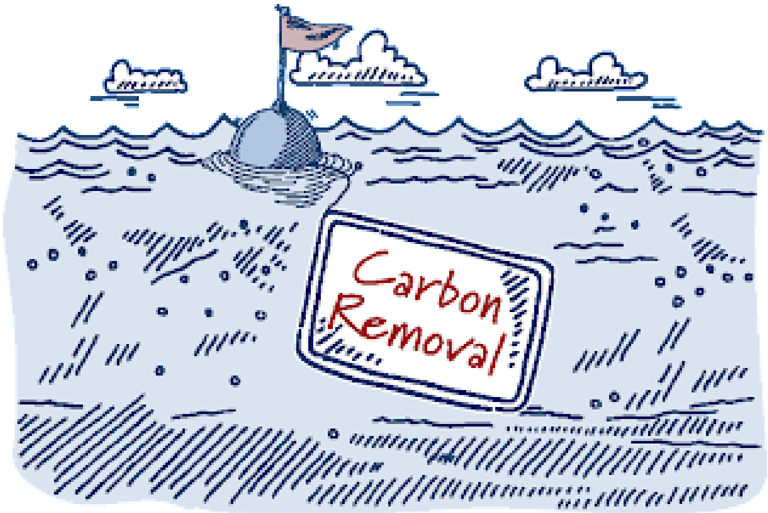

Charting a Course for Marine Carbon Dioxide Removal (mCDR): Policy Sequencing in mCDR Development

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Executive Summary

Carbon dioxide removal (CDR) is an emerging set of technologies, practices and approaches to remove carbon dioxide directly out of the atmosphere and store it. Marine CDR (mCDR), a subset of CDR solutions, can potentially complement the ocean's natural carbon cycle and carbon storage capacity. CDR pathways are recognized by the U.S. federal government, the International Energy Agency, the Intergovernmental Panel on Climate Change and the private sector, including companies like Microsoft, as a necessary tool for achieving net-zero commitments.[1,2,3,4,5,6] Examples of mCDR technologies include electrochemical processes, direct ocean capture, ocean alkalinity enhancement, as well as macro- and microalgae cultivation paired with carbon storage or production of marketable products. Currently, the U.S. is leading research and development (R&D) in the nascent mCDR sector, and enhanced regulatory clarity will keep mCDR innovators in the U.S.

This report (1) identifies policies to support each innovation stage of mCDR technologies: early-stage R&D, wide-scale deployment and commercialization, (2) highlights the growing U.S. federal engagement and resources for mCDR and (3) describes policies that could create the conditions for successful wide-scale mCDR deployment, dependent on the findings from R&D field trials. Major takeaways from this report include:

1. **The U.S. is one of the leaders in the emerging field of mCDR, and federal policies can help the U.S. secure leadership and a competitive edge.**

   The federal government is supporting at least 36 mCDR research projects across 17 states and has published multiple strategic and exploratory reports that envision the role of federal agencies in the growing mCDR industry. These projects are highlighted in Table 2 and detailed in Appendix Table A1. The U.S. has also taken initial steps to ensure coordinated mCDR development by creating interagency working groups, such as the Fast-Track Action Committee on Marine Carbon Dioxide Removal.

2. **Parallel development of a U.S. regulatory framework and research through field trials will be necessary for innovation and maintaining global competitiveness.**

   The existing legal framework for U.S. oceans was designed to encompass many ocean activities, but not mCDR. This results in mCDR projects being shoehorned into several environmental regulations and laws designed for other purposes and could have unintended consequences, such as delaying or halting the R&D of projects in the U.S.. Additionally, field trials are necessary to better understand the potential effectiveness and safety of various mCDR technologies and approaches.

3. **Other federal policy tools, such as financial incentives, can alleviate uncertainties in mCDR pilot projects.**

   Policy mechanisms like federal procurement of CDR, technology transition activities, at-scale demonstrations, loan financing programs and tax incentives could be utilized to advance mCDR innovations.

1. Marine Carbon Dioxide Removal (mCDR)

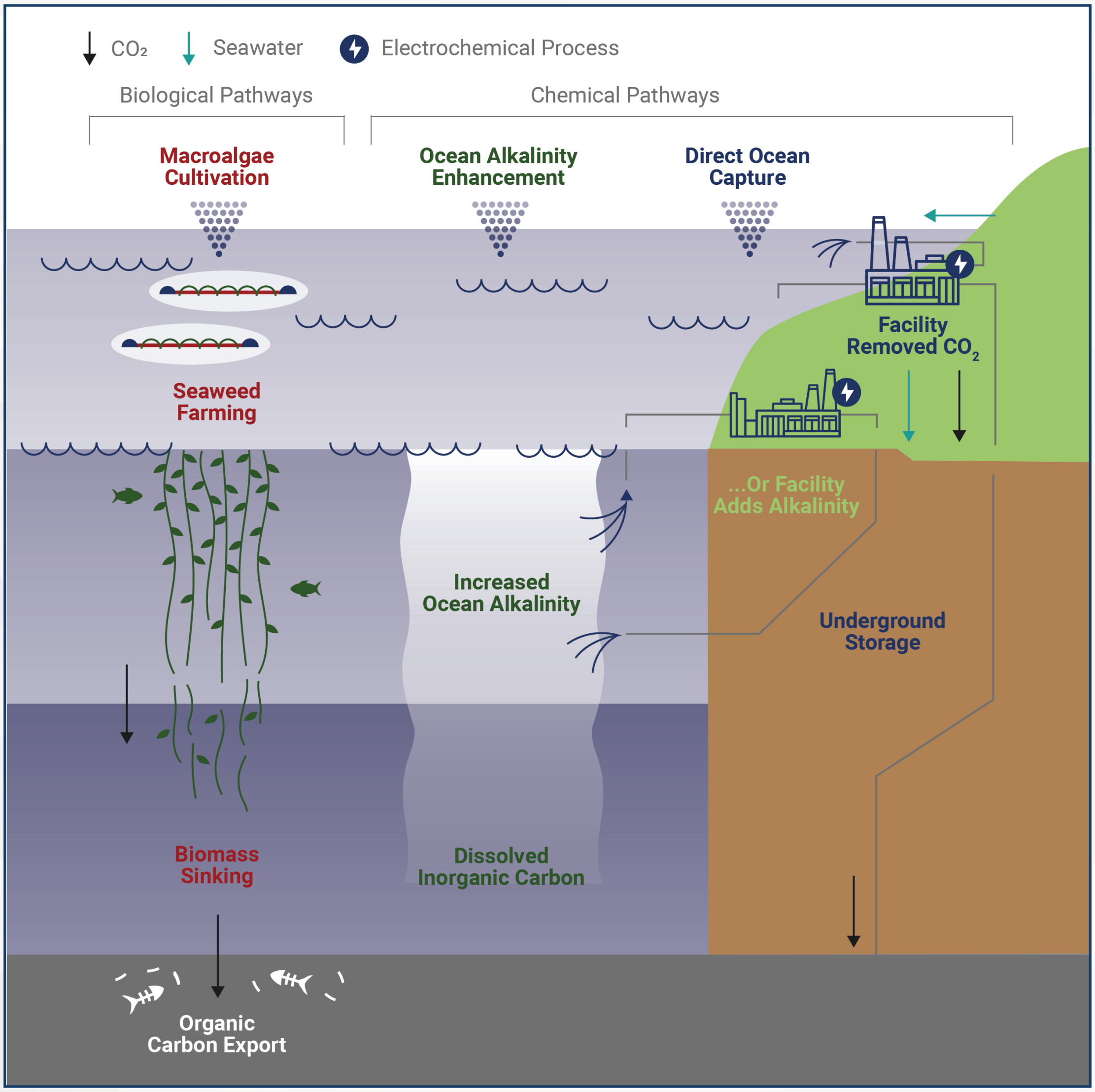
CDR is necessary for the United States to reach 2050 net-zero emission targets by removing an estimated 0.8-2.9 billion metric tons of carbon dioxide (CO_2,), equivalent to emissions from 1.47 billion vehicles.[7,8] The number of corporations with net-zero commitments has more than doubled from 769 in December 2020 to 1,475 in 2023.[9,10] CDR refers to technologies, processes and approaches that remove CO_2 from the atmosphere and store it for long periods of time. There are three categories of CDR: 1) engineered solutions, such as direct air capture (DAC), 2) natural solutions, like afforestation and 3) hybrid solutions that take an engineered approach to natural or biological processes.

The ocean is a natural and vast carbon sink that covers approximately 70% of Earth's surface and has absorbed over 30% of CO_2 already in the atmosphere.[11,12] The ocean removes CO_2 from the atmosphere through a natural balancing act: as CO_2 in the atmosphere increases, the ocean absorbs more CO_2 to re-establish balance.[13]

Marine carbon dioxide removal (mCDR) is a nascent category of CDR technologies that enhance the ocean's biological and chemical carbon processes.[14] Co-benefits of mCDR deployment include local economic development, job production, the co-location and utilization of existing facilities and addressing ocean acidification.[15]

Approaches to mCDR include macroalgae cultivation, ocean alkalinity enhancement (OAE) and Direct Ocean Capture (DOC) (or the DAC of the ocean). These approaches and others are summarized in Figure 1 and Table 1, as well as ClearPath's Carbon Dioxide Removal 101 and Ocean CDR Permitting and Regulations 101.

Figure 1. mCDR Pathways.



Source: Carbon 180

Table 1. Comparison of mCDR Removal Pathways.

Ocean CDR Pathway	Technological Readiness	Cost Range ($/ton CO2 removal)	Scale (Gt CO2 Removal/yr)	Storage Duration (years)	Research Groups and Start-Ups
Macroalgae Cultivation (Seaweed/Kelp)	Moderate	$25 - $125	Low (0.1 - 0.6)	Low - Moderate (10 - 100 Years)	Macro Oceans, Phykos, RunningTide
Alkalinity Enhancement	Low-Moderate	$25 - $160	Moderate - High (1 - 15+)*	High (>20,000 years)**	Planetary, Vesta
Electrochemical Ocean CDR/ Direction Ocean Capture	Low-Moderate	$400 - $600	Moderate (1 - 10)	High, using geological storage (>1,000 years)	Captura, Ebb Carbon, Equatic, Heimdal, Massachusets Institute of Technology
Artificial Upwelling/ Downwelling	Low	$100 - $150	Low (0.1 - 0.4)	Low - Moderate (10 - 100 years)	Ocean-Based Climate Solutions, Inc., The Climate Foundation

Source: NOAA

* The State of Carbon Removal of 2023 report estimates alkalinity enhancement upper-bound to be 100 Gt CO2 removed per year.

** The mean seawater residence time of alkaline dissolved carbon is about 100,000 years, based on the annual input of alkaline carbon from rivers (0.3 GtC/yr), the alkaline pool of dissolved alkaline carbon resident in the ocean (about 34,000 GtC) and assuming steady state.

2. mCDR Research is Gaining Momentum

CDR approaches have proliferated significantly over the last three years. While most large-scale federal policy support has focused on DAC technologies, there has been a growing interest in mCDR pathways. This has been largely driven by initial support from the private and philanthropic sectors. The U.S. federal government has supported mCDR research to increase fundamental knowledge and to enable the potential deployment and commercialization of solutions to effectively and efficiently remove CO_2 from the atmosphere. Table 2 describes the various mCDR-related programs that have received federal resources.

Research is necessary to prove the efficacy and safety of mCDR approaches. Additionally, future research could identify mCDR technologies that may be lower cost, more efficient and provide greater co-benefits than land-based CDR technologies. Therefore, the allocation of federal resources for mCDR may provide significant returns on investment. mCDR project titles, locations and funding amounts are detailed in Appendix Table A1.

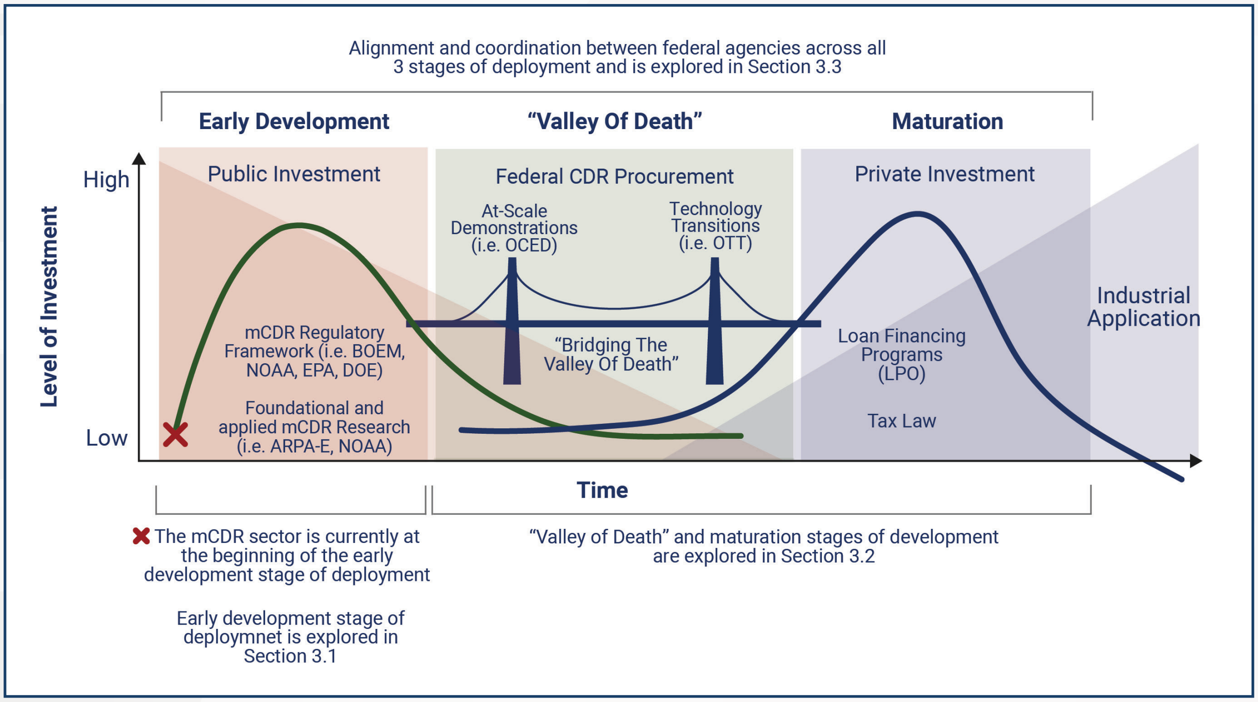
Table 2. Federal Engagement and Resources Supporting mCDR.

Agency	Program	Description	mCDR Projects
Department of Energy (DOE)			
Fossil Energy and Carbon Management (FECM)	Carbon Negative Shot	Supports the potential development and commercialization of a suite of CDR technologies to remove CO_2 from the atmosphere and store it for less than $100 per net metric ton of CO_2eq within the decade.[16]	Up to 5 small mCDR pilot projects in lab, closed-system, and representative field pilot environments to demonstrate the feasibility, cost, and scalability of ocean-based approaches.[17]
	Investments for Carbon Management R&D Projects	19 R&D projects were selected to support cost-effective processes for ocean-based carbon removal technologies and direct air capture technologies to establish the foundation for a successful carbon capture and carbon conversion industry.[18]	8 R&D projects represent ocean-based carbon removal technologies and received around $1.6 million in DOE funding.[19] Project details are listed in Appendix Table A1.
	Carbon Dioxide Removal Purchase Pilot Prize	Will be the first U.S. government initiative to purchase CDR credits from domestic technology providers. Will provide up to $35 million in awards to private entities and academic institutions for CDR.	mCDR projects could qualify for this the purchase prize under "planned or managed carbon sinks, including natural and artificial mechanism within terrestrial and upper hydrosphere".[20]
Advanced Research Projects Agency-Energy (ARPA-E)	Sensing Exports of Anthropogenic Carbon through Ocean Observation (SEA-CO2)	To research ways to develop new approaches to measure and track mCDR transparently and ensure that the quality and quantity of emission removals are correctly valued in carbon markets to support the accelerated adoption of mCDR.[15]	11 projects will support novel efforts to measure, report and validate mCDR and identify cost-effective and energy-efficient carbon removal solutions, using $36 million in funding.[22] Project details are listed in Appendix Table A1.
	Macroalgae Research Inspiring Novel Energy Resources	To develop tools for U.S. leadership in the production of marine biomass for use as feedstock for fuels, chemicals, and animal feed.[23]	22 projects funded since 2017 to develop technologies capable of providing economically viable, renewable biomass for energy applications without the need for land, freshwater, and synthetic fertilizers.
National Renewable Energy Laboratory (NREL)	Mission Analysis for Marine Renewable Energy to Provide Power for Marine Carbon Dioxide Removal	The goal of this study was to understand the CO2 removal potential of mCDR, marine carbon capture, and marine carbon storage, and to understand the compatibility of mCDR, mCC, and mCS with marine and offshore wind energy.	No specific project funding. Published the report investigating mCDR technologies that require power at sea, such as artificial upwelling, deep-ocean storage, electrochemical mCDR and marine carbon capture, offshore microalgae cultivation, seaweed farming and sinking, and monitoring requirements.
National Oceanic and Atmospheric Administration (NOAA)			
National Oceanographic Partnership Program (NOPP)	Investments to Advance mCDR Research	Funding supports collaborative research across academia, federal scientists, and industry to expand understanding of mCDR approaches, risks and co-benefits, and science needed to build regulatory frameworks for testing and scaling of mCDR.[24]	17 projects with partners from 47 institutions utilizing $23.4 million in investments.[25] Project details are listed in Appendix Table A1.
Office of Oceanic and Atmospheric Research National Marine Fisheries Service Office of the Undersecretary for Oceans and Atmosphere	Strategy for NOAA Carbon Dioxide Removal Research Report	This White Paper outlines existing knowledge of mCDR technologies, requirements for increasing foundational knowledge to drive future decisions, and NOAA's role in CDR research.[26]	No specific research projects. Provides next steps for a synthesized research strategy and coordinating research efforts at NOAA.

3. Policies to Develop Conditions for Wide-Scale mCDR Deployment

Wide-scale mCDR deployment can be achieved through a coordinated federal effort, which is important during the early development stage of new technologies and is beneficial for moving pilots and demonstrations into real-world environments. We also highlight federal policy mechanisms, such as demand pulls through federal CDR procurement, that help emerging technologies bridge the "Valley of Death" and provide continued support once technologies reach the mature stage of development. These federal policy mechanisms are highlighted in Figure 2. in reference to the stages of developing technology, time and levels of investment.

Figure 2. Federal Policy Mechanisms that Support Innovation from Early Development to Maturation



3.1 Ensuring a Competitive Research and Innovation Environment

The more nascent technologies and solutions, the more foundational and applied research will be needed, followed by testing, demonstration and deployment. Today, mCDR pathways are in the nascent stages of R&D, mostly performed in a laboratory setting or small controlled conditions simulating ocean environments. At this stage, innovation policies that support R&D through cost sharing and grants for pre-Front-End Engineering and Design (pre-FEED), FEED and pilot lab-scale projects are valuable.

The successful deployment and eventual commercialization of mCDR pathways in the U.S. to address global carbon removal commitments in a timely manner relies on the parallel (1) updating of regulatory frameworks to improve the timeliness and transparency of mCDR projects and (2) establishment of a coordinated, transparent, robust and well-resourced research environment. The

White House Office of Science and Technology Policy (OSTP) has begun coordinating efforts through the establishment of the Fast-Track Action Committee (FTAC) to evaluate the different types of mCDR and shape relevant policy and research on mCDR and carbon sequestration. Additional information on FTAC and other federal coordination efforts is presented in section 3.3 of this report.

3.1.1 A Streamlined and Consolidated U.S. mCDR Regulatory Framework is Needed to Encourage Innovation

The continuation of fundamental and exploratory research is important, but to answer important scientific questions about mCDR approaches, field tests are necessary to understand and validate the effectiveness of technologies in a real ocean environment.[27] However, current regulatory processes and laws in the U.S. for real-world mCDR experiments are highly fragmented.[28] Without changes and clarifications, the current U.S. regulatory processes and laws pose significant challenges, not only for full-scale deployment of mCDR, but for accelerating research to determine whether and how these approaches are worth scaling. This could result in U.S. innovators developing and deploying in other countries with more favorable regulatory systems.

The U.S. has an opportunity to maintain intellectual and economic leadership for mCDR deployment if it can determine an appropriate regulatory regime and policy ecosystem to support leading companies in their efforts to commercialize. Already we've seen U.S. companies begin to deploy pilots internationally.[29] RunningTide, a Maine-based ocean CDR start-up, is building its first global research and development base in Iceland through an Icelandic research permit.[30] Captura, a California-based mCDR company founded at the California Institute of Technology, has two operational pilot plants in California and is building its third pilot plant in Norway to test, mature and industrially scale its DOC technology. Captura is also working to build DOC plants in Canada.[31] Similarly, Equatic, a California-based mCDR company using technology created at the University of California, Los Angeles (UCLA), has partnered with a Montreal-based carbon removal project developer and will install their technology at a pilot facility in Quebec in 2024.[32] Establishing a clear and predictable U.S. regulatory process to indicate U.S. government support for mCDR pathways is needed to ensure that America can lead the world in mCDR research, development and deployment.

The existing legal framework for U.S. oceans was designed decades ago for numerous ocean activities that are not specific to mCDR RD&D considerations. Therefore, mCDR projects would be shoehorned into several general environmental regulations and laws that have not considered innovative mCDR technologies. Under these laws, mCDR projects would be subject to duplicative permitting processes and other legal requirements. A dedicated mCDR framework could reduce the time, cost and complexity associated with the variety of requirements by creating clarity, coordination and a sequential agency review process needed by mCDR technologies to effectively and safely test and develop their solutions.[33]

Additionally, assigning ocean regulations that are not applicable to mCDR projects may result in inaccurate perceptions of mCDR technologies. For instance, the mCDR technologies that utilize OAE or macroalgae cultivation and sinking may require approvals from both the Marine, Protection, Research and Sanctuaries Act (MPRSA) and the Clean Water Act's National Pollutant Discharge Elimination System. These regulations oversee the permitting of materials discharged into ocean waters, primarily the "dumping" of hazardous materials, which could cause harm to the marine environment. However, dumping is defined broadly to encompass the disposition of material.[34] OAE and macroalgae-based mCDR are for purposes other than disposal, as the intent is to remove CO_2 in addition to tracking and monitoring this removal. In January 2024, the EPA published a resource summarizing laws that may impact mCDR, which they plan to continuously update as they gain additional information.[35] A thorough regulatory guidance or framework could further clarify requirements for the mCDR field research trials and potential deployment. Regulatory mismatches not only stymie innovation but can create a negative general perception of mCDR pathways.

A variety of mCDR pathways aim to effectively maximize the ocean's carbon removal ability in the early stages of R&D. Updating regulations can achieve timely and transparent processes that address potential risks without forestalling innovations by addressing overlapping permitting processes and other requirements.[36]

3.1.2 Research Policy is Essential for Driving marine CDR Innovation

While a regulatory framework is being established, it is also essential to create and sustain a transparent and coordinated mCDR research and innovation environment. The current state of research has been primarily laboratory-scale experiments, conceptual theory and modeling on mCDR technologies and pathways.[37] Recently, field trials have begun. For instance, Ebb Carbon is operating its first 100-ton mCDR system at DOE's Pacific Northwest National Lab (PNNL)-Sequim.[38] The parallel acceleration of both a regulatory framework and expanded research that supports field trials of increasing scale would result in identifying optimal mCDR approaches to support global net-zero commitments. Federal engagement in mCDR research has begun at the DOE and NOAA, as highlighted in Table 2. With DOE and NOAA's leadership in carbon management and early support for mCDR research, further engagement and more directed mCDR efforts within the carbon management portfolio could further develop the various mCDR pathways.

In the 118th, 117th and 116th Congresses, legislation has supported the expansion of mCDR solutions by bolstering R&D programs toward mCDR technologies and marine carbon storage.

- The bipartisan **Carbon Removal and Emissions Storage Technologies (CREST) Act of 2023** would expand the DOE's carbon removal R&D programs to include mCDR and marine carbon storage, among other developing carbon removal pathways. It also creates a carbon removal footprint program to provide grant funding to entities seeking financial assistance to complete a techno-economic assessment or life-cycle assessment. This bill is sponsored by Sens. Collins (R-ME), Cantwell (D-WA), Cassidy (R-LA), King (I-ME), and Coons (D-DE).[39]
- The **Carbon Dioxide Removal Research and Development Act of 2023** would authorize funding to support R&D on a range of carbon removal pathways across nine government agencies, such as NOAA, to advance research on mCDR pathways. This bill is sponsored in the Senate by Sens. Schatz (D-HI), Bennet (D-CO), Coons (D-DE), Heinrich (D-NM), Hickenlooper (D-CO), Lujan (D-NM), Smith (D-MN), Whitehouse (D-RI), Welch (D-VT) and Reps. Tonko (D-NY), Clark (D-MA), Peters (D-CA), Kuster (D-NH) and McGovern (D-MA).[40,41]
- The bipartisan and bicameral **Blue Carbon for Our Planet Act**, introduced in 2021, highlights the need for a coordinated research effort between NOAA and the National Academy of Sciences to assess the technologies for CO_2 storage in the deep sea floor environment, solutions for removal of CO_2 from the ocean and feasibility of coastal macroalgae cultivation for carbon sequestration. This bill was originally sponsored in the Senate by Sens. Murkowski (R-AK) and Whitehouse (D-RI), and in the House by Reps. Bonamici (D-OR), Posey (R-FL), Beyer (D-VA) and Mast (R-FL).[42,43]

- The bipartisan and bicameral **Securing Energy for our Armed Forces Using Engineering Leadership (SEA FUEL) Act**, included in the National Defense Authorization Act (NDAA) for Fiscal Year 2020, directs the Departments of Defense and Homeland Security to pioneer new technologies that will capture CO_2 from air and seawater and convert it to clean fuels or other useful products.[44,45] The U.S. Navy has already patented a technology that would remove excess CO_2 from ocean water and turn it into fuel.[46] This bill was originally sponsored in the Senate by Sens. Whitehouse (D-RI), Reed (D-RI) and Sullivan (R-AK), and in the House by Reps. Beyer (D-VA), Schweikert (R-AZ) and Brown (D-MD).

The nascent field of mCDR technologies would benefit from both foundational research and applied R&D through support across federal agencies. Areas for continued research include but are not limited to the following:

The measurement, reporting and verification (MRV) of mCDR pathways locally and globally. Rigorous and transparent MRV is necessary to quantify and evaluate the efficacy and durability of carbon removal and storage of mCDR pathways and supports the understanding of co-benefits and risks, particularly in open systems like the ocean. The development of new MRV tools or the improvement of existing MRV methods would optimize the accuracy, transparency and consistency of ocean data collection. In addition to assessing the carbon removal efficacy of mCDR pathways, MRV tools would monitor ocean properties like partial pressure of CO_2, salinity, nutrients, pH, dissolved inorganic carbon, total alkalinity and dissolved oxygen.[47] This is important to ensure the impact of emission removals is correctly valued and creates a solid foundation for continued support and accelerated adoption of mCDR pathways. ARPA-E's SEA-CO_2 program, released in February 2023, has funded 11 projects to advance mCDR MRV technologies and is a promising step towards more mCDR MRV research.[48]

Further work by a lead federal agency such as the DOE in coordination with national labs and other agencies like NOAA, National Science Foundation (NSF), Department of Defense (DOD) and the Environmental Protection Agency (EPA) is needed to ensure the effective development of MRV guidelines and rubrics, especially for novel approaches like mCDR, which do not have significant historical data to inform MRV. These agencies have already supported mCDR research as outlined in **Appendix Table 1**. For instance, the Department of Defense- Office of Naval Research could also be a likely partner for permitting and regulations over marine spaces. Additionally, the DOE's Earth System Model Development Analysis program supports innovative and computationally advanced earth system modeling capabilities to provide information on Earth systems for energy and related sectoral infrastructure planning.[49] This program coordinates its activities with the climate modeling programs at other federal agencies, primarily NSF, NOAA and NASA. This program released a $16 million funding opportunity announcement in 2023, soliciting applications that, in part, would further the development of marine biogeochemical simulations.[50]

Understanding the economic development potential of existing industries by developing the mCDR sector. Potential co-benefits include local economic development, job production, co-location and utilization of existing facilities and environmental benefits. Coastal Americans overwhelmingly support mCDR, with 82% of coastal residents supporting the enhancement of the ocean's natural ability to remove carbon dioxide. Roughly two-thirds believe mCDR will increase good-paying jobs, improve ocean-based recreation and have a positive impact on tourism.[51]

The economic development potential of existing industries will vary depending on the mCDR pathway and how it will be implemented. Macroalgae cultivation could be used for the production of marketable products like biofuels and food supplements, which would displace or reduce emissions from existing sectors. OAE pathways could mitigate ocean acidification and have potential positive impacts on shellfish aquaculture and fisheries. Electrochemical processes may also mitigate ocean acidification and produce marketable byproducts like hydrogen, chlorine and silica.[52]

A coordinated federal effort to establish an mCDR-specific regulatory framework in tandem with continued mCDR research will be necessary to ensure the timely development of promising mCDR solutions.

3.2 Federal Mechanisms for Deployment and Commercialization

Concurrent policies and existing federal programs can accelerate deployment and support the commercialization of effective and safe mCDR pathways while also reducing emissions.[53] Promising early-stage technologies often receive limited investment because of technical or financial uncertainties, resulting in the “Valley of Death” or the large gap between early-stage scientific research and industry commercialization. The “Valley of Death” can be avoided by incorporating supportive policies during the crucial stage of translational research.[54] The lack of federal deployment incentives to bridge the “Valley of Death” could prevent research, particularly for at-scale field trials, needed to mature the mCDR industry. This section explores federal support mechanisms that could set the course for the maturation of mCDR technologies for successful commercialization. The support mechanisms are also highlighted in **Figure 2** in coordination with the different stages of innovation.

Federal Procurement of CDR — Procurement of innovative technologies helps bridge the “Valley of Death” by addressing uncertainty through guaranteed demand. The DOE Office of Fossil Energy and Carbon Management (FECM) launched the CDR Purchase Pilot Prize, which will provide $35 million in awards to private entities and academic institutions to compete for the opportunity to sell CDR credits directly to the federal government. This program will help build metrics (such as MRV) for successful CDR programs and create a market to encourage technology innovation and the growth of the industry. It also signals to buyers and investors the legitimacy of the carbon removal space through government interest, which can, in tandem, help to bolster the voluntary market. The following recently introduced legislation also supports the creation of a federal procurement program for CDR and could support mCDR.

- The bipartisan **Carbon Removal and Emissions Storage Technologies (CREST) Act of 2023** would establish a five-year pilot carbon removal purchasing program to accelerate the deployment and market commercialization of proven carbon removal technologies within the U.S.[55]
- The **Federal Carbon Dioxide Removal Leadership Act (CDRLA) of 2022** would require the DOE to remove and permanently store CO_2 on a specified schedule, culminating in 10 million metric tons of CO_2 removed for fiscal year 2025 and each fiscal year after.[56]

At-Scale Demonstrations — The DOE Office of Clean Energy Demonstrations (OCED), authorized in the bipartisan Infrastructure Investment and Jobs Act (IIJA), accelerates market adoption and deployment of pre-commercial technologies to achieve net zero emissions by 2050 through at-scale clean energy demonstration projects in partnership with the private sector.[57] The technologies selected for OCED's portfolio face significant barriers to scale, making OCED's role to address those barriers and help de-risk them. At-scale demonstrations are a critical tool utilized by OCED because they validate the performance of technologies in complex real-world environments, allow learning by doing and build confidence in key stakeholder groups such as industry, the financial sector and communities where facilities will be located.[58] OCED supports a carbon management portfolio that includes the Regional Direct Air Capture Hubs and may consider supporting a broader portfolio of CDR pathways as their scalability and viability become established. Therefore, mCDR at-scale demonstrations, or field trials, could be selected for development by OCED as various mCDR solutions achieve a higher technology readiness level and complementary demonstration-level regulatory process.[59]

Technology Transitions for Commercialization — The DOE Office of Technology Transitions (OTT) was formed to expand the commercial impact of the DOE's portfolio of research, development, demonstration and deployment (RDD&D) activities to bolster the U.S's innovation ecosystem and increase the return on investment in federally-funded science and energy research. OTT guides the coordination and optimization of technology transition activities between national labs and the private sector. OTT also oversees the Energy Technology Commercialization Fund (TCF). The TCF is used to provide matching funds with private partners to promote energy technologies for commercial purposes based on future planned activities.[60] OTT using funding from the TFC, in partnership with FECM and OCED, is supporting four national lab carbon management projects, three of which are focusing on MRV of diverse carbon removal pathways.[61] The eventual commercialization of mCDR technologies and MRV frameworks could benefit from efforts at OTT, such as through the TCF.

Loan Financing Programs — The DOE Loan Programs Office (LPO) finances large-scale, all-of-the-above energy infrastructure in the United States. The Energy Act of 2020 expanded project eligibility within the Title XVII Clean Energy Financing Program to include carbon management technologies, such as synthetic technologies to remove carbon from the air and the ocean.[62] With this expansion, LPO can finance early commercial deployments of carbon management technology by 1) demonstrating bankability and readiness for widespread adoption to a range of investors, 2) accelerating commercial deployments and 3) reducing cost uncertainty.[63] The Title XVII Clean Energy Financing Program– Innovative Energy and Innovative Supply Chain Projects (Section 1703) finances clean energy projects that use innovative technologies or processes not yet widely deployed in the U.S. that reduce greenhouse gas emissions or air pollutants. Once ready for early commercial deployments, mCDR technologies may be eligible for LPO financing.

Tax Law — Tax incentives are monetary credits offered by the federal government to private entities or individuals for certain products or activities that reduce the amount of tax due. The 45Q tax credit was introduced in 2008 as a carbon capture sequestration (CCS) specific incentive that provides stable and predictable cash flow for carbon oxide that is geologically stored permanently, stored through enhanced oil recovery, or through other utilization. In 2022, 45Q was expanded to include DAC projects and raised the monetary credit for those types of projects. Expanding existing tax credits or the creation of a new technology-inclusive CDR tax credit to include mCDR solutions would facilitate wide-scale commercialization of mCDR.[64] Eligibility of mCDR technologies under tax law would be done through robust MRV and life cycle assessment methods for assessing and monitoring the net CO_2 removed and stored, which currently do not yet exist and may require investments in R&D. Pragmatic MRV would strengthen confidence in the capability of mCDR solutions to remove CO_2 already in the atmosphere and oceans and safely store or sequester it.

To conclude, each mCDR pathway is unique and in different stages of development. The respective rate of R&D and decision-making on deployment and commercialization will vary. Therefore, a combination of different federal support mechanisms for mCDR technologies will be needed to evaluate different technologies and ensure that the proven solutions can achieve commercialization and contribute to net-zero emission commitments.

3.3 Supporting Alignment and Coordination

Collaboration across the federal government, research entities and various stakeholder groups is also needed to ensure the successful development and commercialization of mCDR technologies.[65] For instance, mCDR research has the tendency to be highly siloed, so technologically focused projects may be designed without consideration of legal issues, environmental considerations, or other research that has already been performed. Additionally, policies and jurisdiction can vary depending on the distance from the coast, resulting in different agencies being responsible for regulations covering separate parts of the ocean. To address redundancies and accelerate technology development, policies may be developed to prioritize early stakeholder engagement, federal agency coordination and research community collaboration.

Coordination for mCDR can leverage the progress made by the Ocean Policy Committee (OPC), which was created to coordinate federal action on ocean-related matters.[66] The OPC does this by engaging and collaborating with the ocean community, facilitating coordination and integration of federal activities in ocean and coastal waters to inform ocean policy, identifying priority ocean science and technology needs and leveraging resources and expertise to maximize the effectiveness of federal investments in ocean research. In March 2023, the OPC released an Ocean Climate Action Plan (OCAP), which highlights advancing mCDR and storage technologies to provide powerful levers for reducing net greenhouse gas emissions.[67] To fulfill one of the recommendations from the OCAP, the White House Office of Science and Technology Policy (OSTP) created the Fast-Track Action Committee (FTAC) to evaluate the different types of mCDR and shape relevant policy and research on mCDR and carbon sequestration. FTAC includes experts from over a dozen federal departments and agencies to develop an implementation plan to advance mCDR. The committee will also 1) draft recommendations for policy, permitting and regulatory standards for mCDR research and implementation, 2) develop a plan for a comprehensive federal research and scaled testing program for mCDR approaches and 3) explore approaches for coordinating public-private funded mCDR research activities.[68] Examples of additional coordination efforts are listed below.

Bolstering Federal Agency Coordination — The bipartisan **Removing Emissions to Mend Our Vulnerable Earth (REMOVE) Act of 2022** would establish the Committee on Large-Scale Carbon Management within the DOE to plan and oversee efforts to remove CO_2 from the air or ocean and store such carbon.[69] The REMOVE Act would also form the Carbon Accounting Coordination Working Group to ensure that government-wide actions on CDR are accounted for and measured.

Integration of mCDR into Existing Marine Industries — Coordinating the nascent mCDR industry with existing marine-related sectors, such as shipping, off-shore wind development, wastewater treatment, beach nourishment and fisheries, could present promising opportunities for easing wide-scale deployment. For instance, leveraging existing permitting regulations of well-established marine-related sectors could clarify and streamline mCDR regulatory processes. The co-location of mCDR pathways with marine infrastructure, like off-shore wind turbines, could provide energy resources for emissions reduction.

Improving Methods for Stakeholder Engagement — Improving global data collection of the oceans can be achieved by partnering with the more than four million fishing vessels worldwide, which cover significant portions of ocean environments with limited data.[70] The Fishing Vessel Ocean Observing Network (FVON) aims to advance fishing vessel-based ocean observation on a global scale by maximizing data value, establishing best practices around data collection and management and facilitating observation uptake.[71] The FVON would outfit sensors onto vessels and fishing gear for fishers to actively participate in closing ocean data gaps without changing their standard fishing activities.

Enhancing Research Community Collaboration — Collaboration across the international marine research community supports information sharing and data collection across different environments. The Surface Ocean Carbon Atlas (SOCAT) is a synthesis of quality-controlled, surface ocean CO_2 observations by the international marine carbon research community.[72] It is key for the quantification of the ocean carbon sink and the evaluation of ocean biogeochemical models. SOCAT data is publicly available, discoverable and citable. It has also been used for the evaluation of climate models and sensor data.[73]

Driving Technological Advancements through Global Competition— International engagement could drive positive technological competition in the mCDR sector, resulting in the most effective and affordable mCDR solutions. For instance, the nonprofit initiative Carbon to Sea was launched in 2023 to systematically evaluate promising ocean-climate solutions around the world. In year one, they awarded more than 22 million to researchers in the U.S, Canada, Germany, Australia and the United Kingdom to advance science and technology and began launching a global network of field research sites.[75] Japan has pledged to lead efforts to achieve decarbonization, economic growth and energy security in Asia and stated a need for $28 trillion to facilitate carbon removal in the region. The Global South has also begun engaging in mCDR discussions, particularly the role developing countries that depend on oceans can play in shaping CDR strategies and technologies.[76]

As interest in the promise of mCDR grows and more stakeholders become involved, it will be necessary to seek alignment to create a competitive and robust mCDR environment.

4. Conclusion

The Earth's oceans provide an incredible opportunity to reduce and remove global carbon dioxide emissions. U.S. federal lawmakers can support marine carbon dioxide removal technologies in several ways. While novel solutions, such as direct air capture, provide another path to removing carbon dioxide already in our atmosphere, ensuring support for a diverse set of solutions will avoid technology lock-in, optimize limited resources for innovation by leveraging the ocean's higher carbon concentration and carbon uptake capacity, as well as retain mCDR innovators ensuring American leadership of this nascent space.

The successful deployment and eventual commercialization of mCDR pathways in the U.S. to address global carbon removal commitments on time relies on the parallel establishment of a regulatory framework specific to mCDR innovations and a coordinated, transparent and robust research environment. Once a regulatory framework is established and comprehensive research has been conducted, policies that support the testing and demonstrating early-stage innovative technologies can be designed to provide targeted support for mCDR technologies. These policies would allow mCDR technologies to avoid the innovation "Valley of Death." Demand-side support mechanisms such as procurement, federal loans and tax policies can support the wide-scale commercialization of mCDR solutions. Finally, policies prioritizing early stakeholder engagement and education, federal agency coordination and research community collaboration provide a cohesive and structured approach to mCDR development that optimizes and coordinates federal and private resources.

Appendix

Table A1. Federal Support for mCDR Projects

Funding Source Abbreviations

- DOE- FECM: Department of Energy- Fossil Energy and Carbon Management
- DOE- ARPA-E: Department of Energy- Advanced Research Projects Agency- Energy
- NOAA: National Oceanic and Atmospheric Administration
- OAP: Ocean Acidification Program
- GOMO: Global Ocean Monitoring and Observing
- WPTO: Water Power Technologies Office
- NSF: National Science Foundation
- ONR: Office of Naval Research

Funding Source	Program	mCDR Project	Lead Institution	Location	Total Value
DOE-FECM	Investments for Carbon Management R&D Projects	Ocean-Based Carbon Capture, Storage, and Alkalinity Improvement by a Seawater-Regenerated Metal-Polymer Hybrid Sorbent	Advanced Cooling Technologies, Inc	Lancaster, PA	$249,999
DOE-FECM	Investments for Carbon Management R&D Projects	Atmospheric CO2 Removal via Direct Ocean Capture on an Offshore Platform	Captura Corporation	Pasadena, CA	$249,919
DOE-FECM	Investments for Carbon Management R&D Projects	Optimizing the integration of aquaculture and ocean alkalinity enhancement for low-cost carbon removal and maximum ecosystem benefit	Ebb Carbon, Inc.	San Carlos, CA	$250,000
DOE-FECM	Investments for Carbon Management R&D Projects	Ocean Energy Carbon Removal	Ocean Energy USA LLC	Sacramento, CA	$250,000
DOE-FECM	Investments for Carbon Management R&D Projects	Development of Modular Electrochemical Tubes to Remove Dissolved Inorganic Carbon from Ocean	University of Houston	Houston, TX	$250,043
DOE-FECM	Investments for Carbon Management R&D Projects	Depolarized Electrochemical Reactor for Ocean Alkalinity Enhancement and Facile Recovery of High Purity Carbon	University of Kentucky Research Foundation	Lexington, KY	$249,998
DOE-FECM	Investments for Carbon Management R&D Projects	Hydrolytic Softening for Ocean Carbon Dioxide Removal	University of North Dakota Energy & Environmental Research Center (EERC)	Grand Forks, ND	$235,935
DOE-FECM	Investments for Carbon Management R&D Projects	TRACER: Electrochemical Removal of Carbon Dioxide from Oceanwater: Field Validation	University of Texas at Arlington	Arlington, TX	$250,000
DOE-ARPA-E	Sensing Exports of Anthropogenic Carbon through Ocean Observation (SEA-CO2)	Scalable, Multiparameter Chip-Size Carbon Sensors	Woods Hole Oceanographic Institution	Woods Hole, MA	$3,738,960

DOE-ARPA-E	SEA-CO2	Acoustic Methods for mCDR based on Blue Carbon Burial in Seagrass Meadows	University of Texas at Austin	Austin, TX	$2,034,903
DOE-ARPA-E	SEA-CO2	Monitoring, Reporting and Verification of Zooplankton-Mediated Export Pathways for Carbon Sequestration	Bigelow Laboratory for Ocean Sciences	East Boothbay, ME	$2,279,867
DOE-ARPA-E	SEA-CO2	SLEUTH: Spectroscopy of Oceanic Liquid Environments Using Towed Optical Sensor Heads	University of Colorado, Boulder	Boulder, CO	$5,904,233
DOE-ARPA-E	SEA-CO2	A Scalable, Integrated, Real-Time, GPU-Based Modeling System to Enable MRV for mCDR	atdepth MRV	Cambridge, MA	$2,524,964
DOE-ARPA-E	SEA-CO2	SEAfloor Self-sustaining CO2 Assessment Probe Edge (SEASCAPE)	University of Utah	Salt Lake City, UT	$2,004,554
DOE-ARPA-E	SEA-CO2	Spatially Resolved Multi-Parameter Sensing Of Ocean Carbon Dynamics Utilizing Fiber Optic Time-Of-Flight Sensors	General Electric (GE) Research	Niskayuna, NY	$4,274,658
DOE-ARPA-E	SEA-CO2	Hybrid Distributed pH, CO2, Temperature, and Acoustic Sensing for Monitoring and Verification of Marine Carbon Dioxide Removal Applications	University of Pittsburgh	Pittsburgh, PA	$2,274,859
DOE-ARPA-E	SEA-CO2	Quantification of Atmospheric Carbon Dioxide Removal Using an Autonomous Ocean Sensor that Measures Sinking Particulate Carbon Flux	Woods Hole Oceanographic Institution	Woods Hole, MA	$4,802,245
DOE-ARPA-E	SEA-CO2	Integrated Experimental and Modeling Assessment of Ocean Alkalinity Enhancement for Scalable Marine Carbon Dioxide Removal	Pacific Northwest National Laboratory	Seattle, WA	$2,080,715
NOAA OAP and NOPP	Investments to Advance mCDR Research	Carbon capture and ocean acidification mitigation potential by seaweed farms in tropical and subtropical coastal environments	Scripps Institution of Oceanography	San Diego, CA	$1,451,575
NOAA	Investments to Advance mCDR Research	Assessing chemical and biological implications of alkalinity enhancement using carbonate salts obtained from captured CO2 to mitigate negative effects of ocean acidification and enable mCDR	Scripps Institution of Oceanography	San Diego, CA	$995,891
DOE-FECM and WPTO	Investments to Advance mCDR Research	Electrolysis-driven weathering of basic minerals for long-term ocean buffering and CO2 reduction	Oregon State University	Corvallis, OR	$2,000,000
NOAA-GOMO, NOAA-OAP, NSF	Investments to Advance mCDR Research	Multiscale observing system simulation experiments for iron fertilization in the Southern Ocean, Equatorial Pacific, and Northeast Pacific	Woods Hole Oceanographic Institute	Woods Hole, MA	$1,983,731
NOAA	Investments to Advance mCDR Research	An opportunity to study Ocean Alkalinity Enhancement, CDR, and ecosystem impacts through coastal liming	University of Rhode Island	Kingston, RI	$1,538,452
NOAA	Investments to Advance mCDR Research	Tidal wetlands as a low pH environment for accelerated and scalable olivine dissolution	United States Geological Survey	Reston, VA	$1,895,531
NOAA	Investments to Advance mCDR Research	Assessing the laboratory and field responses of diatoms and coccolithophores to ocean alkalinity enhancement	Woods Hole Oceanographic Institution	Woods Hole, MA	$1,026,045

NOAA	Investments to Advance mCDR Research	Determining the Influence of Ocean Alkalinity Enhancement on Foraminifera Calcification, Distribution, and CaCO3 Production	Vassar College	Poughkeepsie, NY	$510,359
DOE-FECM	Investments to Advance mCDR Research	Assessing the effects and risks of ocean alkalinity enhancement on the physiology, functionality, calcification, and mineralogy of corals and crustose coralline algae in the Pacific	University of Hawai'i, Manoa	Honolulu, HI	$1,999,835
NOAA	Investments to Advance mCDR Research	Assessing Carbon Dioxide Removal and Ecosystem Response for an Ocean Alkalinity Enhancement Field Trial	Woods Hole Oceanographic Institution	Woods Hole, MA	$1,877,644
NOAA, ClimateWorks Foundation	Investments to Advance mCDR Research	Assessing efficacy of electrochemical ocean alkalinity enhancement at an existing outfall using tracer release experiments and oceanographic models	University of Hawaii	Honolulu, HI	$1,915,600
NOAA	Investments to Advance mCDR Research	Quantifying the Efficacy of Wastewater Alkalinity Enhancement on mCDR and Acidification Mitigation in a Large Estuary	University of Maryland Center for Environmental Science	College Park, MD	$1,864,561
NOAA	Investments to Advance mCDR Research	Biotic calcification impacts on marine carbon dioxide removal additionality	University of Washington (CICOES)	Seattle, WA	$1,250,482
NOAA	Investments to Advance mCDR Research	Developing a coupled benthic-pelagic biogeochemical model to evaluate the effectiveness of mCDR interventions	Northeastern University	Boston, MA	$1,258,967
ONR, ClimateWorks Foundation	Investments to Advance mCDR Research	Engaging U.S. Commercial Fishing Community to Develop Recommendations for Fishery-Sensitive mCDR Governance, Collaborative Research and Monitoring, and Outreach to Fishing Communities	Responsible Offshore Development Alliance	Washington, DC	$1,258,967
ONR	Investments to Advance mCDR Research	Coupling Desalination with Novel mCDR Membranes	University of Pittsburgh	Pittsburgh, PA	$1,403,802
NSF, NOAA OAP	Investments to Advance mCDR Research	Data requirements for quantifying natural variability and the background ocean carbon sink in mCDR models	Columbia University	New York, NY	$589,464

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