Technological Innovation Opportunities for CO_2 Removal

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List of Acronyms

BiCRS	biomass carbon removal and storage
CAPEX	capital expenditures
CDR	carbon dioxide removal
CO_2	carbon dioxide
$CO_2(aq)$	aqueous dissolved carbon dioxide
DAC	direct air capture
DACS	direct air capture and storage
DOC	direct ocean capture
DOE	U.S. Department of Energy
ERW	enhanced rock weathering
mCDR	marine carbon dioxide removal
MRV	measurement, reporting, and verification
OAE	ocean alkalinity enhancement
OPEX	operating expenditures
pCO_2	partial pressure of carbon dioxide
RD&D	research, development, and demonstration
$scCO_2$	supercritical carbon dioxide
SME	subject matter expert
TASC	total as-spent cost
TOC	total overnight cost
TRL	technology readiness level

Executive Summary

Addressing our climate change challenge requires both significant reductions in greenhouse gas emissions and removal of carbon dioxide (CO_2) from the atmosphere on the gigatonne scale. The U.S. Department of Energy's (DOE's) Carbon Negative Shot™ is an all-hands-on-deck effort to catalyze gigatonne-scale CO_2 removal (CDR) at an ambitious cost target of $100/net metric ton of CO_2, accounting for full life cycle emissions and requiring durable storage for at least 100 years. Given the emerging yet rapidly expanding nature of the CDR industry, the relatively high costs of delivered CDR today, and the diversity of CDR approaches, technological innovation can play a pivotal role in achieving this challenging target.

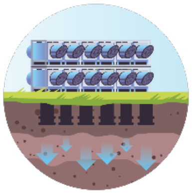
To that end, this report aims to evaluate opportunities for technological innovation to enhance the economic viability of CDR, with the overarching goal of stimulating innovation within the CDR field and directing R&D efforts toward areas with the greatest potential impact on cost reduction. Our approach leveraged diverse technological, modeling, and analysis expertise from across the DOE national lab complex to identify and characterize these innovation opportunities across direct air capture and storage (DACS), biomass carbon removal and storage (BiCRS), mineralization, and marine CDR (mCDR) pathways, with our approach and assessments being vetted through an external advisory board and subject matter expert elicitation. We prioritized technological innovation needs and opportunities based on two main considerations: (1) potential to impact relative cost reduction weighted by the probability of success and (2) the extent to which the innovation impacts multiple technologies/pathways. While we frame the study around cost reduction, we also include in this context revenue generation and co-benefits as they impact economic viability.

To further help guide R&D efforts, we categorized technological innovation opportunities as either "incremental" or "disruptive." Incremental innovation represents small or minor improvements to existing processes, while disruptive innovation represents a new or novel concept or approach that dramatically changes how a process operates or the value that it creates.

In this report, we elucidate these technological innovation opportunities through three main components: (1) qualitative heat maps for each CDR pathway that help identify areas with the greatest potential for cost reduction (see Sections 4.1.4 for DACS, 4.2.4 for mineralization, 4.3.4 for BiCRS, and 4.4.4 for mCDR); (2) identification, characterization, and prioritization of these innovation opportunities (see summary in Table ES-1); and (3) quantitative evaluation of the cost reduction potential of technological innovation for a single example case, direct air capture (DAC) coupled with in situ mineralization (see Figure ES-1). As shown in Table ES-1, there are ripe opportunities for innovation across disciplines and technology readiness levels, highlighting the value of an R&D strategy that crosses many offices within DOE as well as other agencies. We hope that the identified technological innovation opportunities can serve as a blueprint for targeted R&D to drive down the CDR cost curve.

Table ES-1. Summary of Prioritized Innovation Opportunities for Each CDR Pathway.

Further details are provided in Section 4.

CDR Pathway	Innovation Type	
	Incremental	Disruptive
 **Direct Air Capture and Storage**	**Reducing energy for regeneration** will also reduce the burden on our energy systems and critical material supply chains. **Improving sorbent lifetime** will eliminate costs associated with material replacement and also minimize or eliminate environmental disbenefits arising from emissions. **Reducing sorbent capital cost** is complementary to lifetime improvement and may be able to leverage earth-abundant materials. **Reducing non-sorbent capital cost** may help for some processes that require specialized or novel capital equipment. **Improving sorbent capacity and capture-release kinetics** allows efficient utilization of materials and capital equipment.	**Coupling DACS with valuable noble gas (e.g., xenon and krypton) harvesting from the atmosphere** can provide a source of revenue for DACS and subsidize or even pay for the process of carbon removal. **Coupling DACS with renewable energy storage technologies** may enable reduction in the DACS system energy burden through clever integration. **Coupling DACS with capture or destruction of short-lived climate forcers (e.g., CH_4, N_2O, hydrofluorocarbons)** can simultaneously achieve reduction in multiple greenhouse gases, leveraging air movement already occurring for DACS.
 **Mineralization**	*In Situ* **Advanced injection methods and storage field development strategies** could optimize storage field management while maximizing the per-well storage capacity and reducing the area of review. **Optimization of integration with CO_2 source (i.e., DAC or BiCRS).** For certain injection methods and sites, cost savings may be driven by integration and system design that considers the injection method.	*In Situ* **Valorization of coproducts through CO_2-enhanced critical mineral recovery.** **Microbial- or biologically enhanced mineralization** that enhances dissolution rates, accelerates carbonate precipitation, or improves critical mineral recovery potential. **Development of injectates that pre-seed mineralization sites** and expand in situ mineralization to traditionally nonreactive or long-term, reactive rock formations (i.e., sedimentary rocks). **Advanced remote sensing and aerial geophysical sensing** to track and characterize subsurface changes due to mineralization in real time.

CDR Pathway	Innovation Type	
	Incremental	Disruptive
	Ex Situ **Optimization of reactor system and tailings pile design.** Ex situ reaction rates and extents can be improved through innovative reactor and tailings pile designs that enhance gas-solid contact without introducing large pressure drops. **Advanced feedstock preparation techniques to maximize reactivity.** *Enhanced Rock Weathering (ERW)* **"Pay for practice"-style measurement, reporting, and verification.** Integration of ERW into soil carbon models through extensive field trials across a range of soil types, rock types, climates, and land use practices could lead to general ERW practices that consistently provide CDR. **Quantifying co-benefits of ERW.** Increased crop yields, reduction of fertilizer or lime addition, and other financial co-benefits could help not only increase adoption, but also motivate farmers to consistently deploy ERW even if CDR prices wax and wane.	*Ex Situ* **Advanced remote sensing paired with ground-truthing to detect highly reactive rocks.** **Salt and brine sources of CO_2 reactive minerals.** The calcium and magnesium content of the ocean, brines, and salt deposits can be leveraged to generate magnesium/calcium hydroxides for CO_2 mineralization. *Enhanced Rock Weathering* **Biological hyperaccumulators.** Organisms capable of promoting economically interesting (e.g., nickel) or environmentally deleterious (e.g., chromium) elements and compounds from source rocks or soils could allow for exploitation of more rocks in more environments for ERW. **Improved, alternative, or autonomous sensors to track mineralization and coproducts.**
 **Biomass Carbon Removal and Storage**	**Process intensification and downscaling** to enable improved yields and shorter transportation distances for waste feedstocks that are widely distributed. **Pairing BiCRS with renewable sources of heat and electricity** to support biomass drying, pretreatment, and conversion. **Understanding and engineering** enhanced biochar durability for soil amendment. **Supply chain optimization to improve feedstock sourcing**,	**Enhancing photosynthetic efficiency and resilience** of plants. **New feedstock pretreatment strategies, including mobile systems, to enhance homogeneity**, remove inorganic contents, improve feedstock density for transport, and improve long-term stability during storage. **Low-cost biohydrogen storage, transport, and high-value utilization** are needed to enable biomass gasification and biohydrogen production.

CDR Pathway	Innovation Type	
	Incremental	Disruptive
	preprocessing, and delivery at low costs. **Lower-cost nutrient recovery** to mitigate wastewater discharge impacts from facilities utilizing organic wastes and add another revenue stream.	
 **Marine CO_2 Removal**	Design **closed-loop processes to increase CDR certainty.** Enhance **ion-exchange membrane performance and lifetime.** Develop **high-density cultivation** capabilities to improve scalability. Improve **energy efficiency through system design and operation.**	Design **low-cost, high-sensitivity carbon flux sensors** for distributed monitoring. Develop **durable system components to eliminate need for pretreatment** of seawater. **Enhance primary productivity** of marine photosynthetic organisms. Identify **sustainable routes to use of all coproducts** generated.

Cost waterfall charts, derived from process models coupled with techno-economic analysis and life cycle assessment, are a critical tool for assessing and quantifying the impact of technological innovation. Figure ES-1 illustrates the potential cost savings (and additional revenue generation) for a single DAC + in situ mineralization case through both incremental and disruptive innovations. As shown, these innovations can reduce cost of CO_2 removal for the modeled system by more than 50% from the baseline, highlighting the critical role that technological innovation can play in achieving the cost target set forth by the Carbon Negative Shot. Importantly, the cost reduction scenario presented here does not represent a prediction of likely cost reductions or an attempt to set an upper or lower bound on potential cost reductions for any DAC or mineralization technology. Instead, this is an illustrative analysis meant to highlight the value of joint techno-economic analysis and life cycle assessment for guiding R&D priorities.

In support of the Carbon Negative Shot, we recommend that this type of analysis be performed for other CDR pathways and multiple, specific technologies within each pathway to help guide R&D prioritization. This type of analysis can also be used to track innovation progress in relation to the Carbon Negative Shot. A systematic modeling effort, coupling techno-economic and life cycle assessment for all key pathways of interest to the Carbon Negative Shot, could translate achieved and targeted technological advances in specific subsystems (e.g., energy efficiency improvements or increases in process or reaction speed) into a quantitative assessment of overall implications for the levelized cost of CDR.

The science of translating lab-scale results into cost reductions at scale is necessarily uncertain, but the more quantitative and rigorous the impact assessment mechanism used, the more likely critical research, development, and demonstration funding will be allocated toward a portfolio of projects with the desired combination of overall impact and likelihood of success.

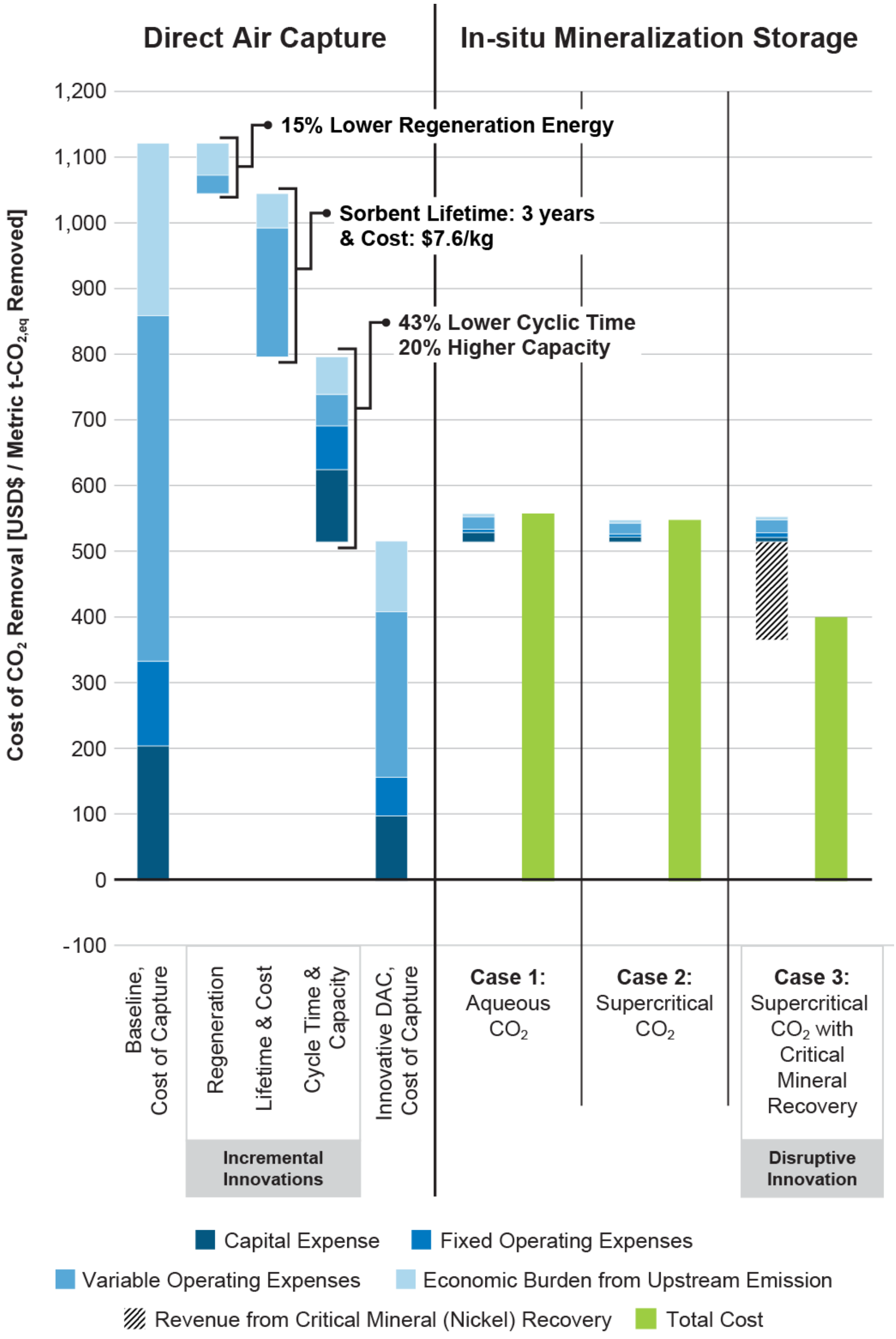


Figure ES-1. Waterfall chart illustrating possible impacts of selected technological innovations in reducing the cost of CDR via DAC + mineralization.

The scenario represented in this figure is a system located in California with our moderate assumptions for potential improvements. While we included revenue generation from co-products (i.e., recovered Nickel) of CDR in this scenario, market analysis is needed to ensure that increasing supply can be supported by demand and that product quality meets required specifications. Further details are provided in Section 5, Appendix B, and Appendix C.

Table of Contents

List of Figures

List of Tables

1 Carbon Dioxide Removal: Overview and Role in Climate Change Mitigation

Global net anthropogenic greenhouse gas emissions reached a new high of more than 55 gigatonnes in 2019 (1). To reach our "net-zero" emissions goal by midcentury, our first priority is to reduce carbon dioxide (CO_2) entering the atmosphere, in alignment with the United States' near-term net target of 100% clean electricity by 2035, with a 40% reduction in greenhouse gas emissions from 1990 levels by 2030 (2). To counteract any remaining emissions from hard-to-decarbonize sectors, we will also need to actively remove CO_2 from the atmosphere (see the callout box below for the difference between carbon removal and carbon reduction).

Carbon Removal

Carbon removal is the process of removing carbon dioxide from the atmosphere and durably storing it for extended periods, spanning decades to millennia.

Carbon Reduction

Carbon reduction or avoidance focuses on the prevention/reduction of future carbon emissions into the atmosphere.

To this end, we must pursue negative emissions (Figure 1) through robust and verifiable nature-based and technological carbon dioxide removal (CDR) pathways. CDR simply refers to a wide array of approaches that remove CO_2 directly from the atmosphere and durably store it on land, in geological formations, in ocean reservoirs, or in value-added products for decades to millennia (3). Although there is no clear scientific basis for a threshold of durability to define CDR, nor consensus among policymakers, duration of storage largely depends on the characteristic timescale of a carbon pool (e.g., biochar, marine sediment, geological formations, minerals) and risks of reversal. Globally, the largest natural sinks for anthropogenic CDR remain oceans and vegetation (4). Although human-driven activities to enhance those natural sinks and expand engineered solutions have increased in recent years, we are nowhere near the desired CDR levels yet—or close to matching natural cycles. To meet the objectives of the Paris Agreement, aiming for net-zero greenhouse gas emissions by 2050 and limiting global warming to below 1.5°C by 2100, integrated assessment models indicate that large-scale commercial CDR projects must successfully extract 5–10 gigatonnes of CO_2 per year globally by midcentury in addition to nature-based solutions (5–7). In this direction, the U.S. Department of Energy (DOE) launched the Carbon Negative Shot™, an effort to catalyze gigatonne-scale CDR at an ambitious cost target of $100/net metric ton of CO_2, accounting for full life cycle emissions and requiring durable storage for at least 100 years (8).

CDR methods encompass a range of capture processes and storage pools, including natural processes, technological solutions, and hybrid approaches. Natural methods involve afforestation and reforestation, improved land management to enhance carbon sequestration in forests and soils, and acceleration of natural ocean processes that store atmospheric carbon as ocean plants or dissolved minerals. Technological methods include direct air capture (DAC) and direct air capture and storage (DACS), biomass carbon removal and storage (BiCRS), direct ocean capture (DOC), mineralization, and enhanced weathering (see Table 1 for further definitions).

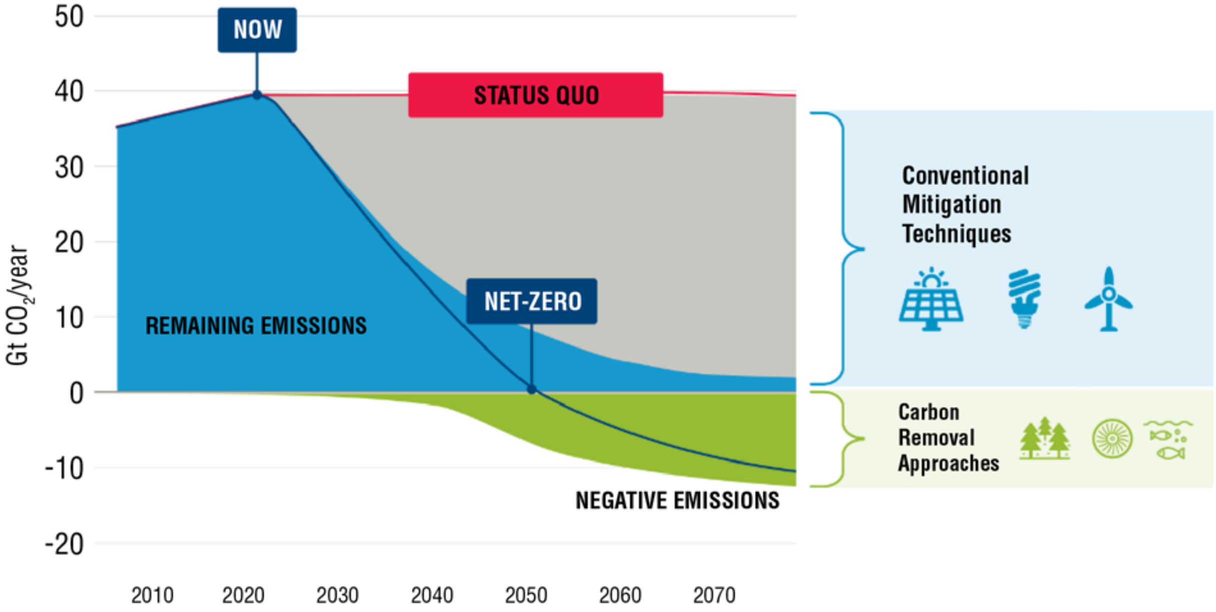


Figure 1. Role of negative emissions to meet net-zero emissions target by 2050

Source: Based on (9,10). Adapted from (11)

The commercial CDR landscape is rapidly evolving as industries and climate innovators respond to the urgent global need for mitigating climate change. Here, we provide just a quick look into the commercial CDR landscape, but the second edition of *The State of Carbon Dioxide Removal* conducts a thorough assessment of the status of the field (12). In 2023, the carbon removal industry experienced significant growth due to company acquisitions, government funding, startup fundraises, and high-profile announcements. Policy frameworks and incentives play a crucial role in shaping the commercial CDR landscape, influencing both research and market dynamics. The number of carbon removal credits sold surged by 650% in 2023. As of the time of this report, here are a few recent announcements in the CDR landscape:

- CDR.fyi reported a 6.5-times increase in carbon credit sales, from 800,000 tonnes in 2022 to more than 5.2 million tonnes by the end of 2023, totaling $2.1 billion in purchases (13,14).
- Microsoft signed the largest carbon removal credit agreement to date, purchasing 2.76 million tonnes from Ørsted's bioenergy with carbon capture and storage plant (15).
- Occidental Petroleum acquired Canadian carbon removal firm Carbon Engineering (DAC) in a landmark $1.1 billion deal, marking the first major acquisition of a carbon removals company.
- DOE awarded $1.2 billion for two Texas- and Louisiana-based projects under its DAC Hubs program. In fact, from 2010 to 2022, approximately $4.1 billion was globally invested in research, development, and demonstration (RD&D) programs for CDR, with an overwhelming majority of $3.5 billion allocated exclusively to DAC hubs in the United States.

- DOE also launched a $35 million carbon credit procurement program to directly purchase carbon credits, the first of any government worldwide (16).

A closer look at the funding deals driving growth in technological CDR shows the field is evolving in response to global net-zero emissions targets. Figure 2 provides an overview of the CDR startup company investment landscape highlighting company age, funding stage, and total funding raised, with the latest funding round serving as a proxy for market adoption. This figure emphasizes the sheer extent of commercial activity, the breadth and diversity across the four represented technological CDR pathways, and the early stage of the industry.

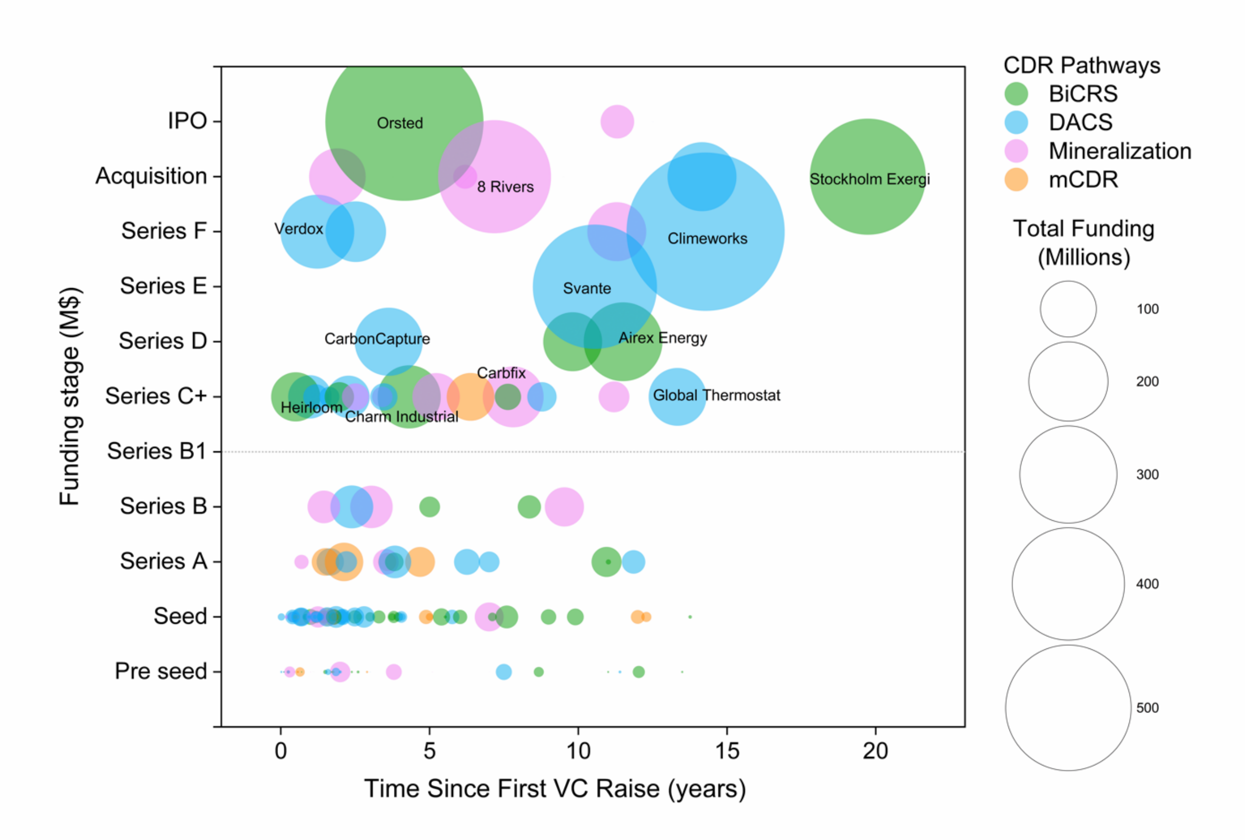


Figure 2. Technological CDR startup investment landscape.

The authors categorized more than 175 companies from across the globe into one of four CDR pathway categories—DACS, mineralization, BiCRS, and marine carbon dioxide removal (mCDR)—using initial characterizations assigned by Sightline VC as a starting point. Each company was then placed into a startup stage based on their most recent venture capital raise. The Series C+ category served as a catch-all for companies that had surpassed the Series C funding round but had not yet exited or reached the growth stage. For each company, the total funding attributed was calculated by adding together dilutive and non-dilutive deals. A few CDR companies (Ørsted and Climeworks) received funding exceeding $500 million and are not shown in the graph at their true scale for simplicity.

While this commercial activity is promising, CDR is an emerging industry and faces various challenges, including high costs; resource constraints (e.g., minerals, energy, biomass); measurement, reporting, and verification (MRV) complexities; low technology readiness level (TRL); and uncertain scalability, among others. **Technological innovation across multiple domains is needed to overcome these challenges and achieve the targets of the Carbon Negative Shot.**

2 Intent and Approach for This Report

This report aims to evaluate the role of technological innovation in enhancing the economic viability of CDR, with a specific focus on aiding the United States in meeting ambitious yet realistic climate targets. The primary objective is to provide a balanced and vetted assessment of the cost reduction potential, technical barriers, and research needs of various CDR approaches in support of DOE's Carbon Negative Shot. Our approach (Figure 3) leverages diverse technological, modeling, and analysis expertise from across the DOE national lab complex to identify and characterize opportunities for cost reduction through technological innovation across DACS, BiCRS, mineralization, and mCDR pathways. Our approach and assessments have been vetted through an external advisory board and subject matter expert (SME) elicitation. More details on our SME survey can be found in the callout box on the next page and in Appendix A.

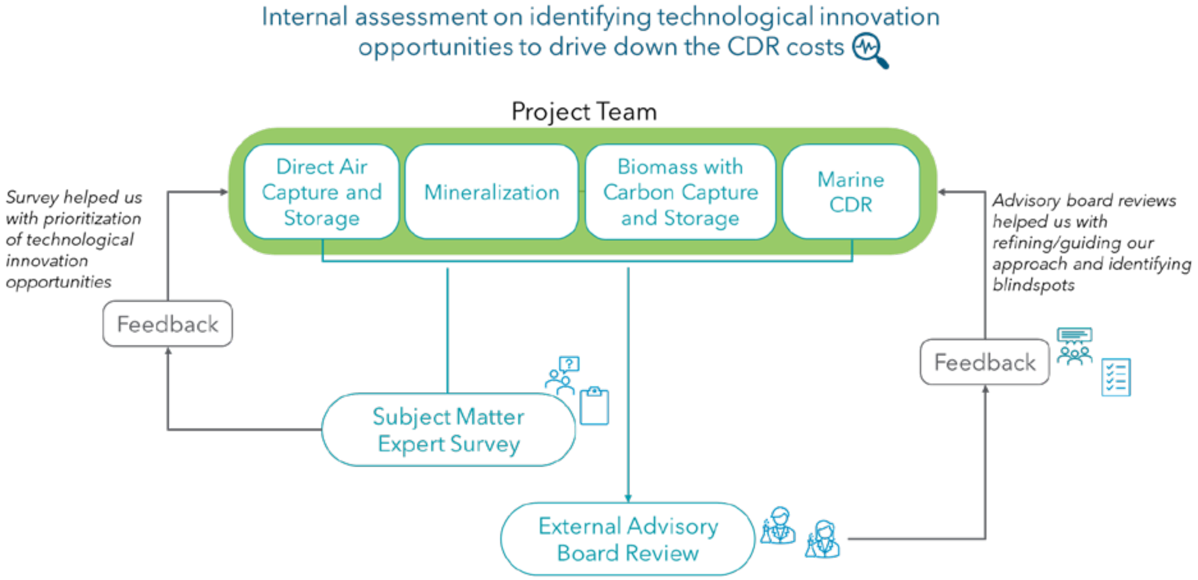


Figure 3. Our approach for this study

Ultimately, we hope that this report stimulates innovation within the CDR field, directing R&D efforts toward areas with the greatest potential impact on cost reduction. To that end, we prioritized technological innovation needs and opportunities based on two main considerations: (1) potential to impact relative cost reduction weighted by the probability of success and (2) the extent to which the innovation impacts multiple technologies/pathways. While we frame the study around cost reduction, we also include in this context revenue generation and co-benefits as they impact economic viability.

To further help guide R&D efforts, we categorized technological innovation opportunities as either "incremental" or "disruptive." Incremental innovation represents small or minor improvements to existing processes. These improvements are "line of sight," meaning that engineers, scientists, and researchers can envision how these improvements can be achieved. Disruptive innovation represents a new or novel concept or approach that dramatically changes how a process operates or the value that it creates. For this report, disruptive innovation offers a potential step change in reducing the cost (or increasing the value) of a CDR technology, yet our understanding of how this innovation can be achieved is limited. We hope that this categorization will help to inspire R&D efforts across TRLs.

This report does not seek to compare one CDR pathway or technology against another or prioritize the technologies, but rather focuses exclusively on fostering technological innovation. Some methods, such as nature-based solutions—mainly afforestation, reforestation, and algae-based BiCRS—are out of the scope of this report. This strategic approach deliberately excludes aspects outside the realm of technological innovation, such as permitting and regulatory considerations and policy, to maintain a clear and targeted focus on advancing technological solutions for CDR. This ensures a robust foundation for ongoing R&D efforts, facilitating a concerted push toward achieving sustainable and cost-effective carbon removal solutions.

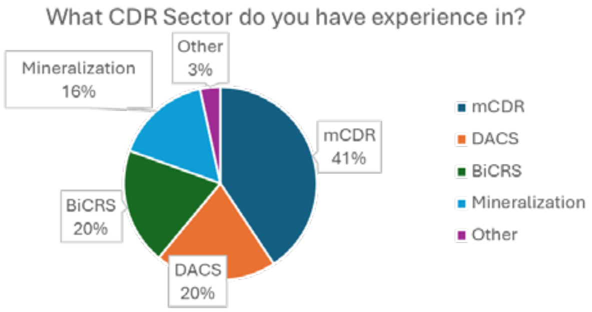
Subject Matter Expert Survey: Approach and Summary

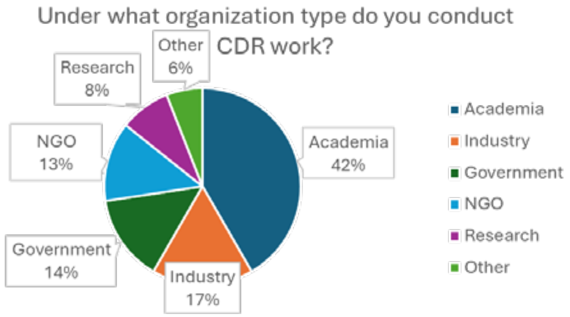
One of the methods for gathering data for this report involved conducting a subject matter expert survey. A list of 123 SMEs was identified based on their involvement in the CDR space. Attention was given to identifying experts that represented a variety of organization types (academia, industry, non-academia research, government, and nongovernment).

The survey included questions on identifying and ranking economic drivers, prioritizing R&D investments, identifying limiting factors to sustainability, and understanding MRV challenges.

Survey results were collected from 84 participants (67% response rate). Of the responses, 24 were received for DACS, 19 for mineralization, 23 for BiCRS, and 48 for mCDR (114 total records). Multiple respondents indicated that they had expertise in more than one field, which is why the number of records is greater than the number of respondents.

Detailed survey results can be found in Appendix A.





While we seek to directly connect technological innovation with cost reduction, one limitation of this report is that most of these connections are qualitative, as described in Sections 4.1–4.4. We only develop and include a cost waterfall chart for one example case: DAC combined with in situ mineralization. This waterfall chart, provided in Section 5, is intended to (1) demonstrate the methodology for developing robust cost assessments and (2) provide an example of direct quantification of cost reduction through technological innovation. We hope that this will set the stage for future quantitative evaluations that are built on this foundational report.

Importantly, this report has been developed within the context set by other recent CDR roadmaps and assessments and complements these other seminal reports, including RMI's *The Applied Innovation Roadmap for CDR* (17), *The State of Carbon Dioxide Removal* (2,12), and the U.S. *Roads to Removal* report (18). Firstly, in line with RMI's objective to advance the technical viability of various CDR approaches, our focus encompasses four specific pathways—DACS, mineralization, BiCRS, and mCDR (17). Secondly, our comprehensive overview resonates with the report *The State of Carbon Dioxide Removal*, contributing insights from research, policymaking, and deployment perspectives (2). Thirdly, the goal of *Roads to Removal* (18) was to evaluate potential supply curves for CDR in the United States, while our report aims to pinpoint opportunities for technological innovation that could facilitate the attainment of these supply curves at reduced costs. Finally, our investigation into pathways for the physical removal and storage of gigatonnes of CO_2 mirrors the objectives laid out in the *Roads to Removal* report, underscoring the importance of large-scale carbon removal in reaching net-zero carbon emissions by 2050 or earlier (18). This synthesis reflects a holistic approach, weaving together technical advancements, the current state of CDR, and pathways for effective carbon removal on a gigatonne scale with a focus on technological innovations playing a key role in driving down the cost of removal.

3 CDR Pathways and Technical Definitions

This report identifies and characterizes critical technological innovation opportunities to help achieve CDR costs below $100/ton across four pathways: DACS, mineralization, BiCRS, and mCDR. It highlights the specific advancements needed for each pathway, acknowledging their unique challenges and considerations. The report integrates insights from marine research to enhance cost-effectiveness and scalability across all CDR pathways. This integration highlights the interconnected nature of these categories, showcasing opportunities for innovation. The report underscores that these classifications are not isolated, but rather form a cohesive portfolio of options, with the categories acting solely as organizational tools throughout the document.

Before proceeding with detailed descriptions of each pathway, we provide a technical overview:

- **DACS** uses chemical processes, often involving sorbent materials, to capture CO_2 directly from ambient air and produces a more concentrated stream of CO_2 through regeneration of the material. The captured CO_2 is typically compressed and can be injected into geological formations for storage or utilized in the production of durable carbon-based products.
- **Mineralization** is a CDR approach that uses technologies or modified land use approaches to use natural or human-made calcium-, magnesium-, and iron-rich rocks or alkaline solutions (e.g., sodium hydroxide) to chemically react with CO_2 to form solid carbonate minerals, resulting in the removal of CO_2 from the atmosphere. Mineralization can provide removal and storage independently, or it can be linked to CDR options as the storage mechanism. Estimated mineralization storage capacities significantly exceed cumulative anthropogenic CO_2 emissions.
- **BiCRS** is a range of processes that use plants' natural photosynthetic abilities to capture CO_2 from the atmosphere followed by human engineering to store the biomass or derived products (e.g., biochar, bio-oil) belowground, where it will not decompose.
- **mCDR** involves removing CO_2 from the atmosphere and upper ocean and securely storing the excess carbon in either marine or terrestrial reservoirs. mCDR pathways can be diverse and include DOC, ocean alkalinity enhancement (OAE), and photosynthesis-based approaches.

Table 1 further provides a list of technical definitions of terms used throughout the report.

Table 1. Key Definition of Terms Used in This Report

Term	Definition
Carbon dioxide removal (CDR)	A wide array of approaches that capture/remove CO_2 directly from the atmosphere and durably store it in geological, bio-based, and ocean reservoirs or in value-added products to create negative emissions for decades to millennia.
Net zero	The balance between the amount of greenhouse gases emitted by anthropogenic activities to the atmosphere and the amount removed from the atmosphere.
Carbon Negative Shot	A DOE call for innovation in CDR pathways to capture CO_2 from the atmosphere and store it at gigaton scales for less than $100/net metric ton of CO_2 equivalent.

Term	Definition
Durability	The amount of time, typically on the order of decades or more, that the CO_2 stays locked away, as well as the risk of its reversal (i.e., being released back into the atmosphere).
Technological innovation	A subset of innovation focused on the development and significant improvements of existing technologies through novel technological advancements. For example, developing advanced sorbent materials with extended or improved lifetimes for DACS represents a technological innovation by significantly advancing the performance and carbon capture efficiency of existing technology.
Carbon capture and storage	A set of industrial methods for the capture of CO_2, concentration into a pure stream, and subsequent geological storage.
Direct air capture and storage (DACS)	These technologies extract CO_2 directly from the atmosphere and produce a more concentrated stream of CO_2 for permanent CO_2 storage in geological formations or for a variety of CO_2 utilization to durable products.
Mineralization	Mineralization technologies accelerate naturally occurring geochemical processes regulating long-term climate, whereby captured or atmospheric CO_2 is reacted with alkalinity to form solid, stable carbonate minerals.
Biomass carbon removal and storage (BiCRS)	Processes that use plants or algae to remove CO_2 from the atmosphere and convert the resulting biomass to long-lived products, including carbon storage materials, and/or capture CO_2 from the conversion process for geologic storage.
Marine carbon dioxide removal (mCDR; also called ocean-based CDR)	A suite of techniques and methods that aim to enhance ocean-based chemical and biological processes to alter the ocean carbon cycle for CDR, with CO_2 stored in marine or terrestrial reservoirs.
Measurement, reporting, and verification (MRV)	The process of measuring CO_2 removal, quantifying potential leakage, and reporting results to a third party for verification in accordance with compliance or voluntary market requirements.

4 CDR Pathway Cost Drivers and Technological Innovations

Each of the following subsections covers one of the four CDR pathways included within this report: DACS, mineralization, BiCRS, and mCDR. The sections maintain a consistent structure: (1) overview of the relevant approaches, (2) identification of key cost drivers, (3) characterization of critical technical challenges and innovation needs, (4) qualitative assessment and prioritization of technological innovation opportunities for impacting cost reduction, and (5) linkages to mCDR, acknowledging the interconnectivity between these pathways and applicability of innovation to marine environments. Overall, we seek to link technological innovation with key cost drivers for each CDR pathway and prioritize these innovations to inform future RD&D efforts in the field.

4.1 Direct Air Capture and Storage

4.1.1 Pathway Options and State of Technologies

DAC technologies remove CO_2 from the atmosphere through contact with a solvent or adsorbent that physically or chemically binds with CO_2. The solvent or adsorbent is regenerated typically through energy input, allowing its reuse and creating a more concentrated (often high-purity) stream of CO_2 suitable for storage. Active approaches to DAC use fans to force airflow to the adsorbent, while passive approaches rely on ambient airflow. Current DAC approaches are typically more expensive than alternative CDR options but have several significant advantages, including (1) relatively simple, highly reliable MRV; (2) mass scalability; and (3) the ability to deploy in a wide variety of locations.

There are many types of materials and chemistries that can be used for capture in DAC. Regeneration methods involve increasing the chemical potential of CO_2 in the bound phase, typically by applying thermal or electrical potential—the combination of capture material and regeneration method defines a DAC technology. Here, we briefly describe the broad DAC technology classes considered in this report.

Amine/Alkali Solid Chemical Adsorbent

Several classes of chemicals, including amines and alkalis, can strongly bind CO_2 via a chemical reaction that results in adsorption (19–22). These functional groups are typically dispersed on a solid support (e.g., mesoporous oxide, carbon, metal-organic framework) that increases the accessible surface area compared to bulk materials, resulting in high CO_2 adsorption capacity and improved adsorption kinetics. These materials are typically regenerated under near vacuum using an 80°C–150°C thermal swing, increasing the temperature of the substrate using steam, indirect heat exchange, or microwave/induction/joule heating. The lifetime of the adsorbent can be a concern in some cases. Amines are among the most mature technology systems for DAC, due in part to the widespread use of amines for gas separation in oil and natural gas operations (23).

Metal-Organic Framework/Zeolite Solid Physical Adsorbent

In contrast to chemical adsorbents, physical adsorbents weakly bind to CO_2, typically via Van der Waals or dispersion interactions (24–26). Some metal-organic frameworks and zeolites are commonly studied due to their high surface area and porosity, ability to tune pore size and chemical functionality, and regular crystalline structure allowing facile gas diffusion. Zeolites, in particular, are highly stable and commercially available. Because CO_2 is only weakly bound in these physical adsorbents, they typically require lower temperature (less than 50°C) for regeneration compared to chemical adsorbents. However, these materials may suffer from competitive adsorption of water, which can bind more selectively than CO_2 and is more abundant in the air.

Mineral Solid Adsorbent

Natural calcium- and magnesium-based minerals can react with atmospheric CO_2 to form strongly bound carbonates; heating above 700°C releases the CO_2 (27). The high temperature requirement for this process makes oxy-combustion of natural gas a ready choice for providing heat, but electric calciners/kilns are an emerging option. These types of adsorbents are highly durable and benefit from high surface area, ambient temperature, and humidity to increase adsorption kinetics.

Moisture-Swing Solid Adsorbent

Under dry conditions, ion-exchange resins containing quaternary ammonium cations with hydroxide or carbonate counterions can adsorb CO_2 as bicarbonate (28–30). In the presence of humidity or liquid water, the bicarbonate/carbonate equilibrium is reestablished, releasing CO_2. The adsorbent is then dried to complete the regeneration. These materials are somewhat durable to oxidative degradation and do not require heating for regeneration but may result in large water consumption.

Electro-Swing Solid Adsorbent

Redox-active organic compounds, such as quinones, can react with CO_2 under an applied reducing potential to form carboxylated species (31,32). Upon reversal of the polarity, the compound is returned to its neutral state, releasing the CO_2 without application of heat. Proper structuring of these adsorbents is critical to allow facile gas flow and electrical conductivity.

Hydroxide Liquid Solvent

Aqueous solutions of hydroxides naturally react with CO_2 to form carbonates; these can be reacted with calcium and magnesium salts to precipitate carbonates, regenerating the hydroxide solution (33–35). Heating of the carbonates above 700°C releases the CO_2 and regenerates the calcium or magnesium salt, similar to the mineral solid adsorbent process. Solvent-based processes enable continuous operation using equipment that benefits from economies of scale, developed from other industries. However, aqueous systems can suffer from water loss in arid environments, making that a potential concern.

Amino Acid Salt Liquid Solvent

Aqueous solutions of amino acid salts, such as potassium sarcosinate, readily react with CO_2 to form bicarbonates (36,37). Reaction of the captured CO_2 with solid guanidines allows precipitation of carbonate salts, regenerating the amino acid salt solution. Mild heating of the guanidine carbonate salt to 60°C–120°C releases the CO_2, regenerating the guanidine. This process operates similarly to the hydroxide liquid solvent process, except using organic capture and precipitation components instead of inorganic, as well as lower temperature for regeneration, and therefore shares many of the same advantages and drawbacks.

Carbonate Liquid Solvent

Similar to the hydroxide liquid solvent, the high pH of carbonate liquid solvents is sufficient to capture CO_2 as bicarbonate. Regeneration of these solutions can be performed at lower temperature than the hydroxide process, but near 100°C. The weaker driving force provided by the reaction and the slow kinetics of CO_2 dissolution means that these processes are typically used to capture higher-concentration CO_2 from pressurized processes, such as in urea synthesis (38).

pH-Swing Liquid Solvent

Rather than using heat to regenerate solvents, the pH of the system is manipulated to control the aqueous carbonic acid/bicarbonate/carbonate equilibrium (39–42). Under low- to neutral-pH regimes, CO_2 primarily exists as bicarbonate, carbonic acid, and physically dissolved CO_2, promoting release. Bipolar membrane electrodialysis produces acid and alkaline solutions, which can be used to release and capture CO_2, respectively. See Section 4.1.5: Linkages to the mCDR Pathway for additional detail.

Electro-Swing Liquid Solvent

Similar to electro-swing solid adsorbents, redox-active organic compounds can capture CO_2 in the liquid phase when negatively charged (43–45). These processes may operate similarly to pH-swing solvents, except that the organic component is contacted with an electrode to control the state of charge and CO_2 binding.

Membrane

CO_2-selective membranes can be used to concentrate CO_2 from the atmosphere (46). However, many polymer-based membranes suffer from CO_2-induced plasticization, resulting in loss of CO_2 selectivity over time and with membrane aging. Typically, a single membrane is insufficient for direct production of high-concentration CO_2 from the atmosphere, and a multistage vacuum or compressed membrane system must be used.

4.1.2 Key Cost Drivers and Opportunities for Cost Reduction

DACS is typically the most expensive out of all CDR options due to the fact that it does not leverage processes that occur in nature to capture CO_2 and requires energy input to create a high-purity stream of CO_2. Estimates of the likely future cost of different DACS approaches vary widely in the literature, from approximately \$100/tCO_2 to more than \$700/tCO_2, and even the cost of present commercial systems is somewhat uncertain, as only a limited number of facilities have been built, typically at pilot to demonstration scale (47). Existing cost estimates typically rely on techno-economic modeling, estimating the cost of constructing a facility at commercial scale, either with present-day technology or assuming years or decades of technological progress.

Such estimates highlight large differences in the cost structure of different DACS technologies. Figure 4 shows the cost breakdown, in percentage terms, for four major DACS technologies, assuming a 1-Mt/yr facility built with current technology, for which an adequate breakdown of the cost could be found. These costs represent illustrative point-estimate case studies for each technology and do not reflect the full range of uncertainty and variability. For a comparison of estimates of the overall levelized cost of DACS for these technologies, see Table 2.

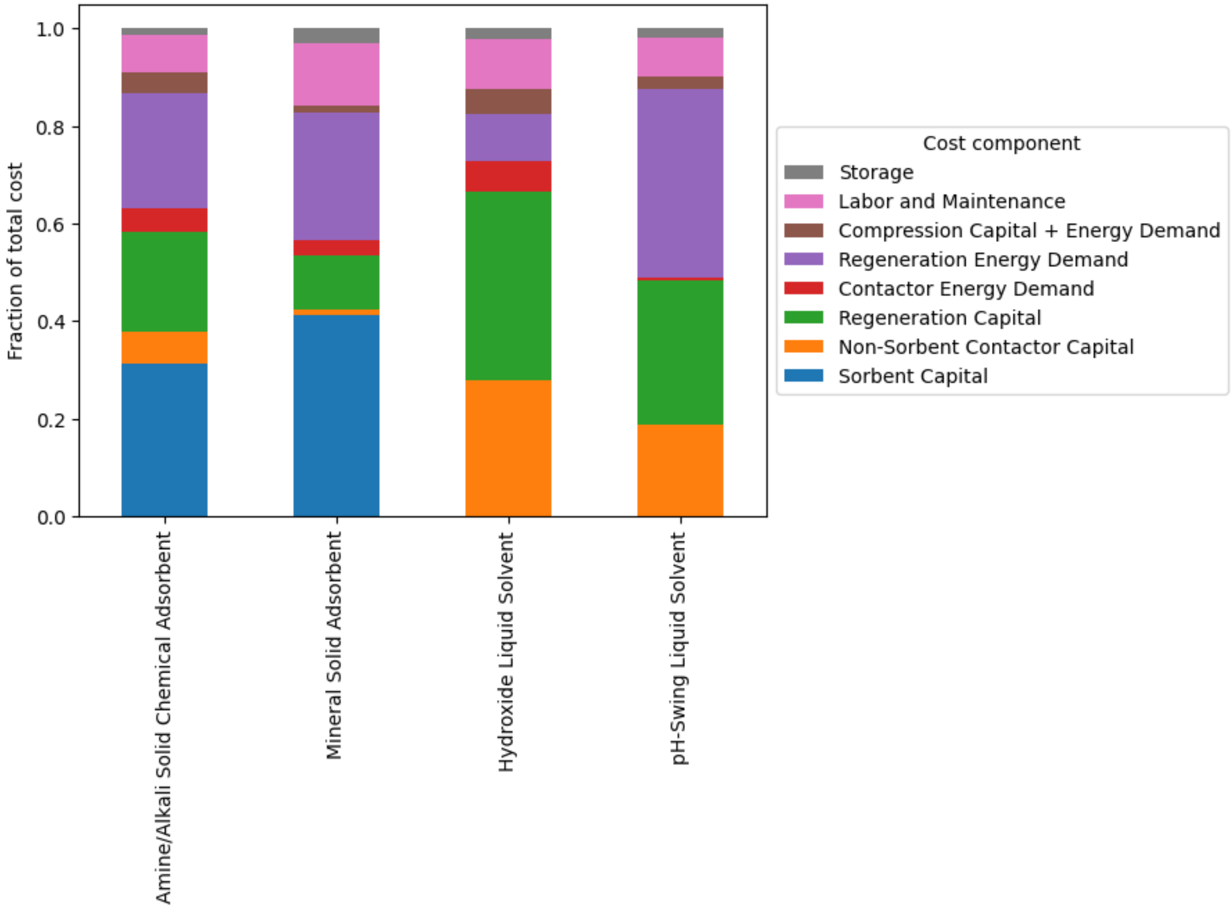


Figure 4. Illustrative breakdown of levelized cost of DACS for selected example pathways.

Based on (18,20,48)

For amine-/alkali-based solid chemical adsorbent systems, as well as mineral solid adsorbent systems, sorbent capital costs are the largest single factor, contributing 30%–40% of the total cost. For these systems, reductions in levelized sorbent costs, which could include extending sorbent lifetimes, could yield some of the largest reductions in the levelized cost of DACS.

Regeneration energy costs for thermal or electrical energy required to ensure CO_2 is released from the sorbent or solvent, which can then be used to capture more CO_2, is a major cost contributor for most technologies, approximately 10%–40% of the total cost. Six of 16 surveyed experts listed regeneration energy demand as the most sensitive factor, the most of any cost driver, and 11 of 16 listed this in the top three. Increases in process efficiency are the main system innovations capable of reducing energy costs.

Regeneration capital cost is another important cost driver for several pathways, constituting 10%–40% of total levelized cost for amine/alkali solid chemical adsorbent and mineral solid adsorbent systems, as well as hydroxide and pH-swing liquid solvent systems. One surveyed expert listed regeneration capital cost as the most important cost driver for DACS, with 7 of 16 placing it in the top three. R&D efforts to reduce the capital cost of regeneration systems, such as inexpensive electrified calcination systems, could help achieve cost reductions here.

Non-sorbent capital costs related to the air contactor are significant for hydroxide and pH-swing liquid solvent systems, at 30% and 20% of the levelized cost, respectively. These costs are present but smaller for amine/alkali and mineral solid sorbent systems, at 10% and 1%, respectively. For other systems, air contactor costs are typically integrated with sorbent capital costs. Three experts listed air contactor capital cost as the most important cost driver for DACS, with 8 of 16 placing it in the top three. The survey did not differentiate between air contactor capital cost components, meaning that these rankings include adsorbent costs for some solid adsorbent systems.

Labor and maintenance can constitute as much as 13% of total cost for mineral solid adsorbent systems. Costs related to compression and storage/sequestration, assumed to be \$10/tCO_2, are typically relatively small, at less than 5% and 3% of the total levelized cost, respectively. Estimates for the cost of storage generally range from \$1 to \$20/tCO_2 in the literature, depending on the local geology (49,50). Note that for DACS processes that burn natural gas and capture the emissions, this additional CO_2 must be included in the compression and storage costs. These cost factors are likely lower priorities for RD&D investment to reduce the cost of DACS. No surveyed experts listed these factors as major cost drivers.

4.1.3 Key Technical Challenges and Innovation Needs

In this section, we highlight specific technical challenges and opportunities for innovation that would lead to cost reductions for one or multiple DAC technologies. This excludes cost reduction that occurs through learning by doing and economies of scale.

Increasing Sorbent Lifetime and Efficiency of Use

The sorbent lifetime refers to the time it takes for the sorbent uptake to degrade before it must be replaced due to loss in performance. The lifetime will be dependent on the rate and chemical or physical mechanisms of degradation and the level of degradation acceptable; these factors are both dependent on the specific sorbent material and operation of the DAC process. This factor directly impacts the costs associated with recurring sorbent purchases, maintenance, and operational downtime spent for sorbent replacement. Amines in particular can suffer from oxidative degradation, reducing their useful lifetime.

The approach to DAC operations can also impact the sorbent lifetime. In particular, a longer cycle time, which denotes the time required to undergo a complete capture and regeneration cycle, means that the sorbent undergoes fewer cycles per year, leading to an increased mass of sorbent to achieve the same annual amount of CO_2 captured. However, it can also lead to improved sorbent durability depending on the mechanisms of degradation (e.g., if degradation occurs primarily under regeneration conditions). Hence, optimizing material and operating parameters such as working capacity and kinetics, sorbent degradation rate, cycle time, and exposure to different process temperatures and gases presents a fertile space for improvement with the development of new solid sorbents for DAC, as well as considering the costs associated with currently available sorbents (51). Contemporary research initiatives have outlined a range for sorbent lifetimes, from a minimum estimate of 0.25 years to a maximum projection of 5 years (6). Fundamental R&D into the mechanisms of sorbent chemical or physical degradation and applied R&D in the development of new durable sorbents or process operational strategies to improve the sorbent lifetime, as well as measurement of the kinetics of degradation and methods to project realistic lifetimes from accelerated degradation experiments, are all needed.

In addition to sorbent lifetime, improving sorbent efficacy can lead to cost reduction. This might be done by improving the CO_2 capacity of the sorbent, improving the kinetics of CO_2 sorption, or intelligent optimization of cycle time. A previous analysis (52) highlighted the impact of adsorbent capacity: doubling adsorbent capacity is tantamount to halving materials manufacturing costs or doubling material lifetime, and also brings additional benefits by lowering both capital expenditures (CAPEX) and operating expenditures (OPEX) of the DAC system. Similarly, increasing adsorption and regeneration kinetics and reducing the cycle time can lead to better utilization of the sorbent, effectively reducing the cost attributable to this component. Innovation in new sorbents, surface treatments, and advanced contactor geometries may result in cost reductions.

Increasing Regeneration Energy Efficiency

Many DAC technologies form strong chemical bonds between CO_2 and the sorbent, thus requiring large energy input to reverse formation of those bonds and release CO_2 in a high-purity gas stream. Many processes use heat input for this energy, raising the temperature of the sorbent; this may result in excess energy loss if that heat cannot be efficiently recovered. The regeneration energy requirement of new sorbents may be better quantified by encouraging measurement and reporting of material parameters like the heat capacity.

Methods to cost- and space-effectively recover heat from hot sorbents may help improve the energy efficiency, as well as methods of directly transferring heat to the sorbent (e.g., via microwave, magnetic induction, or ultrasound techniques), avoiding use of thermal energy completely (e.g., via electro-swing processes), and/or directing energy specifically to the CO_2–sorbent bond (e.g., via some photochemical approaches).

Optimizing Air Contactor Design

High gas-solid interface (surface area) between the sorbent and air and low-pressure drop are essential for effective CO_2 capture and reducing pumping/blowing power in the DAC process, respectively. A significant portion of the DAC cost stems from the cost of the adsorbent, making efficient contacting design and sorbent utilization through low-cost materials while maintaining performance critical. A previous study (53) demonstrated that a novel monolithic DAC contactor can achieve the same CO_2 capture with approximately 35% less adsorbent compared to traditional straight channel contactors. Techno-economic analysis indicates that the new contactor has the potential to reduce overall costs by about 30% for some DAC processes.

Reducing Regeneration CAPEX

Regeneration strategies relying on high temperature or pH swings have high capital costs associated with the equipment. In the case of high temperature, this is due to the novelty of electrically powered kilns that can reach the temperature required and effectively separate the sorbent from the stream of CO_2 without diluting it. These kinds of kilns are currently under development; innovation in their design and operation may drive cost reduction and have impacts on other high-temperature processes (e.g., cement manufacturing). The bipolar membrane electrodialysis unit for pH-swing liquid solvent DAC similarly could benefit from innovation to reduce the cost and improve the energy efficiency of ion-exchange membranes and other hardware used to generate the acid and base.

Major Data/Knowledge Gaps and Implications

Emerging challenges are closely tied to the impact of local climate and weather on DAC technologies, as their operation may span regions with diverse temperature and humidity conditions. In hydroxide liquid solvent DAC systems, the overall energy demand decreases from 11 to 8 GJ/tCO_2 as the CO_2 capture rate increases due to faster absorption kinetics in hot and humid climates (35). Conversely, amine solid sorbent DAC systems exhibit significantly lower capture costs in cold and humid conditions due to lower energy consumption and higher CO_2 capacity (54). Additional R&D into how different DAC systems respond to the impact of ambient temperature and humidity and methods of operating DAC processes to maximize the productivity of sorbents while minimizing energy consumption, in light of this climate variability, is necessary to reduce costs.

Additionally, the true lifetimes of sorbents under real-world operational conditions are not known, leading to significant uncertainty in this cost component. Accelerated aging studies begin to get at the relative stability of adsorbents, but only if materials are tested under process-relevant conditions. For example, the majority of accelerated aging studies for amine-based solid adsorbents, which suffer from oxidative degradation, have been performed with CO_2-free, dry air. However, depending on the specific material formulation, both CO_2 and water can have a moderate to significant accelerating effect on the rate of degradation (55–57). Advanced methods for projecting the performance under accelerated aging conditions to realistic DAC cycle conditions are needed to forecast material lifetime and the change in performance over the lifetime (58).

External Factors Impacting Cost

Lastly, it is important to recognize that numerous external factors, independent of the technological process itself, affect the levelized cost of DACS. Figure 5 highlights key regulatory and financial, environmental impact, co-benefits, and societal impact factors likely to affect the cost and feasibility of DACS projects.

Regulatory or market incentives, such as the 45Q tax credit or emissions trading systems, can accelerate deployment of DACS technologies. Increased deployment and a firm long-term policy and regulatory structure can assist in winning investor confidence and reducing financing costs, a major component of the levelized cost of DACS. Regulatory intervention could also increase cost or decrease feasibility of DACS projects, especially in the form of permitting requirements, the stringency of which often reflects social license and public acceptance. Finally, MRV, required either by policy or market-based mechanisms, will necessarily increase system costs in exchange for all-important investor/buyer confidence.

Regulatory & Financial Considerations

- ✓ 45Q tax credit, emissions trading systems could accelerate deployment
- ✓ Emissions trading systems can support DAC deployments and operation
- ✓ Greater maturity, scale can reduce financing cost
- ✗ DACS may not gain local social license to operate due to public concern
- ✗ Extra cost for stringent MRV regulations

Co-Benefits

- ✓ DACS companies can also remove CO_2 from the atmosphere by using captured CO_2 to produce long-lasting products like concrete or plastics

Environmental Impact

- ○ Input renewable energy costs vary by location
- ✗ Indirect emissions from land, water, chemicals, materials usage during installation and operation
- ✗ Net emissions benefits depend strongly on carbon intensity of input energy
- ✗ DAC energy demand can strain local energy system
- ✗ Removal performance depends on climate conditions (hourly or daily)
- ✗ Potential emissions of nitrogen oxides (NO_x) from gas-fired systems

Societal Impact

- ✗ Noise pollution from active DAC could impact siting options
- ✓ DAC is expected to create jobs both on-site to operate the plant and elsewhere associated with manufacturing components and infrastructure
- ✗ Public acceptance considerations could differ from technologies aim to capture carbon emissions from industrial flue gases

Figure 5. External factors impacting cost for DACS.

(✓) indicates expected positive impacts, while (✗) indicates expected negative impacts. (○) indicates that the impacts could be positive, negative, or neutral.

Environmental factors play an important role in the cost of DACS facilities. For facilities relying on local wind and solar energy generation, local climate and weather will affect energy availability and cost, and will also directly impact removal performance (35). For facilities purchasing electricity or natural gas from the local grid, carbon intensity has a major impact on DACS economics. In addition, large energy demands could strain the local system and place indirect costs on other customers. Natural-gas-fired DACS facilities are also possible sources of health-damaging emissions of nitrogen oxides (NO_x), whose impacts must be considered in overall impact analysis (59).

Carbon utilization is a major potential co-benefit for DACS operators. Utilization mechanisms that retain long-term sequestration include transforming captured CO_2 into concrete or plastics or injecting it into geologic reservoirs to enhance oil recovery.

Successful deployment of DACS facilities will depend on public acceptance from a variety of local stakeholders. Potential concerns include noise pollution, safety concerns, and environmental impact. It is important that proposed projects are subject to extensive, rigorous review to guarantee safety. However, such a review is not a substitute for early engagement with local stakeholders to ensure support early in the siting process.

4.1.4 Qualitative Assessment of Impact of Innovation on Cost Reduction

We evaluated the cost reduction potential for the technology categories (columns) defined in the previous section across 11 different types of DAC technology classes (rows) defined at the beginning of this section. The coloring in Table 2 is reflective of the relative cost reduction potential for a given technology category, defined in the footnotes. Because this assessment is on a relative basis, the magnitude of cost reduction for each technology class will vary based on the current estimated levelized cost of DAC—for example, “medium” cost reduction potential for one DAC technology might mean $200/tonne, whereas it may mean $50/tonne for another. To address this, we have also indicated, where possible, various reported costs for technology deployed today at a reasonable scale (i.e., first-of-a-kind facilities) and the scale of that deployment to allow the reader to make comparisons across technology classes.

Table 2. Qualitative Assessment of the Potential Cost Impact Technological Innovation May Have for Various DAC Technologies

DAC Technology Class	Sorbent CAPEX and Lifetime	Non-Sorbent Contactor CAPEX	Regeneration CAPEX	Contactor Energy Demand	Regeneration Energy Demand	Capture Capacity/ Kinetics	Today’s Cost at 1 Mt/yr [2023 $ /tCO_2-(net)]
Amine/alkali solid chemical adsorbent	High	Low	Low	Low	High	Low	\$300–\$700 (20,60,61)
Metal-organic framework/ zeolite solid physical adsorbent	Medium	Medium	Medium	Low	Medium	Low	\$650 (26)
Mineral solid adsorbent	Low	Medium	Medium	Low	Medium	Medium	\$550 (20)
Moisture-swing solid adsorbent	Low	High	Low	Low	Low	Medium	Insufficient data available
Electro-swing solid adsorbent	Very High	Medium	N/A	Low	Medium	Low	\$700 (48)
Hydroxide liquid solvent	Low	Medium	Medium	Low	Medium	Low	\$400–\$700 (20,34,48,62)

DAC Technology Class	Sorbent CAPEX and Lifetime	Non-Sorbent Contactor CAPEX	Regeneration CAPEX	Contactor Energy Demand	Regeneration Energy Demand	Capture Capacity/ Kinetics	Today's Cost at 1 Mt/yr [2023 \$ /tCO_2-(net)]
Amino acid salt liquid solvent	Medium	High	Medium	Low	Medium	Medium	Insufficient data available
Carbonate liquid solvent	Low	High	Low	Low	Medium	Medium	Insufficient data available
pH-swing liquid solvent	Low	Medium	High	Low	High	Low	\$650 (39,48)
Electro-swing liquid solvent	High	Medium	Medium	Low	High	Medium	Insufficient data available
Membrane	Medium	Low	Medium	Low	Low	Low	Insufficient data available

Low: Potential for technology innovation in this category to reduce the cost of DAC by <10%.
Medium: Potential for technology innovation in this category to reduce cost of DAC by 10%–25%.
High: Potential for technology innovation in this category to reduce cost of DAC by 25%–50%.
Very High: Potential for technology innovation in this category to reduce cost of DAC by >50%.
N/A: Category not appliable to this DAC pathway.

Generally, three categories stand out in terms of the potential for cost reduction across technologies: reducing the amount of energy required for sorbent regeneration, reducing sorbent capital cost and/or improving sorbent lifetime, and reducing non-sorbent capital cost associated with the contactor. The importance of these categories was also corroborated by the SME survey as areas of high potential for technological innovation to result in cost reduction. Of course, the relative importance of each of these categories will depend on the specific technology class and will likely depend even on the specific technology within the given class. For example, it is well accepted that the lifetime of the adsorbent is a critical parameter for impacting the cost of amine-based adsorbent DAC; however, this may be less critical for alkali-based adsorbents that will not undergo the same kinds of degradation mechanisms. As a result, R&D into alkali adsorbent lifetime may be less impactful, despite the two types of technologies being combined into the same technology class.

The other dimension to consider for prioritizing R&D funding is the best-case cost estimate for a technology class, assuming all cost reductions could be achieved. Our heat map suggests that some technologies may be able to reach a lower cost than others based on the achievable costs today, though it is important to note that these assessments are general and that specific context (e.g., location/climate, energy supply, material supply chains, community agreements) may favor some technologies over others. These factors are not captured in the simplified assessment presented here.

While all R&D in DAC has the potential for unforeseen breakthroughs in technology that reduce cost, based on our qualitative assessment and the responses from the SME survey, we recommend the following prioritization for applied R&D funding:

1. Methods to reduce the energy required for regeneration for solid chemical adsorbents, mineral solid adsorbents, and hydroxide liquid solvents. The SME survey indicated that these technology classes hold the greatest potential for near-term and long-term scalability and that reducing the energy required, including developing novel methods of regeneration, could help drive down the cost of these technologies. The expert survey also indicated that the energy demand of DAC would place limits on the upper bound of CDR achievable via DACS, underscoring the importance of technology innovation in this area.
2. Long-lived, high-capacity, inexpensive chemical adsorbents. This is particularly underscored for amine-based solid adsorbents, not only for reducing the cost of DAC, but also for minimizing or eliminating environmental disbenefits arising from sorbent-related emissions. Other DAC technology classes, such as electro-swing solid adsorbent and liquid solvent, will also benefit from reductions in sorbent cost and improvement in sorbent lifetime, due to their dependence on redox-active organic molecules that can degrade during operation.
3. Technology-dependent specialized capital equipment on both the adsorption and regeneration side. The SME survey highlighted the need for innovation in efficient, mass-manufacturable contactor designs to maximize CO_2 capture rate with minimal pressure drop and novel equipment for regeneration, including development of electric calciners (e.g., for mineral solid adsorbents) and other equipment that can provide driving force (thermal or nonthermal) for regeneration without involving combustion (e.g., microwave or electrochemical methods).

As described in Section 2, we categorized our innovation opportunities into “incremental” and “disruptive.” The prioritized R&D list above is focused on incremental innovation, yet we recognize that there are opportunities for disruptive innovation within the DACS pathway. These disruptive innovation opportunities are described in Table 3, alongside the incremental innovation opportunities.

A detailed case study of potential cost reductions for a DAC technology paired with mineralization for CO_2 storage is included in Section 5 as an example of how to move beyond the qualitative assessment presented in this “heat map” and develop quantitative cost impacts of technology innovation. Many of the technology innovation categories highlighted here are included in this case study.

Table 3. Summary of Innovation Opportunities for DACS Pathways

Innovation Type	
Incremental (“Line of Sight”)	Disruptive
Reducing energy for regeneration will not only enable significant reduction in the cost of DACS, but also allow it to be more rapidly and widely deployed. **Improving sorbent lifetime** will eliminate costs associated with material replacement and also minimize or eliminate environmental disbenefits arising from emissions. **Reducing sorbent capital cost**, along with lifetime improvement, can help reduce the cost of DAC. This may occur through sorbent synthesis process innovations, expansion of supply chains, and development of alternate pathways for chemicals that are projected to be in high demand. **Reducing non-sorbent capital cost** may help for some processes that require specialized or novel capital equipment. Economies of mass manufacturing may apply for components like contactors. **Improving sorbent capacity and kinetics** is typically the focus of low-TRL R&D and can also result in cost reduction, though improvements in sorbent capacity and kinetics are unlikely to result in significant cost reduction on their own.	**Coupling DACS with valuable noble gas harvesting from the atmosphere** can provide a source of revenue for DACS and subsidize or even pay for the process of carbon removal. In particular, xenon and krypton may be promising targets despite their ultralow air concentration (86 ppb and 1.1 ppm, respectively) due to their high price and uses in the electronics, semiconductor, and medical industries. Detailed market analysis is required to ensure that increasing supply of these gases will be supported by demand from these and other sectors. A disruptive DACS process would concentrate these noble gases sufficiently to the point where their separation from CO_2 is cost-effective and generates revenue. **Coupling DACS with renewable energy storage technologies** may enable reduction in the DACS system energy burden through clever integration. For example, compressed-air energy storage systems might allow DACS to leverage a higher partial pressure of CO_2. Thermal energy storage and concentrated solar power, coupled to a thermal DACS system, can avoid the heat-to-electricity energy efficiency loss. **Coupling DACS with capture or destruction of short-lived climate forcers** can simultaneously achieve reduction in multiple greenhouse gases, leveraging air movement already occurring for DACS. Destruction of greenhouse gases such as CH_4, N_2O, and hydrofluorocarbons during the DACS process can provide additional environmental and community benefits.

4.1.5 Linkages to the mCDR Pathway

Approaches that use the ocean as an air contactor, sometimes termed “direct ocean capture,” could be considered a form of DAC (e.g., pH-swing liquid solvent). These approaches perform CDR by manipulating the pH of seawater, creating acidity and alkalinity using electrochemical, photochemical, or other approaches. The alkalinity can be used, along with the alkaline earth metals naturally present in seawater, to precipitate carbonates using the dissolved CO_2 (e.g., $CaCO_3$ and $MgCO_3 \cdot 3H_2O$), similar to OAE (Section 4.4). The seawater can then remove more CO_2 from the atmosphere (42,63). Alternatively, the acidity can be combined with fresh seawater to evolve dissolved CO_2 as a high-concentration gas stream, and the acidic CO_2-depleted seawater can be neutralized with the alkalinity before returning it to the ocean. Innovations related to reducing the energy required for regeneration are highly applicable to DOC pathways.

4.2 Mineralization

4.2.1 Pathway Options and State of Technologies

Multiple pathways for mineralization-based CDR exist at various stages of commercialization and deployment. Broadly, mineralization describes methods to accelerate reaction of alkaline minerals with CO_2 to produce thermodynamically stable carbonates. Our focus in this report is on three main mineralization technology pathways demonstrating high potential for mineralization-based CDR: in situ mineralization, ex situ mineralization, and enhanced rock weathering (ERW). The following section discusses the state of the science for each technology pathway, status and challenges to commercialization, and similarities and differences across technologies.

Table 4. Summary of Mineralization Pathway Options and Commercialization Status

Mineralization Pathway	General Description	Max Deployed Scale (tCO_2/yr)	Remarks/Notes	References
In situ	Aqueous dissolved CO_2 (CO_2(aq)) injection	~36,000 (commercial)	Carbfix-Climeworks Mammoth project is the largest operating commercial mineralization-based CDR project.	(64–69)
	Supercritical CO_2 ($scCO_2$) injection	~1,000 tCO_2 (pilot)	Wallula Basalt Pilot Project injected 1,000 tCO_2 in a single pilot injection.	(70–73)
Ex situ	Ambient conditions with extant minerals	~1,000 (demo) ~40,000 (mine wastes)	Currently implemented technologies are mainly mineralization of legacy mine tailings and industrial wastes.	(74)
	Ambient conditions with mineral modification	~1,000 (commercial) ~large scale (legacy cement carbonation)	Many startups looking to leverage industrial wastes or use thermochemical methods to increase rock reactivity. Carbonation of legacy cement provides large-scale CDR. Carbon capture and storage applied to cement making would make the built environment carbon negative.	(75,76)
	Reactors using non-ambient conditions	~1,600 (commercial)	Most systems focus on mineralization of mine tailings under non-ambient conditions to accelerate mineralization.	(77,78)
ERW	Mineralization in soils	~1,200 (commercial)	Most systems are connected to agricultural activities, but there are also systems being applied to remediation of acid mine drainage.	(79,80)

In Situ Mineralization

In situ mineralization describes technologies that leverage the geologic conditions (e.g., temperature, pressure, fluid and rock composition) of the subsurface to accelerate mineralization and permanent storage of injected CO_2. This technology pathway includes two mature storage mechanisms: CO_2(aq) injection and $scCO_2$ injection. Both pathways provide a solution for mineralization-based CDR when the CO_2 is sourced via DAC or BiCRS. The aqueous dissolved storage mechanism involves dissolution of CO_2 into water or brine prior to, or during, injection and subsequent reaction with formation minerals to mineralize carbonates in the subsurface. The $scCO_2$ storage mechanism involves injection of pure CO_2 into reactive formations, where the CO_2-rich fluid becomes water-bearing and simultaneously dissolves into the formation water to generate $CO_2(aq)$, leading to mineralization. Both storage mechanisms rely on similar trapping mechanisms (i.e., structural, residual, solubility, and mineral trapping), but to varying degrees, with mineral trapping occurring on timescales of years to tens of years (Figure 6).

Both mechanisms have been pilot tested and field validated through extensive MRV to confirm mineralization and permanent storage of injected CO_2. To date, one commercially operated project has been injecting 4,000 tCO_2/yr into basalts in Iceland (Climeworks-Carbfix Orca Project) utilizing the aqueous dissolved injection method, while only one scientific pilot project has conducted an injection of 1,000 metric tonnes of $scCO_2$ into layered basalts in the Pacific Northwest (Wallula Basalt Pilot Project). A scaled-up 36,000-tCO_2/yr project injecting $CO_2(aq)$ was recently launched in Iceland (Climeworks-Carbfix Mammoth Project).

Advantages of the $CO_2(aq)$ storage mechanism include immediate solubility trapping (i.e., the injected fluid is less mobile—and denser—than a buoyant single-phase $scCO_2$ fluid), less reliance on a caprock to structurally trap the injected fluid, potentially less well cementing at closure due to lack of buoyancy, and enhanced mineralization rates (65). Advantages of the $scCO_2$ method include substantially lower water requirements, a smaller area of review (plume extent), and lower initial investment because of the ability to inject more CO_2 per well. Across both storage mechanisms, mineralization offers short-term storage security that could prevent the need for long-term MRV. For example, the U.S. Environmental Protection Agency's Underground Injection Control Class VI permit program mandates a standard post-injection site care time frame of 50 years, but mineralization storage allows operators to propose a shorter time frame based on indications of storage permanence provided by mineralization. Technical limitations for both storage mechanisms include uncertainties regarding reaction rates, risk of reservoir degradation due to reaction-driven permeability feedback (i.e., cracking/clogging), and the lack of simulation tools capable of accurately modeling CO_2-rich fluids in reactive reservoirs.

Globally, on-land basalt, peridotite, and submarine basalts have an estimated storage capacity of 62,000–950,000 Gt-CO_2 (6). Despite storage capacities significantly exceeding cumulative anthropogenic CO_2 emissions and requirements to meet our climate goals, significant challenges to commercialization and scalability remain for in situ mineralization technologies. Scalability for the $CO_2(aq)$ mechanism is primarily limited by the significant fluid volumes necessary to fully dissolve the CO_2 prior to or during injection—roughly 25 tonnes of water per tonne of CO_2 (81). Significantly more CO_2 can be injected per well when using the pure CO_2 mechanism or a combination of both. Regardless of storage mechanism, reservoir injectivity, reservoir pressure dynamics, potential contamination to potable water, resource requirements such as water and clean energy availability, simulation of fluid-rock interaction for different injection compositions, and delineation of the area of review may limit the scalability of these in situ mineralization CDR technologies.

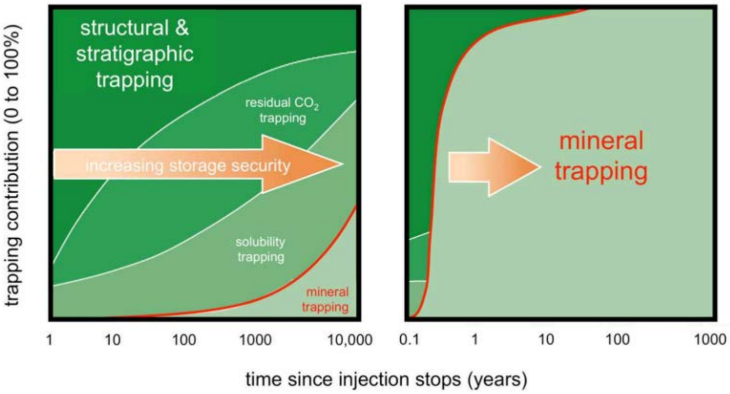


Figure 6. Evolution of CO_2 trapping mechanisms relevant to in situ mineral storage.

Relative to dominant trapping mechanisms in traditional sedimentary reservoir CO_2 storage (left), injection of CO_2 into reactive reservoirs (e.g., mafic or ultramafic) shifts the timing (i.e., beginning in years to tens of years) and contribution of the primary trapping mechanism toward mineral trapping (65,66).Image reproduced from (65)

Ex Situ Mineralization

In this report, ex situ mineralization includes all aboveground, closed system activities that generate a stable, solid carbonate. Ex situ methods have the advantage of thermodynamic stability and direct verification of CDR and storage. These methods are often limited by energy requirements needed to accelerate processes normally occurring on geologic timescales to rates commensurate with industrial activities (i.e., hours to months). Ex situ mineralization can be broadly grouped into those methods that apply purely physical alterations to the rock or air (e.g., grinding, control of gas-solid contact geometry), those that alter the minerals through thermal or chemical pretreatments, and those that alter the reaction conditions (e.g., temperature, pressure, CO_2 concentration). Processes that focus on physical alteration typically have the lowest energy requirements but often require less common mineral feedstocks and larger process footprints to overcome the lack of rate accelerants. Processes focusing on alteration of the minerals or reaction conditions come with increased energy consumption but hold promise for faster material throughputs and smaller-scale systems.

CO_2 mineralization occurs at the ~1-Gt-CO_2/yr scale via carbonation of cement in the built environment (75). For legacy cement—created prior to the Paris Agreement coming into force—the carbonation can be considered removal and storage of legacy CO_2. However, because the CO_2-reactive minerals in cement are generated from calcination of $CaCO_3$, cement produced after the Paris Agreement can only provide CDR through carbonation if cement kilns are outfitted with carbon capture and storage. Measurement and verification of the decadeslong carbonation process would bring about non-negligible, but solvable, logistical challenges and costs. Legacy slag generated from iron and steelmaking could provide approximately 8 Gt of CDR in total via mineralization, but newly generated slag would need carbon capture and storage applied to the flux, iron, and steelmaking processes for its potential ~270 Mt-CO_2/yr of mineralization to be applicable as CDR instead of emissions reduction (82).

Some mining activities have unintentionally been mineralizing CO_2 for decades, typically at the scale of ~1–40 kt-CO_2/yr (83–88). Note that not all mining operations have mineralization potential, as only certain minerals are reactive with CO_2 at relevant timescales. Even so, there may be ~3.7-Gt-CO_2/yr mineralization potential in the waste rock and tailings from existing mining activities (89). Note that this is not equivalent to a CDR potential, as the upstream commodity mining activities have substantial CO_2 footprints. Mineralization must first offset any of these remaining emissions before CDR comes into effect. Including the CO_2 mineralization potential as a resource when selecting deposits for exploitation could make economically viable CO_2 mineralization more commonplace.

Purposeful CO_2 mineralization for CDR exists primarily at the lab scale, with a few field-scale demonstrations and small-scale commercial operations (e.g., (74,76,90)). Once again, the calcination-hydration-carbonation cycle from the cement industry is being leveraged. Some companies are using this cycle as an alternative form of DAC by tying the release of CO_2 to durable storage. Other approaches use unreacted cement phases in demolition waste and slightly elevated CO_2 concentrations to achieve sufficient reaction rates. The use of much lower CO_2 concentrations than provided through DAC (e.g., ~1% vs. ~95%) provides substantial energy and cost savings. Many lab-scale processes exist that aim to alter the temperature, pressure, and CO_2 concentration to generate rapid reactions at minimal energy consumption. Though the thermodynamics of CO_2 mineralization are favorable (i.e., spontaneous and exothermic), the bottlenecks are often not the reaction kinetics, but rather have to do with mass transport such as dissolution, water-mediated ion diffusion through solids, and the like (91). More extreme conditions require more extreme materials of construction, robust or complicated reactor design, and more complex balance of plant, which can offset much of the cost savings obtained from the smaller plant footprint.

An emerging effort is the search for mineral deposits that are well suited to provide CO_2 mineralization (i.e., rather than trying to tack CO_2 mineralization on to industries that are optimized for other purposes). This “mining for CDR” methodology—where the industry begins on the highest-grade ore, and learning by doing allows for expansion to lower-grade ores—is more attuned to how the mining industry has developed new commodities in the past. Brucite, one of the most promising minerals for CO_2 mineralization, is difficult to identify in the field and challenging to distinguish from commingled minerals even in the lab. Rapid field and lab identification, paired with a focused effort to map these deposits, would drastically accelerate the development timeline for new or expanded mining operations for CDR.

Other technologies that would increase commercialization of all ex situ mineralization technologies are expanded use of high-pressure grinding rolls to create finely ground rocks at low energy consumption, modifications to conveyor and rail transport technologies to reduce energy expenditure and costs, further electrification of the mining value chain, and decarbonization of explosives production.

Enhanced Rock Weathering

ERW technologies apply crushed magnesium or calcium silicate rocks to soils or other land to accelerate the natural weathering of the feedstock and subsequent CDR from the atmosphere under ambient conditions (6,92–96). ERW removes carbon by transporting dissolved alkalinity to rivers and oceans where it will be safely and permanently stored, with some carbon remaining in the soil. The technological simplicity of mining or acquiring suitable alkaline feedstock (e.g., basalt), comminuting the rock into optimal grain sizes, and applying to land has made this suite of technologies relatively well developed. A variety of technologies exist in terms of preparation (i.e., comminution, biomineralizers) and distribution (e.g., mixed with fertilizers) of feedstock materials with the aim of reducing life cycle CO_2 emissions. There is significant room for optimization of processes within the ERW sector, including material/feedstock selection, transportation and distribution design, determination of optimal grain size, and identification of optimal soil and agronomic conditions to promote maximum weathering and CDR. Uncertainty remains regarding appropriate MRV techniques for ERW and transfer of theoretical or lab-validated kinetics to field-scale practice under diverse conditions. Another significant uncertainty lies in the long-term impact of ERW practices on overall soil health. There are indications that application of calcium- or magnesium-rich silicate rocks (e.g., basalt) could improve soil health or crop yields, but this still needs to be validated and accepted to de-risk the technology (92,97,98). Improved crop yields may be a double-edged sword for ERW, as it is an obvious co-benefit for the process, but it also forces the issue of modeling not just the inorganic system (e.g., dissolution and CO_2 equilibration), but also its interactions and feedback with organic carbon fluxes and stocks.

ERW technologies are relatively cheap (~\$25–\$211/metric ton CO_2), show significant scalability potential (~0.5–2 Gt-CO_2/yr), and may provide ecosystem and agricultural co-benefits (92). The ease of deployment via traditional means (i.e., road transportation and spreaders) may support scalability of ERW. However, long-distance transport may also act as a limitation by driving up energy expenditures and carbon emissions, thereby increasing the overall cost and reducing the CDR potential. Other limitations to scalability for ERW include challenges with awareness and adoption of the technology, difficulties with MRV and tracking of carbon flows, and ecosystem feedback concerns common to open system approaches. Ultimately, scale-up of ERW depends largely on the rate and extent of agricultural adoption of the practice. There are millions of acres of suitable agricultural land that could be used for ERW, but it is unclear today what fraction of suitable agricultural land could practically be used for ERW. Additionally, although there is a large available supply of alkaline rocks that could be utilized for ERW, comprehensive detailed evaluation of suitable source rock compositions and related impacts to soils have yet to be undertaken. ERW could provide a substantial increase in the overall mineralization-based CDR capacity if barriers to commercialization can be eliminated or overcome through R&D innovation.

4.2.2 Key Cost Drivers and Opportunities for Cost Reduction

Mineralization CDR includes a wide range of technology options with diverse cost profiles and key cost drivers. Across mineralization pathways, cost components vary, but can be divided into CAPEX, fixed OPEX, and variable OPEX. Where simple processes leverage existing feedstocks, ambient conditions, and industry-standard conditioning techniques (e.g., ultramafic or brucite mine tailings), costs may be some of the lowest across all CDR pathways at <\$10/tonne CO_2 (6,65). On the other hand, upper estimates for complex reactor-based ex situ mineralization systems have total cost >\$850/tonne CO_2 (6). Some mineralization pathways (e.g., in situ and ex situ) are closely linked to the cost of other CDR pathways in this report (e.g., DAC, BiCRS), where the CO_2 is concentrated separately and mineralization acts as the storage mechanism. The cost of storage via in situ mineralization is relatively well constrained through pilot- and commercial-scale data in Iceland, with costs of storage (excluding capture) estimated between \$6.30 and \$50/tonne CO_2 (6,68,99,100). The lower end of the cost range represents conditions found at the CarbFix2 site in Iceland, co-located with infrastructure from a geothermal power plant (e.g., cheap water and energy, existing data), while the higher cost value represents greenfield, or newly developed sites. The cost of these mineralization pathways using concentrated CO_2 from an external source should be considered with respect to the cost of the CO_2 capture. For more nascent technologies (e.g., air capture in peridotites), costs may be even greater than early-stage DACS at >$3,000/tonne CO_2 (6).

To date, there are both field-validated cost estimates (e.g., in situ mineralization, ERW) and techno-economic modeling-based estimates (e.g., seafloor basalt). Table 5 and Figure 7 presents the economic state of key mineralization pathways discussed in this report.

Table 5. Economics of Mineralization CDR Pathways

Pathway	General Description	Key Cost Drivers	Current Costs ($/t$CO_2$)	References
In situ	CO_2(aq) injection	CAPEX: drilling, equipment OPEX: water, energy	$14–$50	(66,99,101, 102)
	scCO_2 injection	CAPEX: drilling, equipment OPEX: energy (compression)	Onshore: $5–$20; Offshore: $200–$400	(101,102)
Ex situ	Ambient conditions with extant minerals	CAPEX: mining and comminution, rock support structure OPEX: energy, labor	$10–$300	(101,103)
	Ambient conditions with mineral modification	CAPEX: mining and comminution, pretreatment reactor OPEX: energy, chemicals	Profitable: $57–$117	(104,105)
	Reactor with non-ambient conditions	CAPEX: DAC/BiCRS, reactor, mining and comminution OPEX: energy	$52–$784	(106,107)
ERW	Mineralization on soils, beaches	CAPEX: mining, grinding/ processing/application equipment OPEX: energy for mining/crushing/grinding feedstocks, transportation, application	$25–$211	(92,101,108)

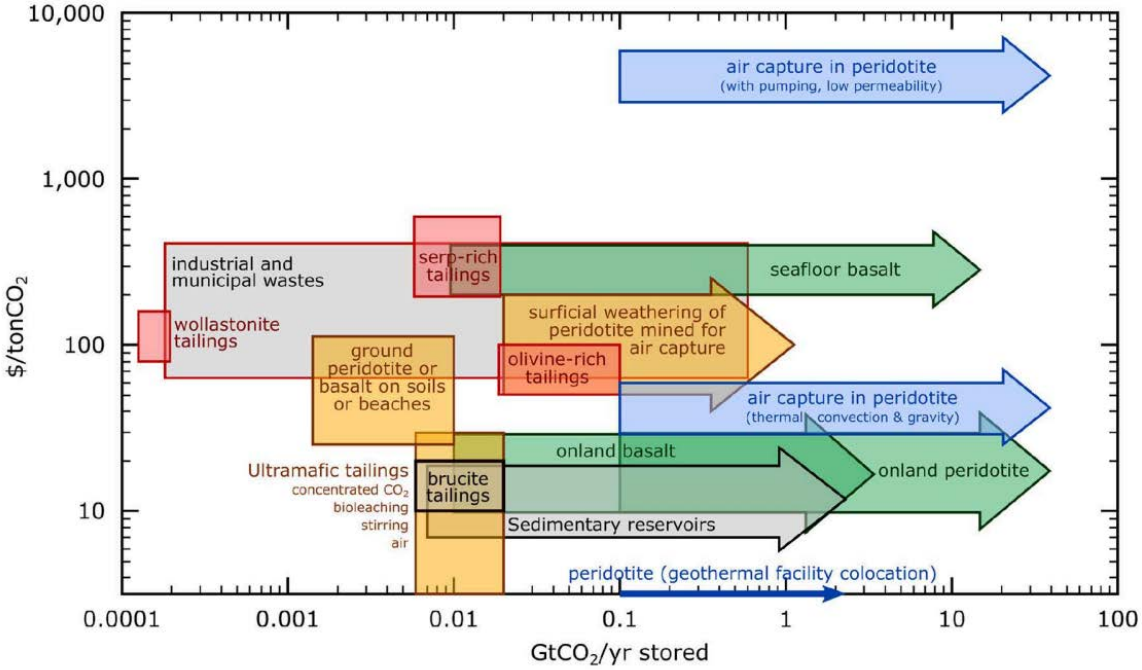


Figure 7. Summary of mineralization cost ($/t$CO_2$) versus storage potential (GtCO_2/yr) for a variety of mineralization technologies and approaches.

Red boxes illustrate costs and rates for *ex situ* CO_2 mineralization using heat and concentrated CO_2. Yellow boxes are for surficial CO_2 mineralization of mine tailings, ground peridotite added to soils or beaches, and peridotite mined and ground for the purpose of CDR from air with solid storage. Green arrows are for *in situ* carbon storage by injection of CO_2-enriched fluids into mafic and ultramafic formations (e.g., Carbfix). Blue arrows are for *in situ* carbon sequestration by circulating water saturated in air into peridotite formations, for CDR from air with solid storage. Gray arrow is for *in situ* carbon sequestration by injecting $scCO_2$ into subsurface sedimentary formations. Figure reproduced from (6) Figure 6.19, with data from references therein (Tables 6.1 and 6.2) (65).

For the in situ mineralization pathway, a vast majority of the cost (~66.7%) is associated with CAPEX required for site screening and acquisition, permitting and licensing, design, construction of injection and monitoring wells, procurement of surface equipment (e.g., pumps, compressors, well housing), and installation (99,100). The remainder of the cost is variable OPEX related to energy and water consumption, while a smaller proportion is fixed operation and maintenance and monitoring operational costs. These costs must also be considered with the cost of capture from a DAC or BiCRS source. Efforts to reduce costs for the in situ mineralization pathway have mostly focused on reducing water consumption via recycling reservoir water, or eliminating the use of freshwater through field validation of seawater-dissolved CO_2 injection (109). Sensitivity analyses have also identified electricity costs and drilling depths as influential parameters on overall cost, which can be addressed through optimized site selection (110). It is also well known that subsurface storage benefits from economies of scale, and the in situ pathway will follow this trend (99). Key unknowns that may drive cost reductions include innovations to monitoring techniques reducing overall need for capital-intensive monitoring wells, optimization of storage field designs to minimize injection well costs, and improved workforce development that may streamline operation and maintenance to reduce costs.

For ex situ mineralization pathways that modify the mineral or reaction conditions, a vast majority of the cost (~83%) is CAPEX related primarily to the industrial reactors where mineral alteration and/or mineralization reactions occur (6). Ex situ systems that utilize ambient conditions and extant minerals eliminate the need for such reactors and reduce the main cost drivers to the comminution circuit and any structures used to maintain a large gas-solid interface. OPEX costs are commonly dominated by transport, energy, and labor. Integrating mineralization activities at mine sites can reduce transport and labor costs. For reactor systems using elevated CO_2 concentrations, the cost of supplying the CO_2 must be considered (equivalent to in situ methods). For reactor systems, known cost reduction pathways focus on lowering pretreatment energy consumption, increasing circularity in processes (e.g., heat reuse) and developing new techniques (e.g., microwave treatment, microbial acceleration) (65).

Relative to the previously mentioned in situ and ex situ pathways, ERW costs stem primarily from OPEX (e.g., energy costs) related to mining, crushing, and grinding of feedstock material and material transport and application to the site (111). Capital expenses are primarily tied to the mining process, grinding equipment, and purchase of transport and application equipment, but make up a minor component of overall cost for ERW. Known pathways to cost reduction for ERW primarily involve deployment and learning by doing, because a major data gap exists for ERW techniques regarding MRV. As the market for ERW develops, cost reductions may arise through innovations that target energy efficiency and carbon reduction for rock comminution. Moreover, co-deployment with afforestation/reforestation, agroforestry, or clean energy projects with substantial land footprints (e.g., solar and wind) may drive the cost down further. Finally, acceptance of the safety of ERW and nutrient-enhancing ability of certain rock types (e.g., basalt) may reduce further when considering co-benefits of improved soil health, fertility, and ecosystem services (92).

Finally, while it is not the focus of this report, it is important to highlight external factors that may also have an impact on mineralization cost. These factors include regulatory, environmental, and societal impacts, as well as co-benefits. These external factors are summarized in Figure 8.

	Regulatory & Financial Considerations
✓	Availability of government incentives (such as 45Q tax credits and funding programs) could create a financial incentive for industries to adopt mineralization CDR
✓	Stable and predictable regulations can reduce investor risks and encourage long-term investment in mineralization
✓	Mineralization permanence may reduce financial responsibility
✗	Obtaining necessary permits for geologic storage and land application (ERW) may limit its deployment
✗	Long lead times or delays in permitting may reduce financial feasibility and mothball projects
✗	Strict MRV regulations may increase operational costs

	Co-Benefits
✓	Opportunity for additional avoided emissions by incorporating post-mineralization feedstocks into construction materials
✓	Potential for remediation of feedstocks (e.g., mine tailings, steel slag) can reduce waste and impacts of other industries
✓	Potential for remediation of pollutants (e.g., H_2S, asbestos mineralization) could reduce overall cost for mineralizing CO_2
✓	Permanence of solid storage could be valued by CDR purchasers hesitant to enter CDR market due to risk of credit payback
✗	Utilization of products may be hindered by waste regulations or uncertainties around toxicity

	Environmental Impact
✓	Co-injection or mineralization of secondary pollutants can reduce overall project environmental impacts
✓	Application of certain alkaline feedstocks to cropland could improve soil health and fertility and offset fertilizer use
✓	Noncompetitive with land use (i.e., ERW can be applied alongside other CDR like BiCRS feedstock growth)
✓	Alkalinity enhancement can combat ocean acidification
✗	Large-scale implementation of mineralization technologies may cause local surface water or groundwater contamination
✗	Significant freshwater use for some technologies may do more harm than good depending on regional water stress

	Societal Impact
✓	Opportunities for rural economic development through feedstock supply chains, storage/processing facilities, and employment
✓	Can leverage workforce from mining, agriculture, and oil and gas to alleviate concerns that workers will be left behind in the clean energy transition
✓	Mineralization permanence may promote social acceptance and license to operate
✗	Infrastructure-heavy projects (e.g., large-scale mines, reactors, pipeline/CO_2 transport) face risk of low community acceptance
✗	Potential for induced seismicity can cause public perception risk

Figure 8. External factors impacting cost for mineralization.

(✓) indicates expected positive impacts, while (✗) indicates expected negative impacts.

4.2.3 Key Technical Challenges and Innovation Needs

Key technical challenges and innovation needs for mineralization CDR technologies can be largely broken down into key components of the processes with opportunities for cost reduction. The main components of mineralization CDR with potential for innovation to drive cost reduction are coproducts, reaction catalysts, injection/deployment, upstream/conditioning, site/feedstock characterization, MRV, and transport. Within each of these cost components, there are specific technical challenges that can be addressed or overcome with innovation and lead to cost reduction. The following sections describe the challenges and innovations by cost component, and our evaluation of cost reduction potential for each category is shown in Table 6.

Coproducts

Revenue generation through use of solid carbonates, production of coproducts, or co-benefits may be important for reducing the overall cost of mineralization methods. For in situ approaches, solution mining of metals using CO_2 may be able to offset most of the cost of CO_2 capture via DAC (as detailed in Section 5). Injection into mafic/ultramafic rocks could produce mineralization and metal leaching concurrently, with production (or dual-use monitoring wells) used to produce fluids to the surface for critical mineral (e.g., nickel, cobalt, copper, chromium) extraction and processing (112,113). In addition to producing revenue-generating metals, this strategy could reduce land use and waste production from conventional mining activities and allow mining of traditionally noncompetitive resources (i.e., low-grade ore inaccessible through surface mining). We estimate that innovations to produce critical minerals through in situ mineralization have a very high potential to reduce the total cost of CDR (dependent on site-specific conditions and cost of capture via DAC/biomass) by >50%.

Specific innovations to ex situ mineralization processes are currently being deployed on the waste rock and tailings from mining operations. However, to act as CDR, these systems must first offset all of the upstream mining processes' emissions—in most cases this is not possible. Ex situ mineralization on rocks targeted for CDR (e.g., brucite) could see some coproduct generation from nickel and other serpentinite-hosted metals. Here again, the full mining and refining process requires decarbonization before CO_2 mineralization can be considered to provide CDR. Integrating critical mineral recovery within ex situ mineralization processes could provide valuable revenue alongside carbon credits and potentially turn the process into a net-revenue-generating system (112–116). We estimate these innovations have a very high potential to reduce the total cost of CDR (assuming all upstream and processing emissions are negated) by >50%.

ERW processes may provide co-benefits in the form of improved crop yields, reduced input requirements (e.g., quicklime), remediation of acid mine drainage, and the like (80). While these provide legitimate revenue sources in the form of increased agricultural productivity and lower cost of operation, they may also force the issue of modeling and measurement of the ecosystem's overall response to ERW if CDR credits are to be claimed. Additional innovations to drive down costs of ERW include development and deployment of phytomining plants that can hyperaccumulate valuable trace metals (e.g., nickel) from the applied feedstock (e.g., basalt) that, when harvested, could produce additional revenue from metal extraction (117). We estimate these innovations have a high potential to reduce the total cost of CDR by 25%–50%.

Reaction Catalysts

Expediting reactions through control of the environment (as opposed to modifying mineral feedstock) increases the rate of carbon removal in engineered reactors, geologic structures, and land application settings. The cost of said equipment is then covered by a larger gross CDR over a given time frame. The difficulty comes from the CO_2 emissions associated with producing the enhancing conditions, and equipment that can withstand such conditions, reducing the net CDR (118). Because reaction enhancement methods are highly process-specific (e.g., gas-solid vs. liquid-solid), each type of mineralization requires its own merit order assessment of reaction kinetics (91). Such assessments for each general class of CO_2 mineralization—accounting for the CO_2 emissions of the enhancing mechanisms—would provide useful general guidance to the field. Recent advancements have identified specific microbes that may accelerate the conversion of CO_2 into carbonate minerals that could be catalytic under common in situ conditions (e.g., temperatures of 20°C–150°C, pressures of 250–900 bar) (119). In general, similarities for reaction enhancement exist for ex situ and in situ methods, including cost reduction benefits from enhanced CDR capacity/rates and possible enhanced critical mineral recovery potential (119–123). Innovations that can synthesize extremophile microbes at scale capable of accelerating mineralization could provide a solution to increase mineralization rates in ex situ and in situ processes, shifting the timelines needed for complete mineralization in ex situ settings and reducing post-injection site care (and associated financial responsibility) requirements for in situ settings. We estimate that innovations focused on reaction catalysts/enhancement for in situ and ex situ mineralization have a high potential to reduce the total cost of CDR by 25%–50%.

While ERW techniques would also benefit from enhanced reaction rates, there is significant difficulty inherent to controlling the open system/environment that ERW operates in. There may be pathways to pretreat the feedstock applied to a given plot of land (124), but controlling reactivity once it is applied would be more difficult. Thus, we estimate innovations for reaction catalysts in ERW settings to have a medium potential to reduce the total cost of CDR by 10%–25%.

Injection/Deployment

Key technical challenges for injection/deployment of mineralization CDR include costs associated with injection for in situ methods (e.g., processes occurring at the CO_2 injection well) and deployment for ex situ and ERW (e.g., tailings pile design/application techniques). Mining from or injecting into deposits with rapid and large mineralization potential would provide large cost savings and a means by which the industry could leverage learnings on "easy" sites to expand into less favorable deposits.

For in situ mineralization, the two field-validated approaches to injection include $CO_2(aq)$ and $scCO_2$ injection. Innovative technologies that can maximize the per-well injection capacity (e.g., metric tons CO_2/well/year) such as water-alternating-gas or microemulsion injections may reduce high capital costs associated with drilling more wells (71,125). Moreover, innovations that can optimize well configurations and wellfield management by reducing the CO_2 and pressure plume in the subsurface could reduce the area of review and associated financial responsibility requirements under regulatory requirements and pore space purchasing/leasing costs. Introducing nanoparticles into the injection fluid may also enhance the efficiency of CO_2 trapping and the solubility of CO_2 in the aqueous phase, leading to greater injection capacity for a single well (126). Finally, pre-seeding nonreactive reservoirs with particles (i.e., dissolved cations) could expand the potential for in situ mineralization into other rock types that can serve as a mineral storage solution for CDR pathways. We estimate that innovations focused on injection techniques for in situ mineralization have a high potential to reduce the total cost of CDR by 25%–50%.

For ex situ mineralization, innovations to optimize reactor and tailings pile designs to improve reaction rates, reduce energy/feedstock usage, and simplify design to reduce CAPEX will support cost reduction for these technologies. Specific innovations may include designs that enhance gas-solid contact while minimizing pressure drops (127), or designs with a high volumetric packing density to reduce CAPEX. Additional cost reduction can be made by optimizing the relative humidity to accelerate mineralization reactions while avoiding barriers to mass transport for CO_2 (e.g., condensation clogging pore spaces). We estimate that innovations focused on deployment strategies for ex situ technologies have a high potential to reduce the total cost of CDR by 25%–50%. For ERW systems, innovations to reduce the cost of applying feedstocks to the targeted application site could reduce overall CAPEX/OPEX. For example, integration with existing fertilization or agricultural management practices could reduce cost of application, while autonomous deployment through automation could drive greater savings in the long term for dedicated ERW projects. We estimate these innovations have a medium potential to reduce the total cost of CDR by 10%–25%.

Upstream/Conditioning

Technical challenges for upstream processes such as feedstock preparation, CO_2 conditioning, and pretreatments vary across the specific mineralization technologies but generally focus on reducing upstream energy/resource requirements for feedstock processing (e.g., mining, crushing, grinding), optimizing reaction rates via thermo-physical-chemical pretreatments (e.g., enhancing mineral reactive surface area, leaching of heavy metals), and optimizing CO_2 capture for integration with injection/deployment systems to reduce energy/resource requirements. Innovation could address these challenges by developing technologies or upgraded systems that are optimized to process- or site-specific characteristics. For example, the in situ mineralization pathway could leverage R&D for integrating CO_2 absorption in water-scrubbing towers that utilize medium or low pressure to dissolve CO_2 for injection, reducing overall energy requirements for compression of CO_2 to higher pressure (128). Additional innovation may focus on using seawater to dissolve CO_2 to reduce water costs, which make up a significant portion of the OPEX for the aqueous dissolved method of CO_2 injection. Designing injection systems for direct integration with the CO_2 source (e.g., dissolving DAC-sourced CO_2 in water within the wellbore at depth rather than the surface) could drive energy savings (129). We estimate innovations focused on optimizing conditioning and systems integration for in situ mineralization technologies have a low potential to reduce the total cost of CDR by <10%.

For ex situ and ERW methods, there are multiple opportunities for cost reduction innovations related to optimizing reactivity, system efficiency, and reducing resource requirements. For example, processing feedstock materials to separate target reactive minerals from unreactive minerals can decrease downstream system size and cost proportionally. High-pressure roller grinders could provide significant cost savings through more efficient fine grinding, and if paired with an air separation system can further increase energy efficiency and provide tighter particle size distribution control. Pelletization of fine powders can give major CAPEX savings by structuring the powders instead of putting the powders on structures (without driving up pressure drop). Overall, electrification of mining will save some energy and maintenance costs, but will have a larger impact on CDR cost by significantly reducing CO_2 emissions, thereby increasing net CDR. For ex situ mineralization technologies, we estimate innovations focused on upstream processing have a high potential to reduce the total cost of CDR by 25%–50%. For ERW technologies, we estimate innovations focused on upstream processing have a medium potential to reduce the total cost of CDR by 10%–25%.

Site/Feedstock Characterization

Site characterization (for in situ methods) and feedstock characterization (for ex situ and ERW methods) can drive savings if more effective, rapid, and accurate methods of characterization are developed. For in situ methods, this may include leveraging existing subsurface characterization techniques (e.g., geophysical methods) through new approaches (130–133) that can overcome typical challenges with imaging mafic and ultramafic rocks (134,135). Innovative site and reservoir characterization techniques that reduce or eliminate the need for drilling stratigraphic wells for geologic characterization could significantly reduce the CAPEX and project development timelines associated with in situ mineralization. Moreover, techniques to streamline mineralization parameterization (e.g., dissolution rates, precipitation rates, mineral storage capacity) could reduce modeling requirements and associated costs. We estimate innovations focused on site characterization for in situ mineralization have a medium potential to reduce the total cost of CDR by 10%–25%.

For ex situ and ERW methods, techniques for rapid assays of mineralization potential of both alkaline industrial feedstocks and surficial mafic-ultramafic outcrops could reduce costs of costly and time-intensive characterization while accelerating the scale of deployment of these CDR methods (136). Moreover, accurate assessment of potential sources of contaminants (i.e., metal mobilization) could provide more safety assurance to the public and reduce risk of low public acceptance leading to projects being mothballed. For ERW, rapid assessment of optimal sites for deployment (i.e., ranking climates and soil types) could reduce costs by enhancing mineralization and CDR efficiency. For both ex situ mineralization and ERW technologies, we estimate innovations focused on site/feedstock characterization have a medium potential to reduce the total cost of CDR by 10%–25%.

MRV

Challenges for monitoring, reporting, and verifying carbon removal for mineralization technologies largely depend on the nature of the system. In situ mineralization systems may find cost savings relative to traditional geologic CO_2 storage by reducing the footprint of the area of review and reducing the timeline of monitoring and post-injection site care (137). For in situ mineralization, specific innovations include advanced remote sensing and geophysical monitoring techniques capable of tracking subsurface mineralization in real time, which could reduce field sampling OPEX and monitoring well CAPEX (e.g., 119). Other related innovations such as development of injection fluid additives that enhance geophysical signals at the surface (e.g., acoustic contrast nanofluids) could reduce cost by utilizing readily available seismic technologies (130). For in situ mineralization technologies, we estimate that innovations focused on MRV have a medium potential to reduce the total cost of CDR by 10%–25%.

For a closed system (i.e., ex situ mineralization), where CO_2 is relatively contained within a designed system, MRV will come at lower cost with greater accuracy because all material flows are directly controlled and accessible. As these methods are analogous to commodity industries, setting up standards of practice (e.g., quality assurance/quality control) will be necessary. However, because the cost of MRV is already low for these technologies, we estimate innovations focused on MRV for ex situ systems have a low potential to reduce the total cost of CDR by <10%.

ERW will encounter a similar class of MRV challenges as other open-system CDR methods. Verification of not just the storage integrity, but also the removal quantity, is challenging given the large inherent CO_2 fluxes in the natural environment. Ecosystem-scale sensor networks acting as a common infrastructure for such CDR suppliers would likely accelerate acceptance of claimed removals. Likewise, models that integrate geochemical activity with biological activity will likely be necessary to verify that large chemical additions to the ecosystem do not induce carbon releases or inhibit carbon removals elsewhere. Setting ERW measurement, reporting, and verification practices that generally provide CDR within an acceptable range of uncertainty may be a pathway to reduce the measurement and modeling challenges of ERW. However, such a system would necessarily require conservatively low estimates of CDR. Overall, the cost of MRV can be reduced significantly for ERW if the distribution of credits is viewed as “pay for practice,” as done in other agricultural sectors, instead of “pay for performance,” as is currently done for CDR. This would require innovations that provide accurate modeling capabilities and clearly defined benchmarks/baselines considering material characterization, environmental, and other site factors. For ERW, we estimate innovations focused on MRV have a high potential to reduce the total cost of CDR by 25%–50%.

Transport

Technical challenges for transport for mineralization CDR include high costs for multimodal transport (i.e., pipeline, rail, barge/ship, truck) for in situ methods and well-established but emissions-intensive transport of rock feedstocks for ex situ (if CO_2 source and storage are not co-located) and ERW. For in situ, transportation costs are challenging to reduce because of the relatively established cost curves for pipeline-, maritime-, rail-, or truck-based CO_2 transport (138,139). Energy, materials, and labor costs are dictated by transport safety measures for hazardous waste. The innovation potential for in situ methods lies in creative siting of CO_2 sources (e.g., DAC/BiCRS) co-located with short-range transportation networks and in situ CO_2 storage sites. To maximize cost reductions, sites should be developed in areas with low carbon intensity and low-cost electricity grids to maximize CDR potential and minimize cost per tonne. For example, on-site use of clean and cheap electricity from a BiCRS plant co-located with in situ storage could reduce energy costs for compression needed for pipeline transport to injection wells. Additionally, pairing DAC with geothermal energy can provide low-carbon electricity and heat, existing pipeline and injection well infrastructure, and characterization data valuable to development of an in situ CO_2 storage site. DAC + geothermal has been piloted and proven commercially in Iceland, and research indicates significant OPEX savings potential in the United States when co-locating geothermal and DAC (19). Electrification of specific transport methods (e.g., truck, rail, ship) will also reduce emissions and overall CDR cost. While it remains to be seen if conversion of other pipelines (e.g., natural gas) to carry CO_2 is technically or economically viable, potential R&D could focus on increasing intermodal transportation tied to site-specific analysis (e.g., barge transport up navigable waterways, connected to tanker trucks or rail transport to reach local storage sites). Finally, development of centralized transport and mineral storage hubs using common carrier infrastructure could develop economies of scale and drive transport costs down by splitting the cost of infrastructure (140). For in situ mineralization technologies, we estimate innovations focused on transport have a low potential to reduce the total cost of CDR by <10%.

For ex situ mineralization, some innovation potential lies in electrification of mining equipment and incorporation of new conveyor belt technologies to move feedstock from mine to reactor/tailings piles. However, these projects should be co-located with the mining site to reduce transport emissions and cost. Similar innovation potential for the in situ methods applies to transport of CO_2 to ex situ sites. Thus, we estimate innovations focused on transport for ex situ technologies have a low potential to reduce the total cost of CDR by <10%. For ERW, transport to application sites faces similar penalties for emissions and cost per metric ton as other methods when shipping rocks via rail, ship, or truck to application sites. Electrification will support cost reductions in this regard, but centralized or distributed networks of feedstock sources could reduce transport distance requirements and drive down costs. Autonomous vehicle transport could further reduce costs of transport by reducing labor costs, but it remains to be seen whether this will be a realistic future R&D or innovation opportunity. However, due to the generally lower cost of ERW, innovations focused on reducing cost of transport have a medium potential to reduce the total cost of CDR by 10%–25%.

4.2.4 Qualitative Assessment of Impact of Innovation on Cost Reduction

The impact of technological innovation on cost reduction potential was assessed across all cost categories of mineralization to define key cost categories (columns) for each mineralization pathway (rows) as defined in Section 4.2.1. The color coding in Table 6 indicates the relative cost reduction potential for each mineralization pathway, as detailed in the footnote. Note that this assessment, like other CDR pathways presented in this report, is on a relative basis; the magnitude of cost reduction will vary among different technology options. The cost basis for this assessment is provided in Section 4.2.3 and other references in this section.

Table 6. Qualitative Assessment of the Potential Cost Impact Technological Innovation May Have on Various Mineralization Pathways

Pathway	Coproducts	Reaction Catalysts	Injection/ Deployment	Upstream/ Conditioning	Site/Feedstock Characterization	MRV	Transport
In situ	Very High	High	High	Low	Medium	Medium	Low
Ex situ	Very High	High	High	High	Medium	Low	Low
ERW	High	Medium	Medium	Medium	Medium	High	Medium

Low: Potential for technology innovation in this category to reduce the cost of mineralization by <10%.
Medium: Potential for technology innovation in this category to reduce cost of mineralization by 10%–25%.
High: Potential for technology innovation in this category to reduce cost of mineralization by 25%–50%.
Very High: Potential for technology innovation in this category to reduce cost of mineralization by >50%.

Combining this qualitative assessment with the described key technical challenges and innovation needs, we have identified the following prioritized list of technology innovation opportunities for mineralization (Table 7).

Table 7. Summary of Innovation Opportunities for Mineralization Pathways

Mineralization Pathway	Innovation Type	
	Incremental ("Line of Sight")	Disruptive
In situ	**Advanced injection methods and storage field development strategies.** Innovative injection strategies (e.g., water-alternating-gas, microemulsions) (125) could optimize storage field management while maximizing the per-well storage capacity and reducing the area of review. Leveraging horizontal drilling techniques from the oil and gas industry could maximize the surface area exposed to CO_2 in the subsurface and increase mineralization rates. **Optimization of integration with CO_2 source (i.e., DAC or BiCRS).** For certain injection methods and sites, cost savings may be driven by integration and system design that considers the injection method—for example, by dissolving CO_2 at the surface in dedicated absorption towers at wellhead pressures, energy (and associated emissions penalty) costs can be reduced relative to compressing to pure CO_2. If the CO_2 source is delivered to the in situ storage provider in a pure state, downhole mixing of CO_2 with water could reduce energy requirements needed to dissolve CO_2 into water at the surface while leveraging the enhanced reactivity of $CO_2(aq)$.	**Valorization of coproducts through CO_2-enhanced critical mineral recovery.** This technological innovation can not only transform the cost profile for in situ mineralization to become a revenue generation source, but also unlock low-grade critical mineral resources that were previously sub-economical that would be transformative for U.S. critical mineral supply resiliency (112,113). **Microbial- or biologically enhanced mineralization** that enhances dissolution rates, accelerates carbonate precipitation, or improves critical mineral recovery potential (120–123). **Development of injectates that pre-seed mineralization sites** and expand in situ mineralization to traditionally nonreactive or long-term, reactive rock formations (i.e., sedimentary rocks). Injecting colloidal iron, magnesium, or calcium with CO_2 could enhance mineralization in sites previously developed for CO_2 storage and increase the security of storage for CDR. **Advanced remote sensing and aerial geophysical sensing** to track and characterize subsurface changes due to mineralization in real time. Methods may include development of additives to injection fluid that enhance geophysical signals received at surface (i.e., acoustic contrast nanofluid) or processing techniques that can detect acute geophysical property changes due to mineralization (e.g., gravity inversion techniques that can pick up changes in layer density due to mineralizing a fraction of the formation porosity with a carbonate mineral of differing density) (130,133).
Ex situ	**Optimization of reactor system and tailings pile design.** Ex situ reaction rates and extents can be improved through innovative reactor and tailings pile designs that enhance gas-solid contact without introducing large pressure drops (127). Designs with a high volumetric packing density of rock with minimal supporting structure, while	**Advanced remote sensing paired with ground-truthing to detect highly reactive rocks.** Detection of surface formations containing significant quantities (>5 wt %) of highly CO_2-reactive minerals such as brucite, $Mg(OH)_2$, would reduce the time and financial risk of new mine development. Flyover detection methods trained to find known reactive minerals could identify promising

Mineralization Pathway	Innovation Type	
	Incremental ("Line of Sight")	**Disruptive**
	allowing low-resistance airflow, could meaningfully reduce capital expenditures. Further gains can be made by optimizing the relative humidity to accelerate mineralization reactions without introducing new mass transport barriers for CO_2 (e.g., condensed water plugging pore spaces). **Advanced feedstock preparation techniques to maximize reactivity.** Utilizing detection and separation techniques (e.g., X-ray topography, hyperspectral) early in the extraction and processing stages to upgrade the feedstock with the most reactive minerals. Reducing the content of non-target minerals decreases the downstream equipment sizes and energy consumption. Utilization of high-pressure roller grinders, air classification, and other modern comminution techniques could generate the very fine particle size distributions that generate fast mineralization rates at much lower energy consumption than more traditional methods.	deposits. Such methods may use traditional techniques (e.g., hyperspectral) or more indirect methods (e.g., high background uptake of CO_2, high alkalinity in watersheds). Reduced cost and increased efficacy handheld sensors that can be deployed in the field could further filter down potential deposits. Radiocarbon analysis may also provide useful rapid characterization to differentiate between atmospheric and biogenic CO_2 once mineralized (141). **Salt and brine sources of CO_2-reactive minerals.** The calcium and magnesium content of the ocean, brines, and salt deposits can be leveraged to generate magnesium/calcium hydroxides for CO_2 mineralization. The generation of coproducts (e.g., potable water, gypsum) and co-benefits (e.g., waste treatment) could provide material revenue streams to make such processes profitable. Such coproducts would also provide important emissions reduction relative to the existing production methods and potential new chemical production pathways (105).
ERW	**"Pay for practice"-style MRV.** Integration of ERW into soil carbon models through extensive field trials across a range of soil types, rock types, climates, and land use practices could lead to general ERW practices that consistently provide CDR. This may open up funding from governments that support agricultural, forestry, and conservation practices that provide CDR. Generating sufficient data to support model development may require advanced measurement technologies (e.g., area measurements instead of point measurements) or remote sensing strategies (e.g., drones, satellites). **Quantifying co-benefits of ERW.** Increased crop yields, reduction of fertilizer or lime addition, and other financial co-benefits could help not only increase adoption, but also motivate farmers to consistently deploy ERW even if CDR prices wax and wane.	**Biological hyperaccumulators.** Organisms capable of promoting economically interesting (e.g., nickel) or environmentally deleterious (e.g., chromium) elements and compounds from source rocks or soils could allow for exploitation of more rocks in more environments for ERW (117). **Improved, alternative, or autonomous sensors to track mineralization and coproducts.** Significant overlap with OAE; see Section 4.4.1. Sensors or methods that can cover the large footprint of an ERW intervention and return data autonomously would help to increase the signal-to-noise ratio of CDR. This could ultimately lead to ERW that is paid for measured, net removals instead of a model-centric approach. The reduced uncertainty could be catalytic in supporting widescale adoption.

4.2.5 Linkages to the mCDR Pathway

The use of alkalinity to drive carbonate mineralization in the ocean, often referred to as OAE, overlaps with mineralization in terrestrial systems. The alkalinity may be naturally sourced rocks or electrochemically or chemically produced base. For mCDR methods that produce pure CO_2, offshore storage in seafloor basalts could provide synergies with the in situ mineralization CDR pathway. Note that mineralization pathways that interact with oceans, either to use ocean subsurface for storage or to source alkalinity to mineralize terrestrial CO_2 sources, do not induce ocean CO_2 uptake and storage, and are hence not considered mCDR here.

4.3 Biomass Carbon Removal and Storage

4.3.1 Pathway Options and State of Technologies

Among CDR options, BiCRS stands out for its relatively lower costs compared to DACS, with nearly half of BiCRS potential in the United States expected to cost less than \$100/tonne CO_2 removed, as well as the large potential scale (approximately 700 million tonnes of annual CDR potential at less than \$200/tonne CO_2) (18). The total technical potential scale of BiCRS in the United States and globally is a function of feedstock availability, economic viability, and the value of such products in carbon markets. In the recently published *Roads to Removal* report, waste/residue feedstocks are prioritized as inputs to BiCRS, and to supplement these waste feedstocks, the production of a limited quantity of purpose-grown lignocellulosic feedstocks is simulated based on the availability of marginal land (18). (Figure 9).

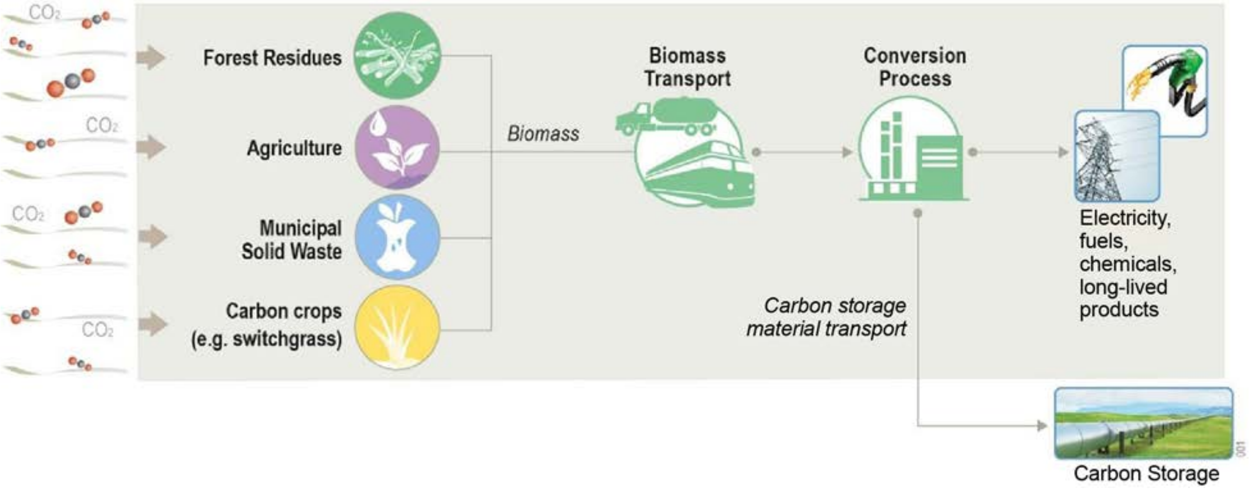


Figure 9. BiCRS technology overview

Adapted from (18).

The diversity of BiCRS pathways available (Figure 10) reflects the diversity of feedstock types, as well as variation in the types of conversion processes and carbon storage materials that make economic sense at small versus large scales. Within the total available feedstocks, some organic materials may be too diffuse or difficult to access and thus cannot be cost-effectively transported to large, centralized BiCRS facilities. The balance between facility scale and feedstock logistics is a crucial consideration for the viability of BiCRS and will be further explored as we discuss the challenges and opportunities within this technology category.

As Figure 10 shows, there are numerous BiCRS pathways that can convert biomass into diverse products and various forms of carbon storage. The balance between products (fuels, chemicals, and longer-lived materials such as inputs to pavements and building materials) and durable carbon storage (CO_2 for geologic storage or other products for injection or burial) varies across BiCRS pathways. Our focus in this report is on BiCRS pathways that demonstrate high potential for carbon removal, addressing their commercialization status and challenges.

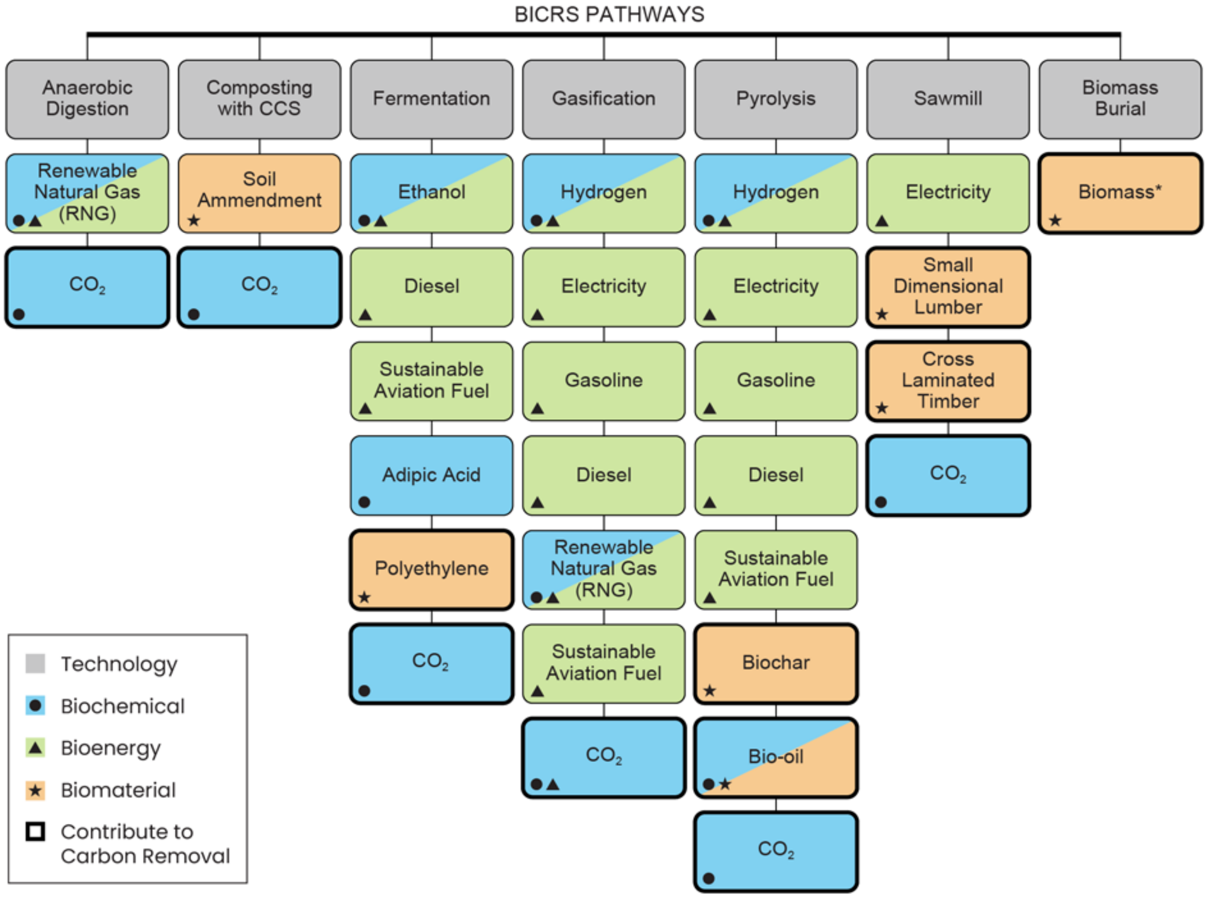


Figure 10. BiCRS pathways (including biomass conversion methods and products) considered in this report.

The biomass burial pathway includes treatment of biomass (e.g., through torrefaction) and/or storage systems to avoid biomass decomposition; adapted from (18). *Buried biomass includes treated or torrefied biomass. The seven different BiCRS technologies are shown in gray boxes across the top of the diagram. Coproduct categories (biomaterials, biochemicals, and bioenergy) are indicated with colors and icons in the lower left corner. The boxes outlined by heavy black lines highlight primary BiCRS product (CO_2) and other value-added bioproducts as coproducts.

One unique feature of BiCRS pathways is the diverse range of forms that carbon storage can take (see dashed boxes in Figure 10), with varying levels of uncertainty regarding their durability. Each of the BiCRS pathways described in the following subsections produces different carbon storage materials, and in some cases different coproducts for use in energy or other applications. Nearly all facilities will produce at least some gaseous CO_2 that could be captured and stored. Anaerobic biological conversion processes (fermentation) and biohydrogen production both produce a relatively pure CO_2 stream that can be compressed and injected into geologic storage with little or no additional treatment, whereas post-combustion streams such as those from facilities that gasify and combust biomass for electricity generation will require a carbon capture solvent to separate the CO_2 from other waste gases. Solvent performance and loss rates depend on how clean and concentrated the flue gas is; higher pollutant concentrations are generally associated with higher solvent losses during post-combustion CO_2 capture (142).

Another potential carbon storage material is a liquid product known as bio-oil or pyrolysis oil that can range from 50% to 70% carbon by mass (143,144). Bio-oil can be generated as the primary product of fast pyrolysis or as a minor coproduct (sometimes referred to as tar) of other thermochemical processes such as gasification, torrefaction, or slow pyrolysis. During storage, the reactive compounds can polymerize to form a solid or sludge-type material (145). Carbon storage can also take an entirely solid form, either as natural or engineered long-term storage of biomass itself (e.g., sinking, burial, or aboveground enclosed storage) or in the form of biochar, generated through torrefaction or slow pyrolysis, that is buried or applied to soils. For solid and liquid products intended for land application, burial, or subsurface injection, process conditions can be adjusted to alter the physiochemical properties of the carbon storage products. The cause-and-effect relationship between process conditions and carbon storage durability is crucial to the success of BiCRS pathways and remains underexplored.

The carbon storage with the lowest risk of release is geologic CO_2 storage in U.S. Class VI wells. Geologic CO_2 storage typically occurs by injecting captured CO_2 into porous underground sedimentary rock formations (often about 1 mile underground), which are overlain and confined by impermeable caprock layers. CO_2 is stored in this pore space as a dense fluid sufficiently far below any freshwater in the area (18). There are other options for CO_2 storage in non-sedimentary rock types, such as injection of CO_2 into basalts or ultramafic rocks, where it can become mineralized and permanently stored as a solid carbonate (18). The only mechanism by which the durability of CO_2 storage can be compromised is leakage. The depth (generally >1 mile), corrosion-resistant steel casing and cement requirements, injection pressure and rate limits, testing and monitoring requirements, and 50-year post-injection site care requirements for Class VI wells are all intended to ensure that CO_2 does not leak out of the well, out of the injection formation, or into drinking water sources (146).

Gasification

Gasification is a process that transforms biomass into a mixture of gases known as syngas, which is primarily composed of carbon monoxide (CO) and hydrogen (H_2) with smaller amounts of CO_2 and methane (CH_4) (147,148). Small amounts of liquid (a mixture of hydrocarbons, termed "tar") and solid (char) products/wastes are also produced. Syngas can then be refined into various valuable products such as hydrogen, heat, power, and liquid fuels. Following biomass gasification, a crucial step involves cleaning the syngas to remove impurities like tar and other particulate matter before further processing. The cleaned syngas can then undergo processes such as water-gas shift and pressure swing adsorption to produce hydrogen, to be utilized in the context of an integrated gasification combined cycle power generation facility, or to be directed toward fuel and/or chemical synthesis. Integrating gasification with carbon capture and storage offers a promising avenue for removing biogenic carbon present in biomass and released during the gasification process, facilitating its underground storage for net carbon removal. Gasification stands out for its potential to produce hydrogen and electricity with among the highest carbon removal per tonne of biomass, as nearly all biomass carbon is converted into gaseous CO_2 or a minimal amount of biochar, both of which can be captured and stored underground for carbon removal purposes (149). A major challenge so far has been the lack of infrastructure and incentives to support a clean hydrogen market, as hydrogen storage and transport is costly and demand is currently limited to industrial facilities (150), although this has changed in recent years. The 45V Clean Hydrogen Production Tax Credit is likely to stimulate more production through incentives for clean hydrogen. While some small-scale gasification plants for power and heat exist in the United States, such as Enerkem (151) and Phoenix Energy (152), large-scale commercial plants for integrated gasification combined cycle or Fischer-Tropsch liquids production, or systems integrated with carbon capture and storage for maximizing carbon removal, are yet to be fully developed, and a limited number of companies are pursuing gasification-based BiCRS (e.g., Mote). Survey results (Appendix A) on the scalability and economics of gasification were split, with different respondents ranking it as both the most and least expensive BiCRS technology.

Pyrolysis

Pyrolysis is a thermochemical process capable of converting biomass into gas, liquid, and solid products. The distribution of these products varies depending on the operational temperature and residence time during the pyrolysis reaction. Fast pyrolysis, characterized by high heating rates and temperatures (around 500°C), predominantly yields bio-oil as a major product, constituting up to 75% of biomass on a dry basis (153). Bio-oil, a complex mixture of oxygenated hydrocarbons and water, can be further refined into various products, including liquid transportation fuels and hydrogen, or utilized for heat and power generation. Bio-oil holds promise for carbon removal, with potential applications such as geologic injection or blending with asphalt for pavement material (assuming other parts of the process are decarbonized). However, the ideal use of bio-oil to achieve durable storage remains uncertain. Challenges exist regarding the lack of data on injecting bio-oil underground and establishing its long-term durability as a carbon removal technology. Blending bio-oil in asphalt is similarly uncertain, both in terms of its durability and impact on pavement performance at different blend levels. Laboratory experimental data suggest that a direct blend of 10%–20% bio-oil into asphalt is possible (154).

In contrast to fast pyrolysis, slow pyrolysis, operating at lower temperatures (around 200°C–300°C) and longer residence times, primarily yields solid char as a major product. This char holds potential as a soil amendment to enhance soil quality, thereby improving crop yields, or it can be directly employed for burial as a means of carbon storage (155). The CDR potential of biochar is contingent upon various factors such as its biochar properties and structure, as well as the soil and climate conditions during biochar sequestration. The properties of biochar resulting from slow pyrolysis exhibit significant variability depending on operational conditions and the feedstock utilized. For example, the carbon content of biochar can vary from approximately 50% to 80%, influenced by the type of feedstock employed and thermochemical generation conditions (156). Overall, pyrolysis to produce bio-oil or biochar is a mature technology that has been implemented at various scales. Plant sizes range from 40 to 240 metric tons per day of dry biomass throughput. Companies like Empyro (157) and Ensyn are prominent players in medium-scale fast pyrolysis for bio-oil production. Additionally, startup companies including Charm Industrial (158) are using pyrolysis systems to generate bio-oil as the final carbon storage materials (e.g., small modular pyrolysis systems to produce bio-oil for injection underground). In summary, the challenges associated with these two types of pyrolysis-based carbon removal are primarily linked to uncertainties surrounding carbon product durability rather than the technology itself.

Fermentation

Fermentation refers to the anaerobic biological conversion of sugars and other organic substrates to final products. Although fermentation processes are best known for producing ethanol, both for human consumption and as a fuel, microbial hosts have been engineered and optimized to produce a diverse array of products, including commodity fuels and chemicals. Fermentation yields a high-purity CO_2 stream because it proceeds under anaerobic conditions, thus producing CO_2 that is more cost-effective to capture and sequester than a post-combustion CO_2 stream (159,160). In fact, some corn ethanol facilities currently sell this captured CO_2 to food and beverage manufacturers (161). Estimates suggest that the corn ethanol industry alone generates approximately 45 million tonnes of high-purity biogenic CO_2 annually; however, this CO_2 represents a modest fraction of the industry's total greenhouse gas footprint, and the overall operations are still net greenhouse gas emitting (162). Expanding into lignocellulosic biomass bioconversion opens up new avenues for true CDR, particularly if residual components of the biomass can be used for heat and power generation in place of fossil fuels (159). It is also possible to expand the range of biological conversion processes to both anaerobically and aerobically produced products using a pure or enriched O_2 source, as is required for cell-based meat (163). However, technical challenges remain for biochemical approaches to conversion of lignocellulosic material, particularly in cost-effective and high-yielding pretreatment and saccharification methods (164). Overcoming these hurdles will be critical in realizing the full potential of lignocellulosic biomass fermentation for CDR.

Other BiCRS Pathways

There are many other BiCRS pathways that can offer carbon removal potential, including anaerobic digestion with carbon capture and storage, biomass or char burial (e.g., companies including Carba), subsurface injection of slurry (e.g., companies including Vaulted Deep), and sawmill wood products or mass timber. Anaerobic digestion is rapidly expanding in the United States for renewable natural gas production (165,166). This process can decompose high-moisture waste such as manure, food waste, and municipal solid waste into renewable natural gas. Biogas comprises approximately 50% CH_4 and 50% CO_2; facilities that upgrade the biogas to compressed biomethane (renewable natural gas) can separate and capture the CO_2. Unlike gasification for biohydrogen production, approximately half of the carbon remains in the fuel product, so the total potential for CDR is more limited unless the remaining carbon is eventually captured and stored after the CH_4 is utilized (e.g., for hydrogen production or for combustion as a fuel). Additionally, sourcing and aggregating distributed wet organic feedstocks for anaerobic digesters remains challenging in some regions. Wood products sourced from sustainable forests can play a role in storing carbon in buildings over multiple decades, thus serving as a more temporary storage mechanism compared to subsurface CO_2 injection. These products encompass various types, including sawmill products, which prioritize small-dimensional lumber, and emerging large-diameter mass timber, which offers potential alternatives to steel in building construction. Challenges arise from the diverse timescales of CO_2 storage in wood products, influenced by the lifespan of buildings and their handling post-demolition. Biomass burial and subsurface injection of organic materials, whether burying raw biomass, torrefied biomass (which removes moisture and volatile gases that trigger decomposition), or other (treated or untreated) wastes presents a straightforward solution for carbon removal (167). However, its challenge lies in ensuring durability, which varies with biomass type, composition, climate at the storage site, and site specifications. While biomass burial and subsurface injection of pumpable organic material are relatively straightforward in terms of the process, their economic feasibility heavily relies on carbon removal incentives, as it does not generate additional revenue beyond carbon removal (168,169).

4.3.2 Key Cost Drivers and Opportunities for Cost Reduction

BiCRS technologies span a continuum between single-purpose facilities that take in a feedstock and maximize the conversion to some form of durable carbon storage to the opposite end of the continuum, where facilities produce one or more primary products and services (e.g., biorefineries or wastewater treatment plants) and have the potential to add a form of CDR. Multipurpose processes typically have comparatively high CDR costs (Figure 11), unless their coproducts are strongly competitive with conventional products or those coproducts receive other types of policy support. In all cases, the costs break down into CAPEX, fixed OPEX, and variable OPEX.

Variable OPEX is often dominated by the feedstock costs, assuming the facility takes in a clean feedstock that requires payment. For example, if the delivered cost of feedstock is \$80/tonne biomass and the biomass contains approximately 50% carbon by mass, this translates to a cost of \$160/tonne carbon or \$44/tonne CO_2 for the biomass feedstock alone, assuming carbon storage is the sole product. Based on the expectation that BiCRS can achieve costs below \$200/tonne CO_2 or even less than \$100/tonne CO_2, the feedstock cost can be one-quarter to nearly half of the total cost. Feedstock costs can be addressed by sourcing cheaper materials. For forest thinnings and agricultural residues, the cost of harvesting/collecting the materials may be modest, but transportation distances and costs become the limiting factor, suggesting that facilities that can be cost-effective at small scales are essential for making use of more diffuse feedstocks. Another technological option for reducing feedstock costs is to design systems capable of handling mixed wastes and higher levels of contamination; mixed waste streams can come at a negative cost (tipping fee) or very low cost if the alternative disposal option is landfilling or composting. Waste diversion policies that prohibit landfilling of certain organic wastes, such as California's SB1383, may increase the tipping fee (or reduce the delivered cost) for these feedstocks because of the more limited options available to haulers.

Beyond feedstock cost, CAPEX is typically the largest contributor to BiCRS costs, and its share of the cost grows for smaller-scale facilities. For example, a recent techno-economic analysis of biomass gasification facilities in the United States for hydrogen production found CAPEX to contribute nearly half of total costs on a net present value basis (170). The gasifier and CO_2 capture are the largest contributors to CAPEX by a wide margin, followed by the boiler and turbines (171). Improved gasifier designs and incorporating innovative heat transfer systems can reduce CAPEX. CO_2 capture strategies are likely to be an area of continued innovation, including new sorbents, and some of these may be well suited to capturing CO_2 from syngas.

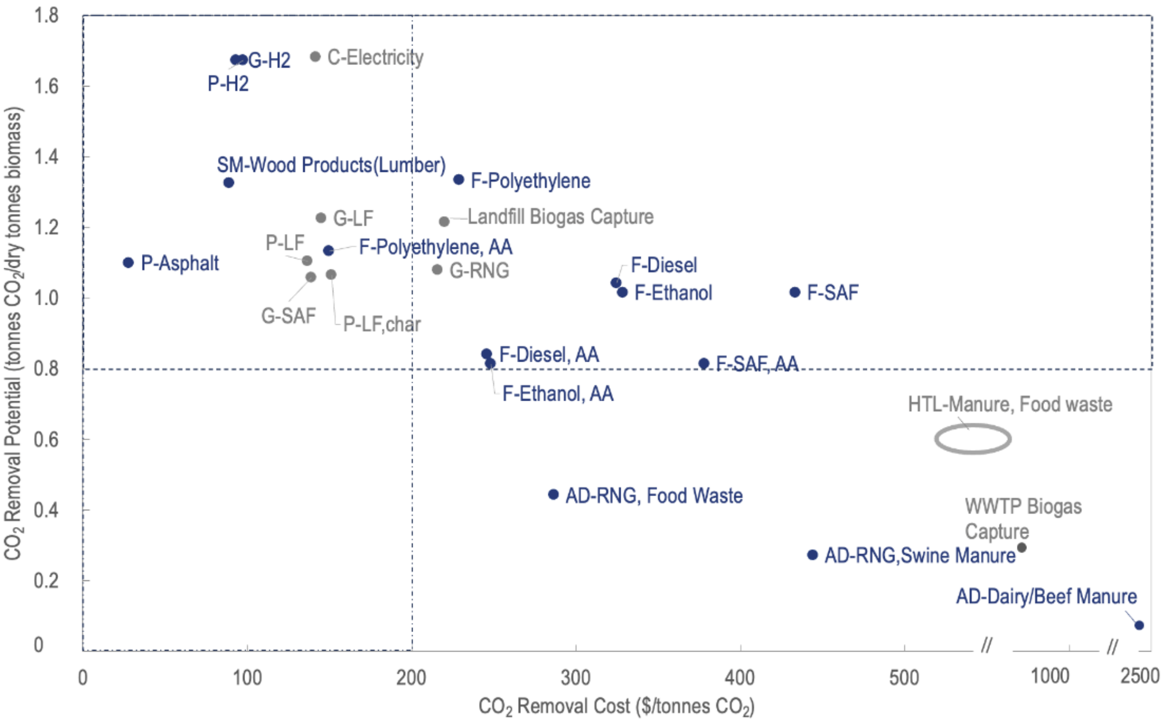


Figure 11. CO_2 removal cost versus CO_2 removal potential for a 1,000 dry tonnes/day facility.

The focus is solely on carbon removal at the biorefinery gate, excluding emissions from biomass harvest, transportation, CO_2 transportation, and injection. All feedstock is assumed to have a biomass cost of $60/dry tonne. Conversion technologies are represented by abbreviations: G (gasification), C (combustion), P (pyrolysis), F (fermentation), AD (anaerobic digestion), HTL (hydrothermal liquefaction), and SM (sawmill). Products include liquid fuels (LF), sustainable aviation fuel (SAF), renewable natural gas (RNG), and adipic acid (AA). We use the abbreviation WWTP to represent wastewater treatment plant. Pathways in blue represent those that have been thoroughly investigated in this report, while pathways in gray indicate other BiCRS pathways that have not been comprehensively discussed in this report. Image reproduced from (18).

Although the plant itself contributes most of the CAPEX, pipeline and grid connections introduce both costs and risks of delay. Depending on the plant configuration, it may need to construct a hydrogen pipeline and CO_2 pipeline and connect to the natural gas pipeline network (172–175). Additionally, if the plant will make use of grid electricity or export power to the grid, interconnecting to the grid will be necessary. Rural facilities located near abundant biomass often face long waits and high costs for grid interconnection or must forgo interconnection entirely. Small facilities that produce too little CO_2 to justify on-site injection wells may only be viable if their CO_2 can be transported via shared pipeline to an injection site that serves multiple nearby facilities. Low-cost CO_2 storage and transport technologies that can be deployed at small scale will be essential to enabling CO_2 sequestration for small facilities. Figure 12 summarizes the range of external factors impacting BiCRS costs. These include but are not limited to policy and regulatory frameworks, carbon credit market dynamics, co-benefits, environmental and logistical constraints, and socioeconomic factors influencing project deployment and scaling. Each of these factors introduces a layer of complexity that can significantly affect the overall cost structure of CDR solutions, although they are not explored in depth in this report.

	Regulatory & Financial Considerations
✓	Availability of government **incentives (such as tax credits and subsidies)** could create a financial incentive for industries to adopt BiCRS, driving demand for carbon removal services
✓	Stable and predictable regulations can **reduce investors risks and encourage** long-term investment in BiCRS
✗	Obtaining necessary **permits for biomass sourcing and land use activities** may limit its deployment
✗	Stringent **MRV regulations** can increase operational costs
✗	Failure to meet **biochar quality standards** may affect its effectiveness as a soil amendment or carbon sequestration agent

	Co-Benefits
✓	BiCRS provides significant and **durable carbon removal** while providing **benefits to farmers** through soil property improvements via biochar soil amendment
✓	**Reduction in forest fire** potential by removing fallen/waste timber for use in a BiCRS technology
✓	Coproduced sustainable (aviation) **fuels** can contribute to **decarbonization** of the global transportation sector
✓	**Reducing methane emissions** from landfills and agricultural waste

	Environmental Impact
✓	Reduce the risk of deforestation and soil degradation, contributing to **ecosystem restoration**
✓	Certain BiCRS approaches could improve **soil fertility**, water retention, and nutrient recycling
○	Care must be taken to site and deploy projects that promote biodiversity, retain or increase carbon stocks in plants and soils, and do not impact production of food or fiber
✗	Large-scale implementation of BiCRS technologies may lead to **land use changes**, including conversion of natural habitats or agricultural lands to carbon removal projects, which can impact local ecosystems and biodiversity

	Societal Impact
✓	Opportunities for **rural economic development** through biomass supply chains, biochar production facilities, and employment in sustainable agriculture
✓	BiCRS projects may promote **community engagement**, as they are more likely to be community owned and operated
✗	Risk of **low community acceptance** (e.g., facility construction, operation, and truck traffic pollution)
○	Large land areas for BiCRS implementation could potentially impact **food security**. Care must be taken to select BiCRS feedstocks that do not impact food production

Figure 12. External factors impacting cost for BiCRS.

(✓) indicates expected positive impacts, while (✗) indicates expected negative impacts. (○) indicates that the impacts could be positive, negative, or neutral.

4.3.3 Key Technical Challenges and Innovation Needs

Many BiCRS pathways, including gasification, fast pyrolysis, and slow pyrolysis, rely on thermochemical processes to convert biomass into carbon storage products. These types of facilities face a range of challenges, including variability in feedstock composition, reliable reactor performance, byproduct formation, in situ cracking, and difficulties in heat recovery. Addressing these challenges requires a multidisciplinary approach involving the development of advanced conversion techniques tailored to specific biomass feedstock chemistry, innovative reactor designs capable of accommodating feedstock variability and ensuring steady operation, and efficient heat recovery systems to maximize energy utilization. Research efforts focused on improving the understanding of fundamental mechanisms underlying biomass conversion processes and optimizing process parameters are essential for overcoming these challenges and fully realizing the potential of BiCRS pathways for long-term CDR.

Process Design and Optimization To Enable Use of Heterogeneous Feedstocks

The inherent heterogeneity of biomass resulting from variation in biomass components not only leads to processing inefficiencies, but also presents a significant challenge in designing BiCRS pathways that need to be almost tailor-made for different kinds of biomass (176). As expert survey respondents noted (Appendix A), feedstock availability is a challenge; while sourcing multiple feedstock types can help address the issue of availability, it creates other problems. This requirement for customization for different feedstocks adds another layer of complexity, posing a technical challenge in achieving commercial deployment (177). Advanced biomass pretreatment (size reduction, drying, and chemical preprocessing) techniques are crucial for enhancing reactivity, reducing processing time, and lowering energy consumption (18,178). They also play a significant role in increasing biomass conversion yields and reducing the formation of undesirable byproducts like tar by minimizing high mineral/ash content in the biomass, essential for reducing carbon intensity across BiCRS pathways (179). These advancements will facilitate efficient downstream conversion and eventually improve carbon utilization.

The efficient thermal decomposition of biomass presents additional significant challenges, particularly in large-scale operations where heat transfer remains energy-intensive and complex. Traditional methods like indirect heating, direct heating, fluidization, and solar energy struggle with efficient and uniform heat distribution, leading to high energy consumption and operational costs, which undermine carbon removal benefits. Innovations focusing on advanced heat exchanger configurations, such as multi-pass and finned tubes, to enhance heat transfer efficiency and minimize thermal losses are needed. Novel reactor designs that ensure uniform biomass exposure to heat and durable, heat-resistant bed materials should be developed to improve reactor performance. Process intensification through the development of integrated “one-pot” process units, where multiple reactions occur simultaneously within a single reactor, can greatly reduce capital costs and enhance the economic feasibility of BiCRS technologies (179).

Controlling, Predicting, and Verifying Stability of Carbon Storage Products

Carbon storage products ranging from biomass (for burial) to bio-oil, biochar, and even sludge/biosolids have uncertain durability that is a function of both the physiochemical properties of the materials themselves and the conditions in which they are stored. This was echoed in our survey responses (Appendix A), in which respondents noted durability for buried biomass and soil carbon as a challenge for MRV. Ensuring the stability and longevity of these liquid and solid carbon storage materials is critical, as is preventing their potential leakage or migration (178). Accomplishing this goal requires the combination of physical material characterization and testing under realistic conditions to understand the relationship between properties and durability. These results need to then be connected to process conditions associated with the material production. Machine learning can be leveraged to identify the primary predictors of durability and elucidate potential causal linkages between process conditions, physiochemical properties, and carbon storage durability. Using the outputs of testing and modeling, additional technology development is possible to tailor the properties of biochar and bio-oil to maximize their effectiveness as long-term carbon sinks. For example, bio-oil stabilization, such as encapsulation or chemical modification, can help ensure long-term carbon sequestration efficacy. Controlling pyrolysis conditions can produce desired bioproducts, such as biochar with specific porosity, surface area, and chemical composition, enhancing its carbon sequestration effectiveness (177). Postprocessing techniques, such as chemical or physical activation, improve biochar's adsorption capacity for pollutants or its suitability as a soil amendment for long-term carbon storage (180). Surface modification strategies, including chemical treatments like acid/base functionalization, further enhance biochar's properties for soil remediation applications.

Stability of carbon storage must also be verified throughout the life cycle of a project while ensuring that such systems do not make the overall project cost-prohibitive. The development of scalable, inexpensive, and robust monitoring and verification systems (e.g., sensors) is needed to track the injected bio-oil or land-applied biochar and verify its effectiveness in carbon removal. For systems that rely on land application of biochar, broader efforts in monitoring and measurement of agricultural greenhouse gas fluxes can be leveraged (181). Key to implementing measurement and monitoring will be the need to develop flexible solutions that vary with scale. Costly monitoring may be possible for large-scale BiCRS systems, but lower-cost options may be necessary to apply for smaller-scale BiCRS operations, particularly for those that are mobile rather than stationary.

Rightsizing BiCRS Facilities and Tailoring Technologies Across Scales

BiCRS biorefinery project developers (e.g., using gasification or pyrolysis) typically align with one of two distinct visions of how the industry will scale: through deploying either small-scale (<100 tons per day) or large-scale facilities (>2,000 tons per day). BiCRS requires collaboration, logistics, and siting, all of which assume something about deploying "rightsized" BiCRS facilities. A key consideration in prioritizing research and development investments for BiCRS is the range of likely facility scales, as well as the technological solutions most likely to reduce the costs at these scales.

The core rationale for small, community-scale facilities located in close proximity to the biomass is to minimize biomass transportation costs. The underlying dogma for extremely small facilities is that it is almost never economical to transport biomass more than 50 miles by truck (182–184). There are a number of advantages that can be gained when deploying BiCRS biorefineries at the community scale. Facilities are more readily financed because of the smaller total investment, more likely to be community owned and operated, and can be used as a resource, such as for backup power generation. Ease of financing, permitting, and community acceptance and benefit means that the project will be deployed faster and technology learning can occur more rapidly. The relatively small biomass demand in these facilities enables more flexible biomass sourcing and reduces the likelihood that biomass will be collected beyond sustainability limits. However, conventional scaling arguments indicate that community-scale facilities cannot be energy efficient or economical, especially when compared with large-scale facilities. The poor economies of scale for small-scale facilities only compound with increases in complexity and with every unit operation. For this reason, the production of purified CO_2 for geologic storage or other coproducts like hydrogen or liquid fuels is not expected to be feasible, preventing these beneficial uses of biomass alongside CDR. Carbon removal pathways from small-scale biorefineries may be limited to biochar and biomass burial types of approaches. Additionally, on-site energy generation can be too capital-intensive for small-scale facilities, yet the cost and wait times for grid interconnection also pose a challenge. Low-cost, low-emission, small-scale technologies for supplying the necessary heat and/or electricity needs of BiCRS facilities (e.g., stationary fuel cells, improved waste heat recovery systems) can accelerate their deployment and reduce costs. Additionally, innovations in the development of hub-and-spoke models for collecting and storing biocarbon intermediates (e.g., bio-oil) at minimal cost will also be essential.

The rationale for large-scale facilities is to take advantage of conventional economies of scale in chemical engineering, where capital cost increases more slowly than production rate. The biofuels community generally assumes that biorefineries must process approximately 2,000 dry tonnes of biomass per day or more to realize most of the economies-of-scale economic benefits (183,185–188), requiring transport of biomass over relatively long distances. Conventional economies-of-scale arguments arise from chemical engineering principles—for example, larger vessels can manage heat more effectively and use less steel than multiple smaller vessels. Processes that require extremes in pressures or temperatures almost always benefit from being larger, increasing the amount of product per unit equipment, which requires its own valving, metering, and other expensive hardware. Labor costs can also be substantially lower per unit product when larger facilities are operated.

A number of challenges may face BiCRS deployment through large-scale facilities: risk of low community acceptance (e.g., facility construction, operation, and truck traffic pollution), the technical risks posed by wider variability of biomass properties when obtained from more diverse sources, permitting, and financing large facilities, as well as securing sustainable biomass purchase agreements (see Figure 12). Addressing these challenges ultimately hinges on (1) designing facilities to tolerate variable feedstocks and (2) minimizing negative externalities in the community. The first solution is discussed in Section 4.3.3. The second solution requires a holistic approach that takes into consideration air quality, water quality, noise, traffic, and other factors. Air pollution control is particularly important for BiCRS facilities. Designing systems to minimize flaring and the combustion of solid fuels is important, and the air-quality-related considerations should be factored into future process design and simulation research. For post-combustion CO_2 capture, the use of amine solvents is expected to substantially reduce emissions that would otherwise occur (142). However, reactive species present in flue gases can interact with solvents in unpredictable ways, potentially increasing solvent losses and negatively impacting the economics of the system. Matching appropriate emissions control technologies and carbon capture solvents can minimize emissions while also ensuring minimal solvent loss. Further testing of CO_2 capture solvents in combination with either real-world or synthetic flue gas mixtures representative of those encountered at BiCRS facilities will be important for minimizing amine emissions, ensuring minimal solvent losses, and identifying solvents best suited for these facilities (189).

4.3.4 Qualitative Assessment of Impact of Innovation on Cost Reduction

The impact of technological innovation on cost reduction potential was assessed across all the major stages of BiCRS technologies operations (columns) and 12 distinct BiCRS pathways (rows) as defined in Section 4.3.1. Table 8 employs color coding to indicate the relative cost reduction potential for each BiCRS technology, as detailed in the footnote. Note that this assessment, similar to other CDR pathways in this report, is on a relative basis; the magnitude of cost reduction will vary among different technology options. Most of the base case cost estimates are taken from biomass facilities processing 2,000 dry tonnes per day assessed for pyrolysis, gasification, and fermentation design reports published by NREL, Pacific Northwest National Laboratory, and other literature resources (187,190–193).

Table 8. Qualitative Assessment of the Potential Cost Impact Technological Innovation May Have on Various BiCRS Pathways

BiCRS Technology Class	Feedstock Costs	Biomass Transportation Costs	Feedstock Preprocessing	Reactor Capital Costs	Downstream Capital Costs (Includes CO_2 Capture)	Operational Costs	Monitoring & Verification Costs	Carbon Storage Costs
Gasification and H_2 production	Medium	Medium	High	High	Very high	High	Medium	Medium
Gasification and electricity production	Medium	Medium	High	High	Very high	Medium	Medium	Medium
Fast pyrolysis and bio-oil injection	Medium	Medium	High	High	Medium	High	Medium	Medium
Slow pyrolysis to biochar (for burial or soil amendment)	Medium	Medium	Medium	Medium	Low	Medium	Low	Low
Lumber products (sawmill)	Low	Medium	Medium	N/A	Low	Low	Low	Low
Mass timber/Cross-laminated timber	High	Medium	High	N/A	Low	Low	Low	Low
Anaerobic digestion and upgrading with CO_2 capture	Medium	Medium	Medium	Medium	Medium	Medium	Low	High
Biomass burial	Low	Medium	Low	Low	Low	Low	High	Medium
Ocean submerged (non-terrestrial) biomass	Low	N/A	N/A	N/A	N/A	N/A	Very high	Low
Fermentation to ethanol or other products	High	Medium	Very high	High	Medium	Low	Medium	Low

Low: Potential for technology innovation in this category to reduce the cost of BiCRS by <10%.

Medium: Potential for technology innovation in this category to reduce cost of BiCRS by 10%–25%.

High: Potential for technology innovation in this category to reduce cost of BiCRS by 25%–50%.

Very High: Potential for technology innovation in this category to reduce cost of BiCRS by >50%.

N/A: Category not appliable to this BiCRS pathway.

Prioritized List of Innovation Opportunities

Thermochemical BiCRS pathways have the potential for meaningful large-scale carbon removal at intermediate costs, as well as the potential to produce coproducts that can address other national priorities, such as producing decarbonized electricity or fuels. However, from our survey respondents and our own domain knowledge we found that the BiCRS technologies and pathways that are most applicable to large-scale deployment and decarbonization co-benefits (e.g., gasification and pyrolysis) also suffer from among the highest capital costs and supply chain cost and complexity among all CDR pathways. The high capital costs arise from highly complex, multistep processes that require harsh operating conditions and must process multiple phases and employ multiple purification steps to produce the carbon storage product and coproducts. The supply chain complexity arises foremost from the feedstock—biomass feedstocks can be highly variable in composition (seasonal, source, and geography) and can be costly to transport distances necessary to amass enough feedstock to supply an economical BiCRS facility using current designs. Also, in most cases multiple stakeholders along the value chain must participate—including landowners, farmers, BiCRS operators, coproduct purchasers and CO_2 storage operators—which increases investment risk. Table 9 provides a set of prioritized incremental and disruptive innovation opportunities that can meaningfully address these challenges.

Table 9. Summary of Innovation Opportunities for BiCRS Pathways

Innovation Type	
Incremental ("Line of Sight")	**Disruptive**
Process intensification and downscaling to enable improved yields and shorter transportation distances for waste feedstocks that are widely distributed. **Pairing BiCRS with renewable sources of heat and electricity** to support biomass drying, pretreatment, and conversion including nuclear small modular reactors, geothermal, and solar thermal. Biomass drying could be done with an intermittent source and at low enough temperatures to use electricity. **Understanding and engineering for enhanced biochar durability**. The stability of biochar products used as agricultural soil amendments or as products for burial dictates the effectiveness of biochar as a form of carbon storage. Biochar with a higher degree of carbonization (low H/C ratio) with fewer functional groups and more aromatic structures performs better than low-temperature chars. Aromatic structures have a high thermodynamic stability and are important for applications such as soil amendment where long-term stability of biochar is required. **Supply chain optimization to improve feedstock sourcing**, preprocessing, and delivery at low costs. **Lower-cost nutrient recovery** to mitigate wastewater discharge impacts from facilities utilizing organic wastes and add another revenue stream.	**Enhancing photosynthetic efficiency and resilience** of plants that can be used as perennial dedicated crops for BiCRS or annual crops that are suitable as winter ("second") crops to avoid impacts on food supply. Specific approaches may include improving rubisco catalytic activity and decreasing photorespiratory losses by blocking C2 photorespiratory metabolism. Genome-wide association studies with breeding and genetic engineering aimed at identifying strategies for improving BiCRS crop sustainability and yields for regions that align with geologic storage. **New feedstock pretreatment strategies, including mobile systems, to enhance homogeneity**, remove inorganic contents, improve feedstock density for transport, and improve long-term stability during storage. **Low-cost biohydrogen storage, transport, and high-value utilization** are needed to enable biomass gasification and biohydrogen production. Much of the BiCRS potential aligns with areas that have substantial wind generation potential. Finding opportunities to use hydrogen to complement intermittent renewables in a high-value way will improve the economics.

Process intensification and the ability to downscale thermochemical conversion facilities are two related research areas that could enable favorable economics for thermochemical conversion pathways with lower capital investment. Process intensification approaches could include modifying processes to combine/eliminate unit operations, and improving the process through improved process (e.g., heat) integration and innovative reactor design to enable higher throughput/productivity per unit capital, ultimately enabling smaller and more compact systems. The ability to downscale facilities while maintaining favorable economics could also include research into reactor modularization to enable economies of mass manufacturing and of number, and the ability to bring down capital costs faster due to more rapid technology learning (as already described). The process intensification and downscaling research areas for BiCRS research needs include research into downscaling the conversion reactors such as gasifiers, pyrolyzers, and downstream processes such as more economic smaller-scale carbon capture and storage. Process intensification and downscaling also could decrease complexity of supply chain logistics, as facilities that are economical at smaller scales can require lower quantities of biomass, reduce transport distances, and in some cases enable co-location with other processes (e.g., hydrogen offtake).

At a more fundamental level, improvements to photosynthetic efficiency can result in disruptive improvements for BiCRS. Higher biomass yields per unit land area translate to smaller feedstock collection radii for facilities (also referred to as catchment areas) and greater national scale without impacting food production. This could occur in the context of crops that produce both food and agricultural residues or in dedicated biomass crops such as switchgrass.

In terms of more incremental improvements, we found that innovation in reducing costs of biomass collection, transport, and preprocessing (drying, size reduction, and removing critical inorganic compounds) is also crosscutting with the potential to reduce costs of the biorefinery and the ability to improve supply chain logistics and reduce biomass and transport costs. Some improvements, such as broadly applicable and effective pretreatment methods, can even be disruptive. For example, biomass pretreatment methods that reach a certain economic threshold (this analysis was not done here), conducted at the source of biomass (e.g., the hub-and-spoke model), could increase the carbon content of the biomass, reducing the cost to transport the biomass over longer distances per tonne of CDR. Cheaper biomass transport costs could enable the abundant supply of uniform feedstock to the biorefinery, thereby enhancing process efficiency and reducing the system complexity and costs associated with handling diverse biomass types within the same facility. Survey respondents also highlighted the need to innovate technologies to reduce the collection costs for forestry residues, potentially using automation. The *Roads to Removal* report found that forest thinning to reduce wildfire risk in the West could produce the largest supply of biomass in the United States, but collection costs are the highest of all biomass sources. If a pretreatment method also increases the homogeneity of the biomass in terms of size, flowability, composition, and decreased the critical inorganic compounds, the capital costs and operating costs for the biorefinery could be dramatically improved because of higher process efficiency and higher capacity factors.

4.3.5 Linkages to mCDR Pathway

The photosynthesis-based mCDR pathways are analogous to BiCRS in the terrestrial setting. The seaweed cultivated in the oceans can either be stored in the deep ocean for long-term sequestration (e.g., Running Tide) (194), used as alternatives for fossil-based materials toward emissions reductions, or included in structural materials (e.g., kelp-crete) or converted to biochar for long-term CDR. Unlike terrestrial plants, marine algae cultivation does not compete with alternate uses for land or freshwater resources, making it an attractive bio-pathway/feedstock. However, large-scale open ocean cultivation remains a challenge that needs dedicated research and infrastructure development.

4.4 Marine CDR

4.4.1 Pathway Options and State of Technologies

mCDR is an umbrella term that refers to approaches wherein CO_2 is removed from the atmosphere via the oceans by exploiting the natural gas exchange equilibrium. mCDR approaches can alter the ocean's carbon cycle through a number of diverse chemical and biochemical pathways (Figure 13) that either accelerate natural photosynthesis rates (e.g., artificial upwelling and downwelling, ocean fertilization, macroalgae cultivation) or alter the ocean chemistry using engineered systems (e.g., OAE, DOC). The different pathways store the carbon in different forms, such as CO_2 gas in DOC, bicarbonate/carbonate in OAE, and biomass in photosynthetic pathways. Based on the form of stored carbon, there may be need for further processing to achieve desired CDR, such as subsurface mineralization of CO_2 gas or marine biomass used in BiCRS. These needs are described under the "Linkages to the mCDR Pathway" sections of the corresponding terrestrial CDR pathways. Further, these sections also highlight cases where the CDR approach does not directly impact the marine CO_2 cycle, such as undersea storage of DAC-sourced CO_2 via mineralization, or methods that source alkalinity from seawater but do not capture ocean CO_2 such as cation separation mineralization.

In general, mCDR approaches are relatively underdeveloped compared to systems deployed on land. Although the mCDR pathways are fairly diverse, our review and the SME survey suggested they all share similar research needs in terms of MRV, social license, understanding ecosystem impacts when deployed at scale, technological innovation in materials, infrastructure for operation and MRV in harsh marine environments, and energy availability and cost. Here we review the status of major categories of mCDR pathways to highlight research needs and innovation opportunities to reduce the overall costs per tonne of CO_2 removed.

A summary of major mCDR pathways, status of the technology, and pathway-specific advantages and disadvantages is included in the following subsections. Overviews provided here are brief, but detailed technology descriptions for the different mCDR pathways can be found in recent state-of-technology reports (17,195–198), in addition to pathway-specific references cited in this report.

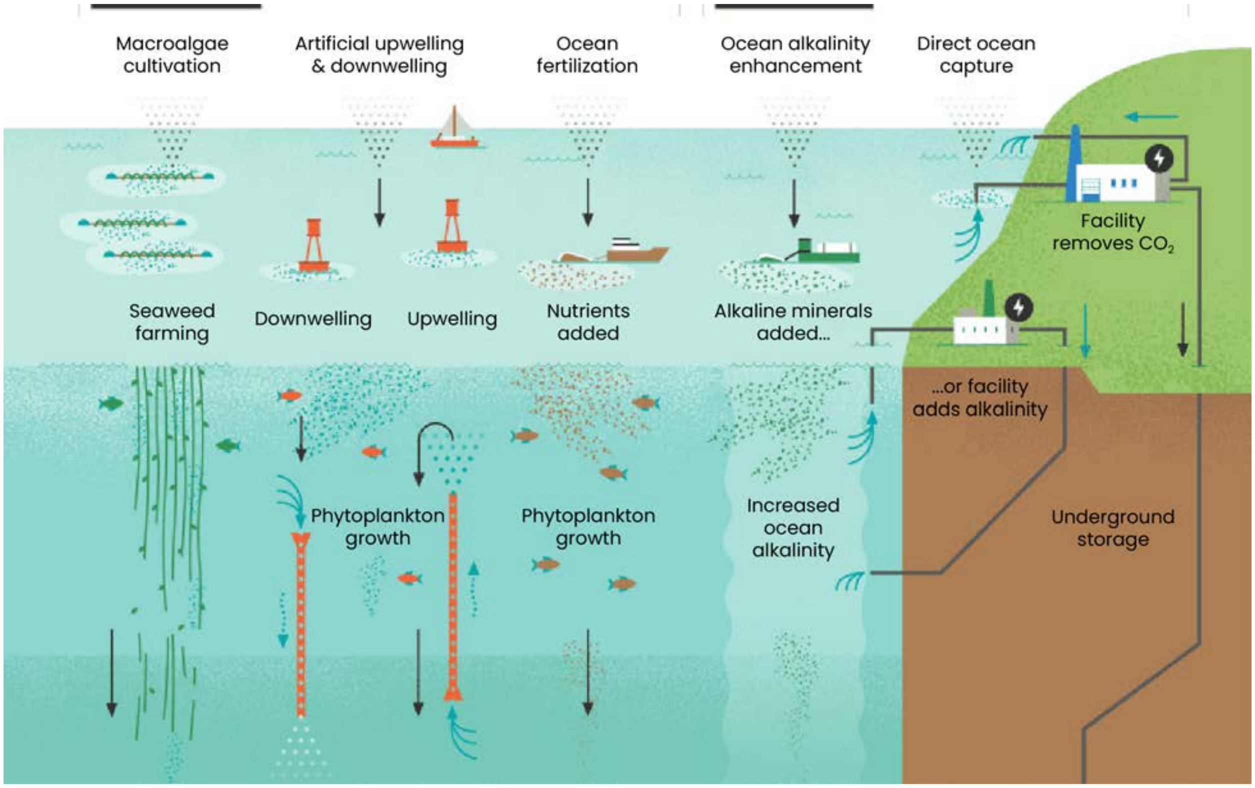


Figure 13. Schematic overview of the diverse mCDR pathways

Adapted from (199)

Direct Ocean Capture

In this mCDR method, CO_2 is directly stripped using chemical or electrochemical methods that acidify a seawater input stream (in this report, we group electrochemical alkalinity approaches as a subset of OAE). Generally, the CO_2 is captured, the pH is restored to pretreatment levels, and the decarbonated water is returned to the surface ocean. This lowers the partial pressure of CO_2 of the surface ocean (pCO_2), and equilibrium reactions drive additional dissolution of atmospheric CO_2 into seawater. Because the CO_2 captured is directly proportional to the subsequent diffusion of CO_2 to the surface ocean, note that this method does not alter surface ocean pH or contribute to ocean acidification; effectively, the system increases the buffering capacity of the surface ocean. The eventual fate of the captured CO_2 determines the overall net efficiency of this method; sequestration in underground reservoirs or biomaterials results in a larger net atmospheric removal capacity and durability of the removed carbon than use in synthetic fuels.

A broad range of electrochemical cells have been reported for DOC, including the cogeneration of acid and base via chloralkali methods or bipolar membrane electrodialysis (39,41,200). The electrochemically generated acid is used to drive dissolved inorganic carbon equilibria toward the evolution of CO_2 gas, which is then directly captured. The process then employs the cogenerated base to re-alkalinize the acidified, decarbonized stream before ejection to the sea (196). Notably, this decarbonized effluent may have a similar alkalinity to the influent seawater but lower overall pCO_2 and a slightly higher pH, and thereby may drive additional oceanic absorption of additional atmospheric CO_2 when released. However, because alkalinity concentrations have not been increased, this process is held distinct from OAE. An alternative approach to electrochemical acid generation is chemical. Recent work has suggested that photoacids can also be used to generate the pH swing required to degas CO_2 (201–203). Photoacids feature acidic groups with pK_a values that are sensitive to illumination state, allowing for light-triggered reversible proton generation and pH swings.

Electrochemical DOC systems have been demonstrated at pilot scale (TRL 5–6) at both the 100-t-CO_2 and 1,000-t-CO_2 levels in the United States and Canada. The chemical DOC approach based on photoacids has been demonstrated only at proof-of-concept scale (TRL 3–4) at the time of writing. Note that the overall scalability of DOC methods relies on the storage of the CO_2 removed. Overall, the SME survey found that DOC was one of the most scalable mCDR technical options (comparable to OAE), although it remains at a mid-level of technical readiness. Respondents to the SME survey suggested that scalability would come from many modest-scaled installations of DOC, rather than a few larger installations (similar to OAE).

One clear advantage of DOC vs. other mCDR methods is the ease of monitoring and quantification of the CO_2 removed, as the processes rely on extracting CO_2 gas in an engineered system. Another advantage is that the process can likely couple with existing ocean-based infrastructure such as desalination without need for additional permitting for operation, making rapid deployment feasible. Further, by controlling the electrode configuration and operation, byproducts such as hydrogen can be generated to offset some of the energy costs.

As with many mCDR technologies that rely on membranes and/or electrodes, the technologies need system components that can resist corrosion, fouling, and scaling. Such materials are often expensive or may not be available. In an effort to protect system components and to ensure sustained efficiencies, the choice has been to rely on extensive seawater pretreatment—which can add to significant process energy and costs. Further, the high concentrations of photoacid required for CDR from seawater will require compounds with moderate to high water solubility or designs stabilizing these molecules on solid supports. The combination of novel photoacid synthesis and its integration into a functional system in the marine environment is expected to need significant research. Overall, the environmental impacts of DOC require further investigation, as the potential risks of this technology are unclear (196). For instance, local reductions in dissolved inorganic carbon concentrations could negatively impact autotrophic organisms. While all of these materials and system challenges for DOC may question its near-term scalability, they also offer opportunities to lower DOC costs.

Ocean Alkalinity Enhancement

Overall, ocean seawater is slightly basic: globally, seawater pH is approximately 8.1–8.2. This stems from the high concentrations of dissolved alkaline minerals from natural geologic erosion. Accordingly, the ocean is an essential component of the Earth's carbon cycle, in large part due to seawater's natural alkalinity. The relationship between surface ocean total CO_2, alkalinity, and pCO_2, as well as the impact on surface ocean pCO_2 from additional alkalinity, has been well established (204,205). OAE adds alkaline minerals (e.g., olivine), chemical bases (e.g., $Mg(OH)_2$, NaOH, CaO), or their dissociation products (e.g., HCO_3^-) to seawater to increase the potential stable storage of CO_2 in the surface ocean. Increasing ocean alkalinity decreases the pCO_2 in surface ocean waters relative to concentrations in the atmosphere, causing the surface ocean to take up additional CO_2 at the sea-air interface, or to lessen potential CO_2 efflux from the surface ocean back to the atmosphere.

The efficiency and scalability of OAE can be determined by the mineral feedstock used, as well as by the delivery mechanism (206). Chemical methods of OAE rely on the addition of alkaline minerals of varying grain sizes, such as silicates, brucite, and limestone. In some cases, these methods require natural weathering reactions to take place in the surface ocean, with the degree of required weathering in part dependent on the grain size of the material added (207). Electrochemical OAE approaches use chloralkali methods or bipolar membrane electrodialysis to split seawater into acid and base streams (39,41,200). The base (often NaOH) is then mixed with seawater and returned to the surface ocean to increase ocean alkalinity, while the acid (often HCl) may be neutralized through existing industrial processes, or used in emerging complementary operations (such as accelerated weathering of silicates or CO_2 stripping of seawater) (196,198,208). Note that the dilute acid from OAE may not be a direct replacement for conventional acid feedstocks, and that the large volumes of acid generated by OAE may require multiple use and disposal pathways, choices that are likely to be site-specific.

OAE approaches have been demonstrated at pilot scale (TRL 5–6) with systems of 1,000 t-CO_2/yr reported for the chemical (209) and 100 t-CO_2/yr for electrochemical pathways. Larger projects are in early stages, with chemical OAE efforts under beach nourishment permitted to add 9,000 tonnes of olivine to a site in North Carolina. The electrochemical OAE systems have largely operated under research contexts or within existing permitted infrastructure such as wastewater treatment plants. Overall, respondents to the SME survey suggested that OAE was one of the most scalable mCDR technologies, although it remains at a mid-level of technical readiness. Respondents to the SME survey suggested that scalability would come from many modest-scaled installations of OAE, rather than a few larger installations (similar to DOC).

Given the durability of carbon captured by OAE, at least 1,000 years and possibly as high as 100,000 years (210), as well as the capacity of the ocean to absorb significant amounts of additional alkalinity, potential CDR could scale to as much as 30 Gt-CO_2/yr. Further, the OAE pathway does not rely on CO_2 storage or utilization pathways to be viable in order to be scalable (unlike DOC). For OAE, another key benefit may be short-term, local mitigation of ocean acidification. While large-scale mitigation of ocean acidification may be challenging to scale, short-term mitigations can be valuable if occurring at critical times or in important habitats for sensitive species (211).

A key consideration for OAE strategies is factoring the full supply chain. For mineral-based OAE this includes the extraction, transport, grinding, and distribution of target minerals, while for electrochemical OAE this includes the full supply chain of feedstock, byproducts, and any waste streams generated. The real-world limitations on the efficiency of the entire supply chain are key to making realistic estimates for net CDR efficiency and ultimate price per tonne of CO_2 removed. Additional considerations include the need for reliable monitoring and verification of carbon removal in the open ocean, and an understanding of how the different types of alkalinity impact the local ecosystem. Though studies report potential benefits of this method reducing local ocean acidification, more research is required to understand the impacts of rapid changes in pH on marine life, as these changes could be detrimental (196,212–215). In general, the OAE efficiency and impact even for a single type of alkalinity are a strong function of the operating site, making a simple linear estimation of impact from scale-up difficult. For the particular case of mineral OAE pathways, CO_2 quantification is made more challenging by variable mineral composition, the complexities of natural weathering reactions, and particulate burial away from the surface ocean. While these considerations for OAE pathways may seem daunting, they also highlight key experimental and modeling research needs to improve certainty of CDR and associated costs for the pathway.

Photosynthesis-Based Approaches

The ocean's biological pump sequesters carbon in organic tissues for eventual transport of carbon from the surface ocean and atmosphere to the ocean's interior. This natural transfer process is the sum of multiple pathways, including those from the natural life cycle of phytoplankton and macroalgal production. Overall, the ocean biological pump drives sequestration of approximately 10–11 Gt CO_2 to the ocean interior each year. mCDR methods that seek to amplify this natural pump do so through additional photosynthetic activity, which reduces the pCO_2 of the surface ocean, favoring influx of additional CO_2 from the atmosphere. The generated biomass can be buried in anoxic ocean basins or used to make bioproducts that replace fossil-based materials for emissions reductions. Therefore, the permanence of the CO_2 sequestered depends on the specific end use pathway. Note that we only consider marine photosynthetic pathways and not ocean burial of terrestrial crops.

Cultivation of both macroalgae and microalgae can drive reductions in surface ocean pCO_2 through local photosynthetic activity. The choice of algal species determines rate of growth, necessary growth and harvest conditions, and end use pathways. If the algal species is not being grown for a specific end use, open ocean phytoplankton production can be amplified by addition of limiting micronutrients, such as iron. The phytoplankton subsequently sink, driving sequestration of carbon trapped in organic matter in the ocean interior. The nutrients can also be delivered through artificial upwelling, which brings deep ocean water rich in organic nutrients to the surface to increase phytoplankton growth, followed by artificial downwelling to sink the biomass. Note that the naturally higher pCO_2 of the ocean interior, and likely subsequent outgassing of this excess interior CO_2 to the atmosphere upon upwelling to the ocean surface, may reduce the overall efficiency of CDR when upwelling is used as a fertilization technique (196,216). Another pathway often considered is restoration of coastal blue carbon, especially given the volume and durability of carbon storage in natural seagrass, mangrove, and salt marsh ecosystems (198).

Some photosynthesis-based approaches have been tested at larger scales and higher TRL compared to DOC and OAE pathways. Ocean fertilization demonstrations include 16 large-scale experiments in the 1990s (TRL 7); however, the experiments were not focused on carbon sequestration, did not quantify the CDR, and have received heightened scrutiny by the scientific community regarding viability and efficacy (217). In comparison, open ocean macroalgae cultivation and sinking are in much earlier stages (TRL 5) and demonstrated at smaller scales. While macroalgae cultivation is a commercial industry in the United States (TRL 8–9), the kelp is harvested and used for food products, where calculating carbon removal is challenging. Artificial upwelling/downwelling has been tested as a carbon removal technique in research settings using natural seawater (TRL 4–5) and tested for enhanced aquaculture yields (218,219), but no mCDR pilots are reported. Pathways to restoring coastal blue carbon ecosystems are relatively well known (TRL 8–9) given a long history of conservation and restoration science

(220), and emissions and removals from coastal blue carbon ecosystems are included in national greenhouse gas inventory guidance (221). Recently, companies have tried to sell carbon removal credits from the control and suppression of harmful algal blooms, but research on the efficacy of this method is limited. A vocal minority of respondents to the SME survey supported iron fertilization as one of the most scalable MRV methods, although they admit that there are important open questions about environmental impacts, social license, and MRV that could limit the deployment of this technology.

In general, societal approval for nature-based methods is higher than for technological mCDR interventions, as there is a perceived risk reduction with these pathways. Hence, the restoration and climate impact offered by the coastal blue carbon pathway is likely to readily garner community support. Furthermore, macroalgae-based approaches could offer economic incentives to the U.S. commercial kelp industry, making it attractive for coastal communities. If biomaterials pathways are considered for end use of the macroalgae vs. sinking, significant carbon emissions reductions benefits may be realized through displacement of fossil-based alternatives.

Primary challenges for photosynthesis-based mCDR include reliable carbon accounting relative to natural baselines, viable pathways for biomass sinking and associated MRV, or alternatively biomass valorization and cradle-to-grave carbon accounting, as well as potential environmental impacts (196,219,222–226). Competing use cases make coastal macroalgae cultivation less economical, and open ocean cultivation may need additional infrastructure. A report from the National Academy of Sciences estimated just 0.1 Gt-CO_2/yr removal by macroalgae if grown 0.5 km in width along the entire U.S. coastline but notes that algal productivity is higher in tropical regions (196). In comparison, ocean fertilization is estimated to achieve higher removal but may result in significant impacts to phytoplankton community succession (227–229). Ocean fertilization, artificial upwelling, and biomass sinking may all have unintended consequences for downstream water quality and ecosystem health (196,223,226,227,230–233). In the case of artificial upwelling/downwelling, the cost of pumps and the energy to pump water from the deep sea are significant relative to estimated CO_2 removals (234). In the case of coastal blue carbon, the overall estimated removal potential is limited (235). More importantly, it is unclear if restoration will achieve carbon removal with strong additionality (236). These considerations highlight the need for dedicated research to improve carbon accounting capabilities and risk reduction for photosynthesis-based mCDR pathways.

4.4.2 Key Cost Drivers and Opportunities for Cost Reduction

Current mCDR pathways are limited to demonstration or pilot-scale systems, and there is limited information on the breakdown of capital, operating, and financing costs. Costs are likely to be highly variable based on the specific approach. Accordingly, many SME survey respondents suggested that research investments in applied demonstrations would be most helpful to advance research. Further, successful deployment and operation of the technologies will depend on meeting regulatory requirements and gaining social acceptance, which can both add to cost and deployment delays. Certain mCDR pathways connected with existing industry, conservation, or restoration may be viewed more positively by communities than technological approaches, but the environmental impacts of such methods when implemented at scale is not known. For most mCDR pathways, our review and SME survey respondents agreed that dedicated research into ecosystem impacts will be required to both inform permitting and gain social license for successful operation. A high-level summary of such external factors influencing mCDR pathways is shown in Figure 14.

	Regulatory & Financial Considerations		Co-Benefits
✓	The Environmental Protection Agency has recently released guidance on how existing federal regulations may apply to mCDR methods.	✓	Some mCDR methods can result in localized ecosystem benefits through reversal of impacts of ocean acidification and/or habitat restoration.
✗	mCDR methods have few existing parallels in current environmental regulations.	✓	Some mCDR methods can have beneficial byproducts that can be used to generate energy or support other climate technologies, such as the production of biomaterials or carbon-neutral cement.
✗	Environmental toxicology of mCDR techniques is poorly understood, leading to improper use of existing environmental regulations that were not specifically crafted for mCDR or climate restoration.	✓	Some mCDR methods can integrate with and offer cost benefits to processes such as desalination or wastewater treatment.
✗	mCDR pathways operating in the open ocean may need ecosystem impact evaluation for each site, adding to cost and delays.	✓	Some mCDR pathways support existing coastal industries (e.g., aquaculture) directly affected by climate change.

	Environmental Impact		Societal Impact
✓	Some mCDR methods have the potential to support ocean acidification mitigation, especially on local timescales.	✓	Opportunities for rural economic development through repurposing of coastal brownfield industrial sites, coastal supply chains, mCDR production facilities, and employment.
✓	Ecosystem restoration activities can have multiple environmental co-benefits, including support of biodiversity.	✓	Ecosystem restoration techniques could support both carbon removal and storage as well as community investments in conservation and biodiversity.
○	Environmental impacts of specific mCDR deployment pathways are poorly understood, requiring more research.	✗	Risk of low community acceptance (e.g., conservation or precautionary approaches to ocean and coastal development).
✗	Some mCDR methods could have negative ecosystem outcomes through nutrient robbing, impacts on phytoplankton community succession or biodiversity, trace metal contamination from alkaline feedstocks, or production of hazardous byproducts.		

Figure 14. External factors impacting cost and feasibility for mCDR.

(✓) indicates expected positive impacts, while (✗) indicates expected negative impacts. (○) indicates that the impacts could be positive, negative, or neutral.

In general, technological mCDR approaches will require extensive seawater pretreatment, which typically increases costs and makes larger deployments preferable relative to many small installations. Energy is a key cost driver for those systems, particularly the energy required for the fundamental process chemistries and the energy consumed by the pumping of seawater (especially if against gravity), along with any necessary thermal, electrical, or chemical pretreatments. Maintenance and replacement costs are also typically higher in marine systems than their terrestrial counterparts, as are materials of construction. Generally, research and development for improved energy efficiencies and cost reductions map onto those for the desalination industry, as reported in the National Alliance for Water Innovation's master roadmap (237). Beyond system operation and access to carbon-neutral energy sources, permitting and monitoring may add significant project cost and risk but are hard to estimate at this early stage of the industry. For photosynthesis-based mCDR pathways, the production of stable biomaterials can add significant costs beyond cultivation. Irrespective of pathways, MRV is likely to introduce additional operating costs not currently accounted for in the estimates.

Although detailed information on the system cost or energy use may not be available at this time, based on the current status of the technology and the fundamental principles of CDR it operates on, we have identified key research needs and technological innovation opportunities that could help improve overall process economics (Table 12). In general, the research needs have been classified into (1) materials R&D—the need for catalysts, membranes, alloys, and other materials designed for long-term use in harsh marine environments to lower the capital and operational expenses of mCDR; (2) process optimization—the device engineering, process intensification, and operational optimization needed to meet sustainability, durability, and efficiency metrics; and (3) uncertainty reduction—the research needed for reliable carbon accounting by modeling, monitoring, and counterfactual baseline improvements.

Given the overall moderate TRL and cost of optimization and demonstration for many of these methods, public infrastructure designed to advance testing opportunities may help advance the emerging mCDR industry, as echoed by our SME survey. In many cases, this infrastructure could be shared by researchers pursuing multiple different mCDR pathways. Previous work has suggested that public-private partnerships, access to testing sites, multidisciplinary on-site expertise, civic integration, and ongoing community relationships can help improve the pace of research and commercialization, as well as public trust (238). While several regions are emerging as potential hubs (e.g., California, Pacific Northwest), it is important to acknowledge that variability in ocean chemistry and ecosystems, place-based concerns, and marine industrial patterns may limit the usefulness of any one particular site, necessitating a national network of testing facilities. While a national network of testing sites may seem a large investment, here we note that this infrastructure and the findings that advance mCDR may also have interdisciplinary uses, including development of critical mineral extraction from seawater and marine renewable energy. Parallel development may help to additively accelerate each of these emerging marine climate technology sectors.

4.4.3 Key Technical Challenges and Innovation Needs

In this section (Table 10), we highlight specific technical challenges and innovation opportunities that would lead to cost reductions the described mCDR pathways.

Table 10. Technical Challenges and Innovation Opportunities for the Various mCDR Pathways

Pathway and Sub-Pathway	Materials R&D	Process Optimization	Uncertainty Reduction
Pathway: Direct Ocean Capture			
Electrochemical	• Improve durability and performance of ion-exchange membranes • Develop efficient, durable, and low-cost, low-overpotential electrocatalysts • Develop low-cost, corrosion-resistant, easy-to-weld alloys • Develop membrane-less systems	• Leverage industrial ecologies for CO_2 valorization • Integrate with desalination and water treatment infrastructure • Incorporate mass transport considerations into device design • Minimize environmental impacts by better management of heat and changes to water quality • Improve energy efficiency by achieving fast reaction kinetics at low-overpotential operation	• Develop low-cost, high-sensitivity sensors for distributed carbon flux and water quality monitoring • Track CO_2 from sea to storage
Chemical	• Improve durability and performance of ion-exchange membranes • Energy efficiency gains by identifying high quantum yield, broad absorption spectra photoacids with high molar absorptivities • Develop low-cost, corrosion-resistant, easy-to-weld alloys • Develop membrane-less systems	• Leverage industrial ecologies for CO_2 valorization • Electrify processes including upstream reagent production • Incorporate mass transport considerations into device design • Minimize environmental impacts by better management of heat and changes to water quality	• Develop low-cost, high-sensitivity sensors for distributed carbon flux and water quality monitoring • Track CO_2 from sea to storage
Pathway: Ocean Alkalinity Enhancement			
Electrochemical	• Improve durability and performance of ion-exchange membranes • Develop efficient, durable, and low-cost electrocatalysts • Develop low-cost, corrosion-resistant, easy-to-weld alloys • Address key materials needs for long-term, reliable open ocean sensing	• Minimize byproduct and waste stream volumes • Leverage industrial ecologies for byproduct/waste valorization • Integrate with desalination and water treatment infrastructure • Incorporate mass transport considerations into device design	• Develop counterfactual baseline on relevant spatiotemporal scales • Generate experimental data to validate computational Earth system models nested across spatial and temporal scales • Develop low-cost, high-sensitivity sensors for distributed carbon flux and water quality monitoring

Pathway and Sub-Pathway	Materials R&D	Process Optimization	Uncertainty Reduction
	• Develop membrane-less systems	• Minimize environmental impacts by better management of heat and changes to water quality • Improve energy efficiency through systems achieving fast reaction kinetics at reduced system overpotentials	• Identify low-cost, effective proxies for environmental and ecosystem monitoring (e.g., sentinel species)
Chemical	• Control reaction rates through particle size optimization • Characterize reaction rate as a function of composition • Address key materials needs for long-term, reliable open ocean sensing	• Select feedstock informed by end use • Accelerate reaction rates • Understand impact of feedstock on water quality	• Develop counterfactual baseline on relevant spatiotemporal scales • Generate experimental data to validate computational Earth system models nested across spatial and temporal scales • Develop low-cost, high-sensitivity sensors for distributed carbon flux and water quality monitoring • Identify low-cost, effective proxies for environmental and ecosystem monitoring (e.g., sentinel species)
Pathway: Photosynthesis-Based Approaches			
Macroalgal bioproducts	• Develop materials for moorings and other open ocean infrastructure	• Increase nutrient use efficiency of macroalgae • Develop high-density cultivation capabilities	• Track carbon from sea to storage for biomaterials
Macroalgal sinking	• Develop materials for moorings and other open ocean infrastructure • Advance research on material sinking	• Increase nutrient use efficiency of macroalgae	• Improve measurements and models of lateral and vertical organic carbon export • Improve understanding of potential ecosystem and species dynamics, especially in sediments
Ocean fertilization	• Develop highly controllable and precise nutrient delivery process • Address key materials needs for long-term, reliable open ocean sensing	• Build nutrient feedstock transportation/emissions into design • Develop strategies for maximum nutrient use efficiency and low-dose delivery	• Develop counterfactual baseline on relevant spatiotemporal scales • Improve measurements of vertical organic carbon export

Pathway and Sub-Pathway	Materials R&D	Process Optimization	Uncertainty Reduction
		• Design systems for rapid shutdown for minimizing downstream impacts	• Develop low-cost, high-sensitivity sensors for distributed carbon flux and water quality monitoring • Identify low-cost, effective proxies for environmental and ecosystem monitoring
Artificial upwelling	• Develop low-cost, corrosion-resistant, easy-to-weld alloys • Develop energy-efficient pumps	• Couple with marine renewable energy generation to offset energy costs	• Develop low-cost, high-sensitivity sensors for distributed carbon flux and water quality monitoring • Improve measurements of vertical organic carbon export
Coastal blue carbon	• Develop robust nutrient mix to support reliable restoration	• Develop technology to assist with rapid repopulation	• Quantify actual removal of CO_2

4.4.4 Qualitative Assessment of Impact of Innovation on Cost Reduction

A combination of technical and nontechnical factors controls the effectiveness, cost, and scalability of mCDR pathways (Table 10), as shown by our review and echoed by respondents to the SME survey. These include energy efficiency of the process, the cost and durability of system components, full supply chain considerations, process co-benefits, MRV needs, ecosystem impacts, and social license, among others. While several of these factors are difficult to quantify, they are crucial to address. For example, some survey respondents indicated that limited knowledge of potential ecosystem impacts and co-benefits at varying scales of deployment and poorly resolved environmental monitoring strategies can be significant social and regulatory barriers to mCDR deployment. Additionally, the lack of suitable coastal and open ocean infrastructure both in terms of availability of renewable power and the ability for monitoring at spatial and temporal scales to minimize risks can limit mCDR feasibility in the open ocean. In terms of scalability, mCDR pathways would often benefit from coproduct markets. However, such markets may quickly saturate or may not be widely available across all regions, making it difficult to scale up mCDR systems or to rapidly replicate deployment across the country. For many mCDR pathways, it may be best to integrate with existing or new desalination facilities and multiple commodity markets to minimize permitting/legal challenges and reduce large capital expenditure. Such integrated processes may also open up opportunities for on-site utilization of coproducts such as electrochemically generated hydrogen and acid.

The impact of technological innovation on cost reduction potential was assessed across all the major mCDR pathways discussed here. Table 11 uses color coding to indicate the relative cost reduction potential for each mCDR pathway and, given that most pathways are in very early stages and there are limited data available, the assessment is largely qualitative. The color coding indicates the relative importance of the factors in achieving cost reduction.

Table 11. Qualitative Assessment of the Impact of Critical Innovations to mCDR Pathways

Pathway	Sub-Pathway	Energy Efficiency	Component Durability	Supply Chain, Coproducts	Process Co-Benefits	MRV	Ecosystem Impacts	Social License
Direct ocean capture	Electrochemical	High	High	High	Low	Medium	Low	Medium
	Chemical	Medium	High	High	Low	Medium	Medium	Medium
Ocean alkalinity enhancement	Electrochemical	High	High	High	Medium	High	Medium	High
	Chemical	Medium	Low	High	Medium	High	High	High
Photosynthesis-based approaches	Macroalgae sinking	N/A	Low	Low	N/A	High	Medium	Medium
	Macroalgae bioproducts	N/A	Low	High	High	Medium	Medium	Low
	Ocean fertilization	Medium	N/A	N/A	Low	High	Medium	High
	Artificial upwelling	High	High	N/A	Low	High	Medium	Medium
	Coastal blue carbon	N/A	N/A	N/A	High	Medium	Low	Low

Low: Potential for innovation in this category to increase trust or reduce the cost of mCDR by <10%.
Medium: Potential for innovation in this category to increase trust or reduce cost of mCDR by 10%–25%.
High: Potential for innovation in this category to increase trust or reduce cost of mCDR by 25%–50%.
Very High: Potential for innovation in this category to increase trust or reduce cost of mCDR by >50%.
N/A: Category not appliable to this mCDR pathway.

Based on this qualitative assessment, the SME survey, and the technical challenges noted in Table 10, we have identified the following prioritized incremental and disruptive innovation opportunities for mCDR.

Materials R&D: Key innovation opportunities for engineered mCDR systems such as electrochemical OAE or DOC involve improving durability of membranes, alloys, and electrodes and other system components in harsh marine environments to reduce capital and operational expenses. Currently, the lack of durable materials imposes significant pretreatment of seawater, adding to overall process costs, and may limit system siting to couple with existing water treatment infrastructure. Such materials advancements could also reduce system energy use, which is another key cost reduction opportunity. The durability of components and energy use is also a key cost driver for photosynthesis-based approaches such as artificial upwelling, where large-volume seawater pumping infrastructure is central to operation. Examples of specific materials R&D to lower pathway costs are included in Table 12.

Process Optimization: A second category of cost reduction opportunities across pathways is in the full supply chain—identifying feedstocks and coproducts to improve the economics of the overall process. This is particularly challenging considering the scales of mCDR needed to achieve climate goals and the often remote and rural settings of mCDR deployments. For electrochemical pathways, this translates to ensuring all coproducts are sustainably utilized and their carbon footprint is accounted for, and for chemical methods of OAE or ocean fertilization, the sourcing and transport of the alkalinity or nutrient is included in the full life cycle. For macroalgae cultivation, the costs of either sinking or alternatively the drying, transport, and processing of the biomass must be optimized for cost reduction and to ensure CDR. Finally, a key aspect of process optimization is in designing systems to be energy efficient through a combination of module design, operational control, and coupling to renewable energy sources. In the specific case of electrochemical DOC, processes that allow electrochemical reactions to proceed at high current densities and relatively low overpotentials will be the key channel for realizing higher energy efficiencies. In the case of chemical processes utilizing photoacids, significant efficiency gains may be achieved by pursuing the development and synthesis of metastable photoacid absorbers that display high absorptivities and quantum yields across a wide range of wavelengths in the terrestrial solar spectrum.

Uncertainty Reduction: Across mCDR pathways, MRV remains an area of ongoing complexity with need for dedicated research and development. Calculating volumes of CO_2 uptake as a result of downstream ocean-air equilibration, with acceptable degrees of accuracy, will require complex modeling to understand the magnitude of resulting marine CO_2 uptake. Establishing accurate MRV methodologies will also represent a challenge for engineered systems driving in situ mineralization, as mineral carbonates will be metastable at oceanwater pH, and their partial redissolution and potential outgassing of CO_2 will be functions of local variances in ocean alkalinity. In the cases of macroalgal cultivation and sinking approaches, MRV will also be nontrivial, and will mandate models capable of describing rates of biological CO_2 incorporation into biomass, how biomass accumulation is impacted by differential ocean fertilization, and balancing accumulation against biomass decay rates (and subsequent CO_2 evolution that arises from cellular decomposition).

Table 12. Summary of Innovation Opportunities for mCDR Pathways

Innovation Type	
Incremental (“Line of Sight”)	**Disruptive**
Closed-loop processes will increase CDR certainty by improving the quality of measurements and models that contribute to MRV. **Enhancements of ion-exchange membrane performance and lifetime** will reduce capital and operational expenses, particularly by alleviating pretreatment requirements. **High-density cultivation capabilities** for photosynthetic approaches to mCDR will improve scalability of CDR, the uncertainty of MRV, and the potential for coproduct uses, such as biomaterials production. Current low yields limit synergistic operation pathways. **Energy efficiency improvements** through system design and operation are especially critical to compensate for high energy needs, particularly from the pumping of seawater across all methods of mCDR.	**Low-cost, high-sensitivity carbon flux sensors for distributed monitoring** will transform open-system mCDR monitoring, contributing substantially to high-quality MRV by reducing the costs of increased spatial and temporal monitoring, as well as potentially improving the pathways for model validation, reducing uncertainty in other areas as well. Given significant potential co-uses for these sensing capabilities, these could also become widely adopted outside the mCDR industry. **Durable system components to eliminate the need for pretreatment of seawater** will allow mCDR to scale beyond current infrastructural limitations. Current economic viability in many cases depends on shared pretreatment processes, such as desalination or wastewater treatment facilities. Decoupling mCDR from these industries will enable the industry to maximize deployment opportunities. Pathways to **enhance primary productivity** of marine photosynthetic organisms can increase CDR. Addition of chemical nutrients is known to accelerate primary productivity but can have unintended ecosystem impacts when conducted at scale. Some of these impacts can be minimized if nutrient delivery methods are developed that offer higher process control, lower nutrient dosing, and do not rely on environmentally persistent chemicals. **Sustainable coproduct uses** will create synergistic deployment opportunities and additional revenue streams for mCDR, improving the economic viability of these pathways, as well as eliminate disruptive or disqualifying waste generation.

5 Quantifying the Potential Impact of Technological Innovation on CDR Costs

In the prior sections of this report, we presented a primarily qualitative assessment of opportunities for technological innovation that would result in significant reduction in the cost of carbon removal. More detailed quantification of the cost impact of specific innovations are needed to prioritize RD&D investment. While there are some innovations that may be applicable to multiple pathways, the relative importance and specific cost impact of a technological innovation will be dependent on the technology pathway.

Therefore, what is required to adequately assess the impact of a technological innovation on the cost of CDR is a comprehensive process model for a complete CDR pathway, coupled to techno-economic analysis and life cycle assessment. The process model must have sufficient detail to be able to adjust parameters such as conversion efficiency and energy requirements at different parts of the process to quantify their impact. While process parameters may be defined as independent in process models (e.g., for a DAC technology, the cycle time and cycle capacity may be specified as independent parameters), in reality these parameters may be coupled, requiring knowledge from technology developers and practitioners to ensure that innovations proposed are grounded in physical reality. There may also be process-specific trade-offs that must be captured by the model to ensure that optimization is being performed in the correct and relevant physical regime. For example, increasing DAC fan speed at the cost of a higher energy consumption requirement may allow for shorter cycle time without sacrificing cycle capacity for adsorbent A with fast adsorption kinetics. However, the same increase in fan speed might have negligible impact on the cycle time and capacity for adsorbent B, with slow adsorption kinetics, that might be amenable to passive contacting approaches.

These process models must be coupled to techno-economic analysis and life cycle assessment in specific contexts to understand the impact of innovation on the quantity of net carbon removed and cost of CDR, as in (60). In the previous fan speed example, if the electrical energy requirement were increased in a location where the local energy is high carbon intensity and high cost, the benefit of reducing cycle time may be outweighed by emissions from electricity use or the high incremental cost of additional electricity use.

A waterfall chart is a succinct data visualization that shows the relative and cumulative impact of multiple technological innovations. However, care should be taken to ensure that the impacts are truly additive and that any dependencies are resolved. Additionally, the order in which interdependent innovations are applied may bias an uninformed reader. As an extreme example, a DAC innovation that reduces the cost of the adsorbent to zero may result in a significant reduction in cost; improvements in the adsorption capacity or lifetime of this adsorbent would then have little to no subsequent impact on the cost, which would bias R&D prioritization toward inexpensive adsorbents. Alternatively, a DAC innovation that creates an infinitely long-lived and effective adsorbent might render the cost of that adsorbent relatively negligible, and hence would bias R&D prioritization toward long-lived adsorbents. Visualization using waterfall charts must therefore be performed with realistic, but ambitious, expectations on the impact of innovation.

We present an illustrative waterfall chart for a DACS pathway that uses an electrically powered, low-temperature, solid sorbent DAC process paired with CO_2 storage through mineralization, either via CO_2(aq) or $scCO_2$ injection. We assess the cost of net CO_2 removal, joining techno-economic analysis with life cycle assessment by presenting the cost of capturing and sequestering net atmospheric CO_2, with any energy-related upstream emissions counting against net CO_2 removed. To highlight the role of location-specific nuances in this form of analysis, we compare results in the U.S. states of California and Washington, which affects the cost and carbon intensity of electricity and the performance of the technology due to differences in temperature and humidity.

For the DAC side of the pathway, we consider a number of the potential incremental innovations identified in expert survey results (as previously described in Section 4.1.4 and in Appendix A.3) focused on (1) regeneration energy demand (required to release the captured CO_2 from the sorbent and prepare it for the next capture cycle); (2) sorbent lifetime and sorbent cost; (3) cyclic time (the amount of time spent during the adsorption and desorption cycles that capture and release atmospheric CO_2); and (4) sorbent capacity (the amount of CO_2 a given sorbent can capture from the atmosphere in a single cycle). For the mineralization side of the pathway, we consider disruptive innovation from CO_2-enhanced critical mineral recovery as a revenue generation pathway, which was described previously in Sections 4.2.3 and 4.2.4. We consider moderate and aggressive cost reduction scenarios in both locations for the DAC process, based on the peer-reviewed literature, with a single cost reduction scenario presented for mineralization with a disruptive innovation. See Appendix B and Appendix C for detailed descriptions of each scenario.

Importantly, the cost reduction scenarios presented here do not represent a prediction of likely cost reductions, or an attempt to set an upper or lower bound on potential cost reductions for any DAC or mineralization technology. Instead, this is an illustrative analysis meant to highlight the value of joint techno-economic analysis and life cycle assessment for guiding RD&D priorities.

Figure 15 shows the results of this waterfall analysis. Reference cases in California and Washington highlight significant regional differences in the starting levelized cost for DAC, approximately \$1,100/tCO_2 in California vs. approximately \$820/tCO_2 in Washington. This is largely due to the higher cost of electricity, \$52.6/GJ_{Elec} in California, as well as its higher carbon intensity, 191 g-CO_{2eq}/kWh, increasing the cost of net CO_2 removal, as shown in the light blue bars labeled “Economic Burden from Upstream Emission.” Future work should examine the impact of specialized electricity contracts, in which DAC developers pay a price premium for renewable electricity with lower carbon intensity. Our economic model also captures the impact of local conditions on (amine-based) adsorbent DAC efficacy, with modest benefits in Washington due to the lower temperature of the simulated site compared with its counterpart in California.

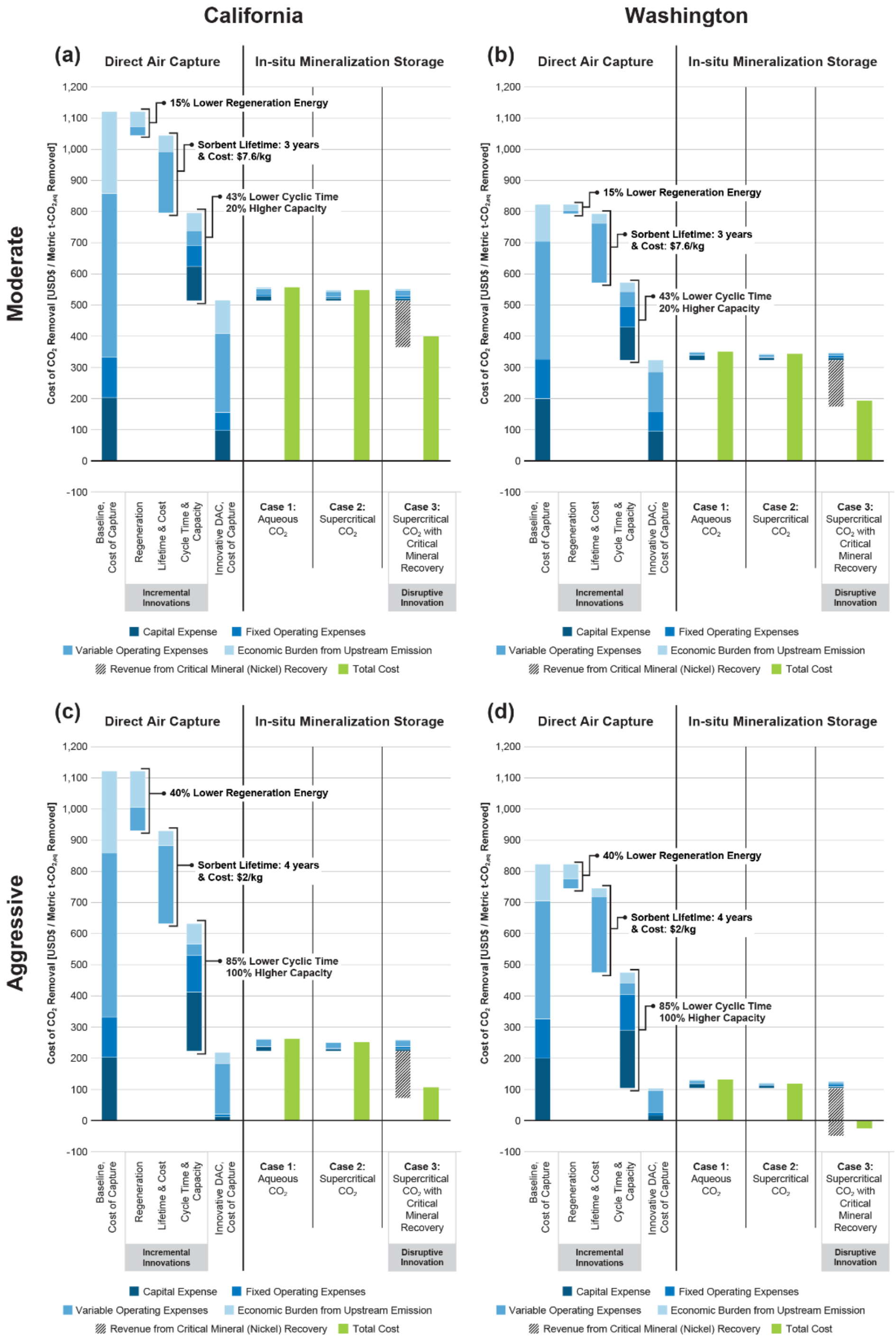


Figure 15. Waterfall chart illustrating possible impacts of selected technological advances in reducing the cost of CDR via DAC + mineralization

Separate analyses in California (a, c) and Washington (b, d) demonstrate regional variability in the impact of key technological advances. Cases (a) and (b) represent a moderate scenario for assumed technological innovations in DAC, while cases (c) and (d) represent an aggressive scenario. All scenarios show the impact of different cases (i.e., aqueous CO_2, supercritical CO_2, and supercritical CO_2 with nickel recovery) for mineralization. While we included revenue generation from co-products (i.e., recovered nickel) of CDR in these cases, market analysis is needed to ensure that increasing supply can be supported by demand and that product quality meets required specifications. Full details on the analysis and modeling are provided in Appendix B and Appendix C.

Along with switching location, cost reductions can be achieved through technological innovation that impacts the performance of the DAC process. While the magnitude of the cost reduction possible is dependent on the specific innovation and the improvement proposed, all of the incremental innovations result in meaningful reduction in the cost of CDR. While the cost reductions proposed are not intended to be predictive of likely outcomes that are simultaneously achievable in a single system, the magnitude of improvement for each innovation is supported by literature data that suggest such an improvement might be possible, as detailed in Appendix B. A sensitivity analysis on the California Moderate Scenario Case is also provided in Appendix B to understand the relative impact of each variable on cost.

In the moderate scenario for DAC, reducing regeneration energy by 15% (239) results in a 7% and 4% decrease in the cost of CDR in California and Washington, respectively. This difference is due to the differences in carbon intensity and cost of electricity in the two states—in locations with higher carbon intensity or higher cost of electricity, the reduction in regeneration energy is more impactful. Increasing the sorbent lifetime from 2 to 3 years and reducing the sorbent cost from \$20/kg to \$7.60/kg (20) results in a >20% decrease in the cost in both locations. As discussed in Section 4.1.3, the actual sorbent lifetime is highly dependent on the specific chemistry used in the DAC process, and the extent to which this parameter can be significantly improved is currently unclear. Finally, a 43% decrease in cycle time and 20% increase in sorbent capacity (240), which together roughly double the annual amount of CO_2 captured by the sorbent over the baseline, results in a >25% decrease in the cost due to the sorbent being used more efficiently.

In the aggressive scenario for DAC, all technological advances are made even better: a 40% decrease in regeneration energy, 4-year lifetime of sorbent and sorbent cost of \$2/kg (241), and an 85% decrease in cyclic time and doubling of sorbent capacity, resulting in more than a 10-times improvement in the amount of CO_2 captured by the sorbent over the baseline, yielding significant overall cost reductions. In these cases, the cost of using DAC to produce a stream of CO_2 suitable for storage falls by 80% in California, to \$220/t, and by 87% in Washington, to \$100/t.

To form a complete CDR pathway, DAC, with the innovations proposed above, is paired with CO_2 mineralization. Cost reductions from switching the injection method from aqueous to supercritical mineralization are 28% and 44% for California and Washington, respectively, but because sequestration cost represents at most 24% of DACS cost in the lowest-cost case analyzed (i.e., Washington aggressive scenario), the effect of these injection strategy cost reductions is a relatively small contributor to overall DACS pathway cost reductions. However, when integrating a disruptive mineralization innovation (i.e., $scCO_2$ injection with enhanced critical mineral recovery) with the DAC process, more significant cost reductions can be delivered that lead to tangible cost reductions for the overall DACS pathway.

Disruptive technologies can result in further significant reductions in overall cost for the CDR pathway, and in some cases result in production of enough revenue to make the process profitable (under the assumptions of our analysis). For example, in California, combining enhanced metals recovery with $scCO_2$ reduces the cost of the DACS pathway by 26% relative to the DACS pathway using $scCO_2$ storage without enhanced metals recovery in the moderate scenario, and by 57% in the aggressive scenario (assuming BASE nickel price; see Table C-4 in

Appendix C). In Washington, the disruptive innovation reduces the cost of the DACS pathway by 43% relative to the DACS pathway using $scCO_2$ without enhanced metals recovery in the moderate scenario and leads to positive revenue generation in the aggressive scenario (assuming BASE nickel price; see Table C-4 in Appendix C). The revenue provided by the sale of recovered nickel allows the overall DACS pathway to achieve profits of approximately \$26/tCO_2—excluding any profits from carbon credits on the voluntary carbon market or tax incentives such as 45Q. Sale of CDR on the voluntary market and leveraging policy incentives would make this pathway even more profitable. However, we do note that this enhanced metals recovery disruptive innovation is still at an early stage of development, and thus there is considerable uncertainty around the costs associated with this approach (see Appendix C for more details).

As demonstrated above, a waterfall chart can be powerful in helping to assess the impact of technology innovation, including location-specific effects. To this end, we recommend that this type of analysis be performed for other CDR technologies and multiple, specific pathways within each technology class to help guide R&D prioritization.

This type of analysis can also be used to track innovation progress in relation to the Carbon Negative Shot. A systematic modeling effort, coupling techno-economic and life cycle assessment for all key pathways of interest to the Carbon Negative Shot, could translate achieved and targeted technological advances in specific subsystems (e.g., energy efficiency improvements or increases in process or reaction speed) into a quantitative assessment of overall implications for the levelized cost of CDR.

The science of translating lab-scale results into cost reductions at scale is necessarily uncertain, but the more quantitative and rigorous the impact assessment mechanism used, the more likely critical RD&D funding will be allocated toward a portfolio of projects with the desired combination of overall impact and likelihood of success. Furthermore, the use of detailed location-specific case studies will highlight important considerations in RD&D allocation, illuminating technical advances that may be promising across a wide variety of deployment locations, or promising areas of focus that are possible only in specific climates, environments, or energy market structures.

Such an impact evaluation effort can build on learnings from the optimization-based techno-economic assessment literature to couple component capacity sizing decisions with operational decisions, especially for systems relying on variable renewable electricity. Such an approach enables assessment of the value of various forms of energy and material storage, process-level operational flexibility (e.g., ramping speed), and other potentially critical RD&D priorities.

6 Conclusions and Future Directions

In our fight against climate change, time is our most limited resource. Our intent is that this report serves as a resource for researchers, funding agencies, and policymakers to guide and prioritize R&D focused on CDR technological innovation, thus ultimately helping to maximize our impact from time spent on R&D. By leveraging diverse technological, modeling, and analysis expertise from across the DOE national lab complex and feedback from an external advisory board and SMEs, we aimed to provide a balanced and vetted assessment of the cost reduction potential, technical barriers, and research needs of several CDR approaches (DACS, mineralization, BiCRS, and mCDR) in support of DOE's Carbon Negative Shot. Our report includes three key components for stimulating innovation in the field: (1) qualitative heat maps for each CDR pathway that help identify areas with the greatest potential for cost reduction; (2) identification, characterization, and prioritization of specific technological innovation opportunities; and (3) quantitative evaluation of the cost reduction potential of technological innovation for a single example case, DAC coupled with in situ mineralization. Collectively, our report highlights the value of technological innovation in driving down CDR costs and amplifies the need for cross-disciplinary R&D to realize these innovation opportunities.

With time as a limited resource, developing robust R&D strategies necessitates continuous feedback and tracking. Building off the foundation set by this report, future work is warranted to (1) expand the quantitative cost waterfall chart analysis demonstrated in Section 5 to other technologies across the four CDR pathways covered in this report, (2) leverage this analysis to track progress toward the Carbon Negative Shot cost target, and (3) deepen our understanding of critical crosscutting themes including impact of scale ("rightsizing systems"), location-specific performance (e.g., feedstock [air, biomass, rock, and ocean water] properties depend on location and local environment), quantification of co-benefits, and integration of CDR systems with existing industrial processes. A key enabler of this future work, and the growth of this industry, is CDR performance data.

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Appendix A. Subject Matter Expert Survey Methodology and Key Results

A.1 Introduction and Objectives

One of the methods for gathering data for this report involved conducting a subject matter expert survey. The goal of the survey was to vet our analysis, assumptions, and interpretations with CDR experts from around the world for the cost reduction potential through technological innovation, as well as to identify research gaps of various CDR approaches and expand diversity of the input included in the report. This process was crucial for ensuring the report accurately reflects the current state of CDR technologies and policies while also anticipating future trends and challenges within this evolving field.

A.2 Survey Methodology and Execution

A list of 123 SMEs was identified based on their involvement in the CDR space. Attention was given to identifying experts that represented a variety of organization types (academia, industry, non-academia research, government, and nongovernment). Area of subject matter expertise was decently distributed across the group; however, nearly twice as many SMEs were identified for mCDR. In our initial list, three identified SMEs were identified for multiple pathways.

SMEs were invited to participate in an informational webinar via email on the purpose of the survey, how the survey would be conducted, and how the results would be utilized. The webinar session included a structured presentation followed by an interactive question-and-answer session, allowing SMEs to delve deeper into the survey's scope and clarify any queries they had regarding the survey process or expected outcomes. Two weeks were allotted for SMEs to submit their responses, during which several reminders were emailed to encourage participation and ensure that all invited experts had the opportunity to contribute their expertise to the survey.

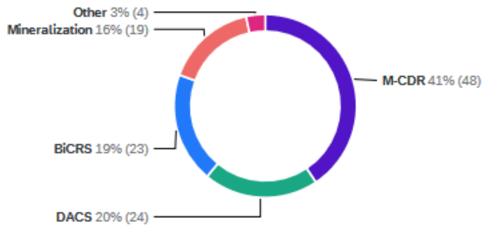
The survey was conducted online, utilizing publicly available web-based survey software, which provided a user-friendly interface for respondents. Upon entering the survey, respondents were presented with a question asking them to self-identify their area(s) of CDR expertise (multi-select enabled). Based on their selections, they were presented with questions specific to the pathway(s) tailored to their expertise. DACS, mineralization, and mCDR pathways had 22 questions; BiCRS had 26 questions. The questions for each pathway mirrored one another, with minor adjustments as necessary to make the questions applicable to the pathway. The additional questions for BiCRS were around feedstock selection and carbon storage methods used in the respondents' own work.

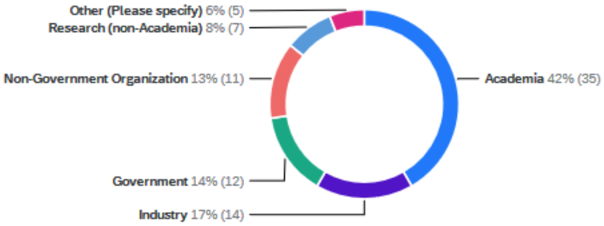
A.3 Results

Survey results were collected from 84 participants (67% response rate). Of the responses, 24 were received for DACS, 19 for mineralization, 23 for BiCRS, and 48 for mCDR (114 total records). Multiple respondents indicated that they had expertise in more than one field, which is why the number of records is greater than the number of respondents.

Data from this survey were collated to provide feedback on prioritization of research, development needs, and opportunities for technology innovation aimed at cost reduction across various CDR approaches. Most questions had respondents select from a list or rank order a list;

however, several questions provided a write-in space for more detailed answers, to include explanations of why respondents answered in the manner they did. All responses were anonymized in the results to ensure confidentiality. Charts and graphs of interest are presented here, as well as insight obtained from text-based responses.

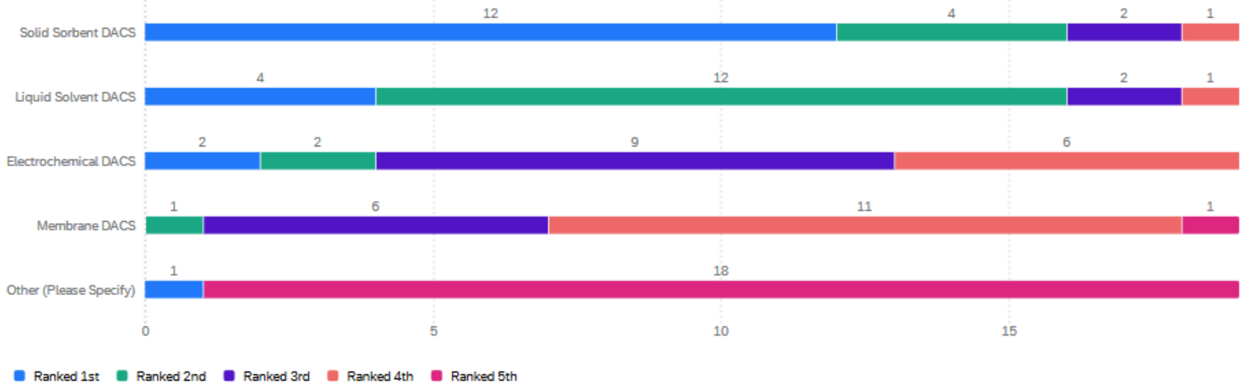

What CDR sector do you have experience in? (multi-select enabled)


What term best describes the type of organization under which you conduct CDR work? (multi-select enabled)

DACS Survey: Select Questions and Responses

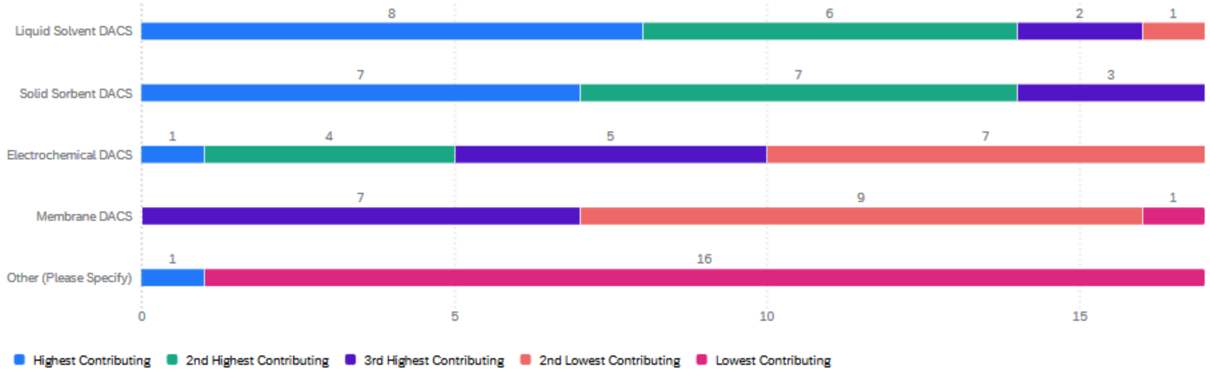
The following is a selection of the questions presented to respondents who self-identified as having DACS experience, along with charts illustrating responses. In a few cases, summaries of respondents' reasoning behind their answers are also included.

Which category of DACS do you believe will contribute the most to achieving the net-zero target by 2050?



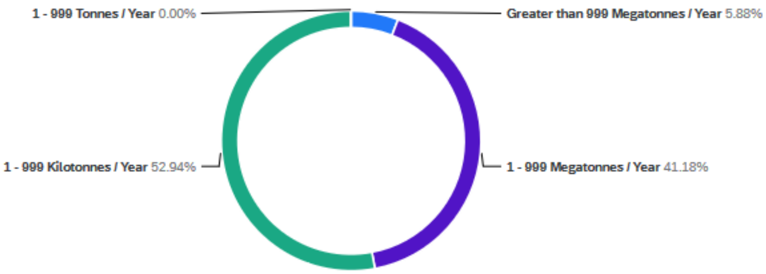
In a follow-on question ("Explain the reasoning behind the order you chose"), many respondents cited TRL, cost, opportunities for cost reduction, materials availability, scalability, and energy requirements as factors behind their ordering.

Which category of DACS do you believe will be the most scalable in the near-term future (by 2030)?



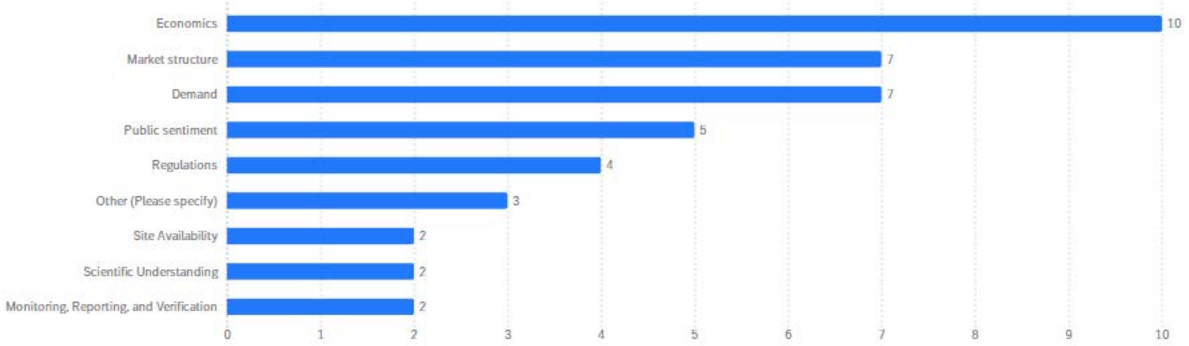
In the follow-on question asking respondents to explain the reasoning behind their ordering, many respondents cited the same reasons as the previous question (highest contributor to achieve net-zero by 2050). Specific mentions were given to the relatively low cost of DAC solvents, as well as their technological maturity—even though it has not been demonstrated at a scale as large as solid sorbent DAC yet.

What do you believe is the practical upper bound (net removal) for a single installation of a DACS project (consider the technology you believe most promising)? Please consider relevant factors such as availability and cost of renewable energy, financing, siting/space limitations, CO_2 offtake, etc.

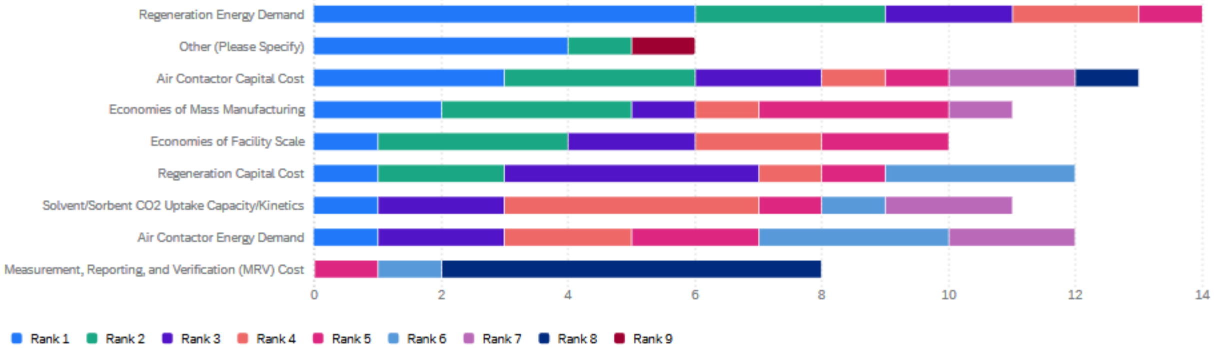


Nearly all respondents cited liquid solvent or solid sorbent-based DAC methods as the DACS technology considered. However, a few respondents brought up constraints such as siting and storage being limiters, and that multiple installations would benefit from economies of scale and net greater results.

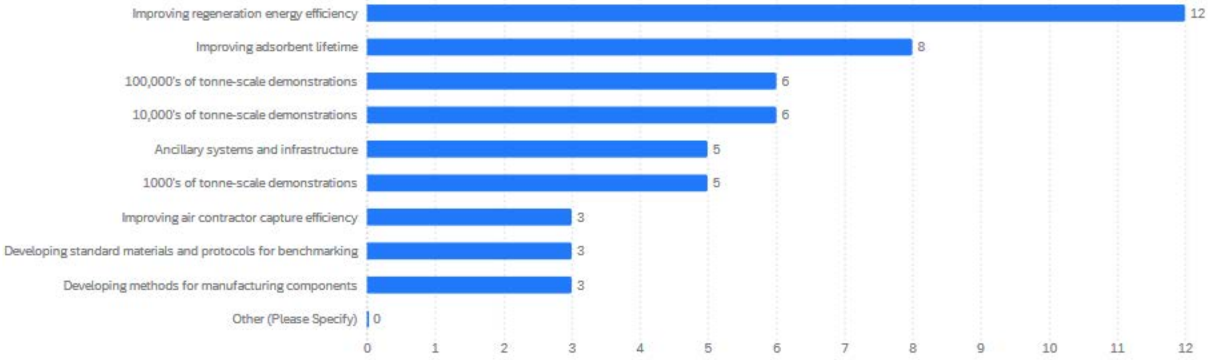
In your option, what is (are) the most limiting factor(s) to global deployment for DACS? Select more than one if you deem their impact of similar magnitude.



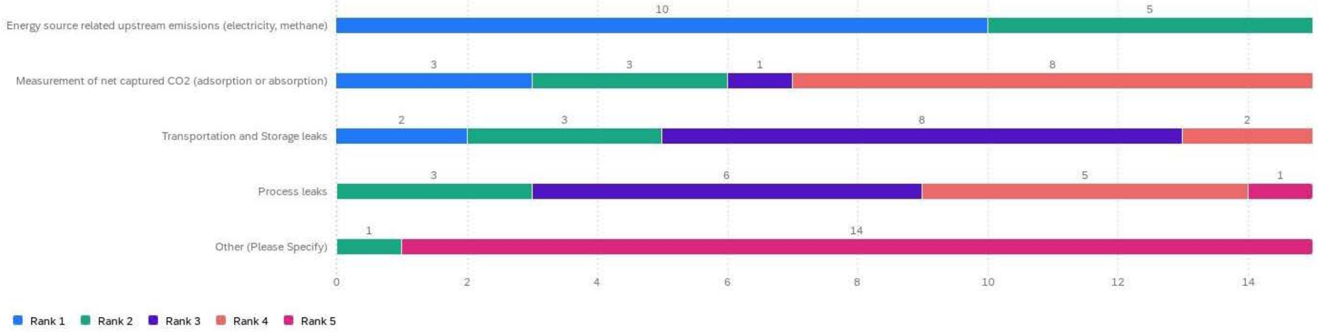
What do you believe are the most sensitive economic drivers to bring down the cost of DACS (US$/tonne)? Please rank the following by numbering (1, 2, 3…) with 1 being the most sensitive, going as far as you see value and omitting those that you don't view as significant drivers.



What are the top areas where we should be directing the bulk of investments for DACS technology development? Please select 3.



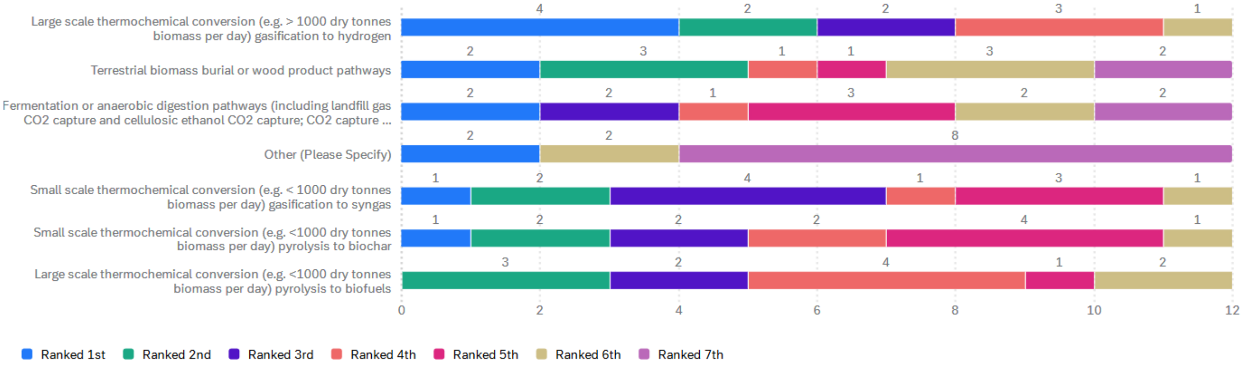
Which aspect of the DACS process is the most uncertain in terms of Measurement, Reporting, and Verification (MRV)?



BiCRS Survey Responses

The following is a selection of the questions presented to respondents who self-identified as having BiCRS experience, along with charts illustrating responses. In a few cases, summaries of respondents' reasoning behind their answers are also included.

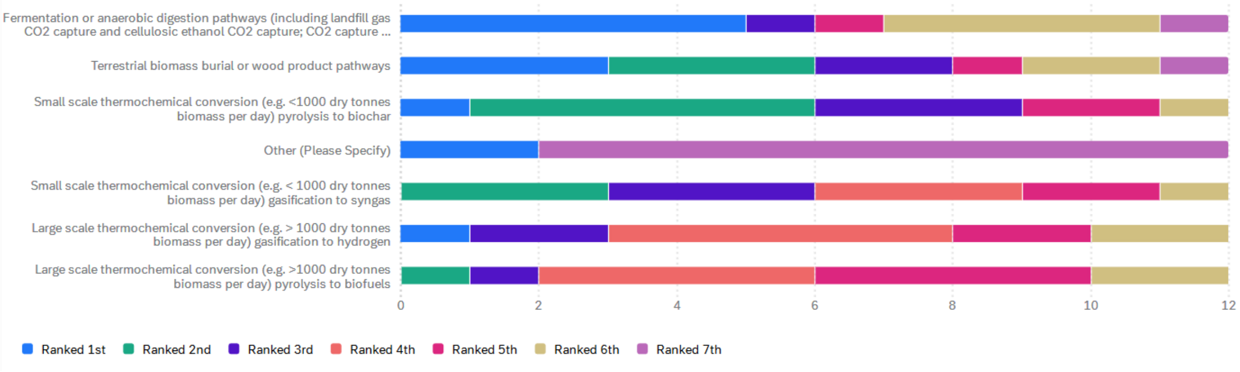
Which category of BiCRS do you believe will contribute the most to achieving the net-zero target by 2050? Consider economic viability in your selection.



Of note was one of the respondents listed a "hub-and-spoke" model as their consideration for "Other," where a medium-scale pyrolysis facility would transport bioliquids to a large-scale, centralized facility for gasification to hydrogen.

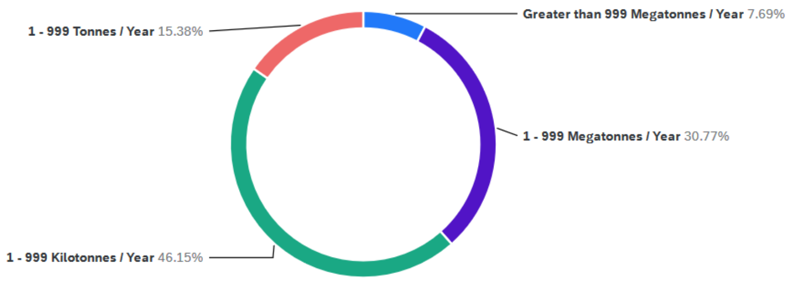
As for the reasoning behind their rankings, respondents were quite varied in their justification. Points that were brought up include the simplicity of biomass burial and the value of byproducts generated (e.g., hydrogen). However, conflicting opinions also arose, such as gasification being the most cost-effective to one respondent yet being expensive and complicated to another respondent.

Which category of BiCRS do you believe will be the most scalable in the near-term future (by 2030)?



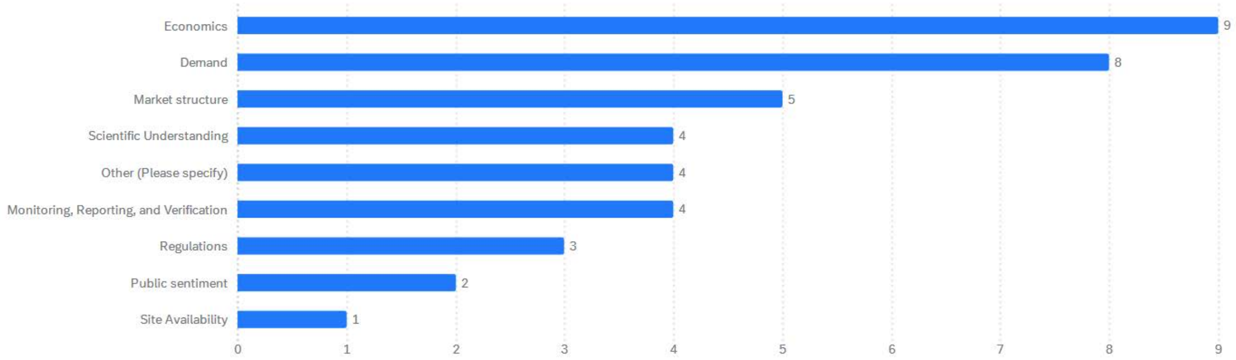
The reasons that respondents cited for their ordering for this question were as varied as the previous question, but two points stood out: the relative ease, simplicity, and feedstock availability of biomass burial; and the simplicity of pyrolysis and fermentation. The combination of fermentation or anaerobic digestion with CO_2 capture was the most common option to be ranked first, likely because of the reduced cost and technological complexity of capturing concentrated CO_2 streams from these processes (in contrast to post-combustion CO_2 capture). For example, some ethanol facilities already capture their CO_2 for use in enhanced oil recovery or food and beverage manufacturing. Similarly, CO_2 streams from biogas upgrading to renewable natural gas can be captured.

What do you believe is the practical upper bound (net removal) for a single installation of a BiCRS project (consider the technology you believe most promising)? Please consider relevant factors such as availability of feedstock, financing, siting/space limitations, CO_2 offtake, etc.



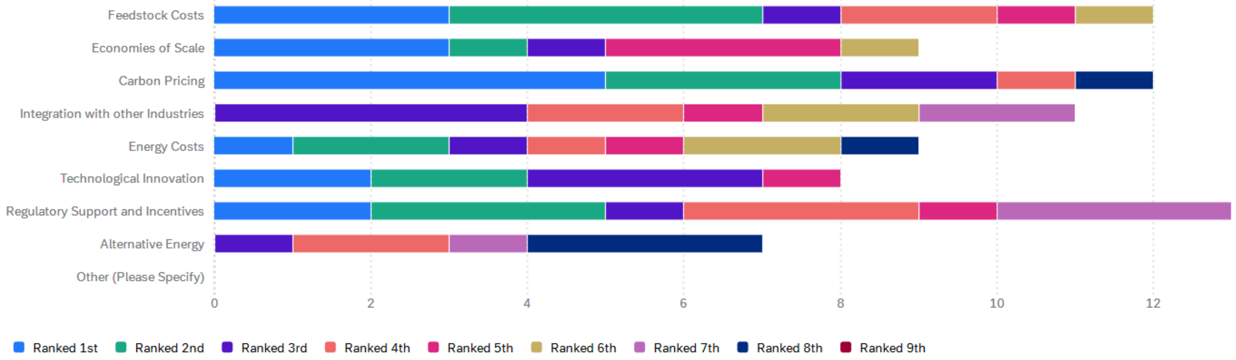
A common limiter to single-installation upper bounds was the availability of nearby feedstock. The cost of transporting biomass by truck can become prohibitively expensive at long distances, and these costs grow as the radius in which facilities must source feedstock increases. For longer distances, other modes such as rail and barge may be more cost-effective than truck but can still contribute to higher delivered biomass costs. Biomass availability can also be a problem for larger facilities, if local availability/production fluctuates year-to-year based on climate conditions or other factors.

In your opinion, what is (are) the most limiting factor(s) to global deployment for BiCRS? Select more than one if you deem their impact of similar magnitude.



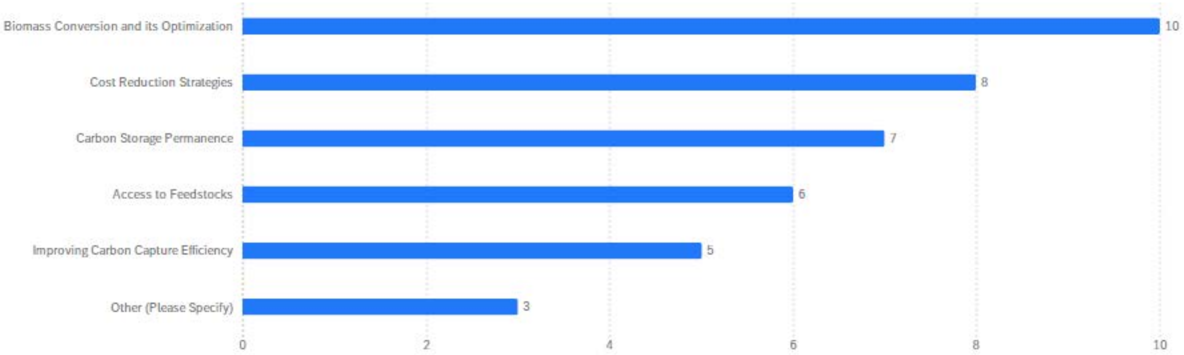
Experts identified economics as the most limiting factor for BiCRS. Even if *n*th-plant economics appear to be favorable, there are limited studies on the cost of first-of-a-kind plants, also known as pioneer plants. This may be one reason for the disconnect between studies indicating cost-competitiveness of BiCRS relative to other CDR methods and the challenges in scaling up BiCRS (excluding biochar).

What do you believe are the most sensitive economic drivers to bring down the cost of BiCRS (US$/tonne)? Please rank the following by numbering (1,2,3…) with "1" being the most sensitive, going as far as you see value and omitting those that you don't view as significant drivers.



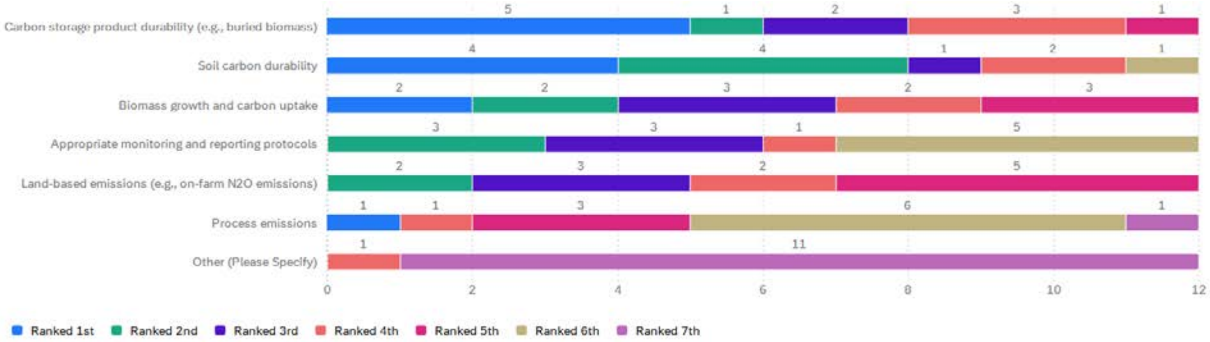
Experts identified carbon pricing, which could improve the economics of BiCRS facilities if buyers pay higher prices for carbon removal. Feedstock costs and economies of scale both received the second most votes as the top driver, which can address operating costs and capital costs, respectively.

What are the top areas where we should be directing the bulk of investments for BiCRS technology development?



Experts highlighted the importance of biomass conversion technologies and the need for technological progress. The cost of conversion processes, and their ability to handle mixed feedstocks, continues to be a challenge and requires more work to optimize and scale up these processes.

Which elements of BiCRS Monitoring, Reporting, and Verification (MRV) are the most challenging/uncertain?

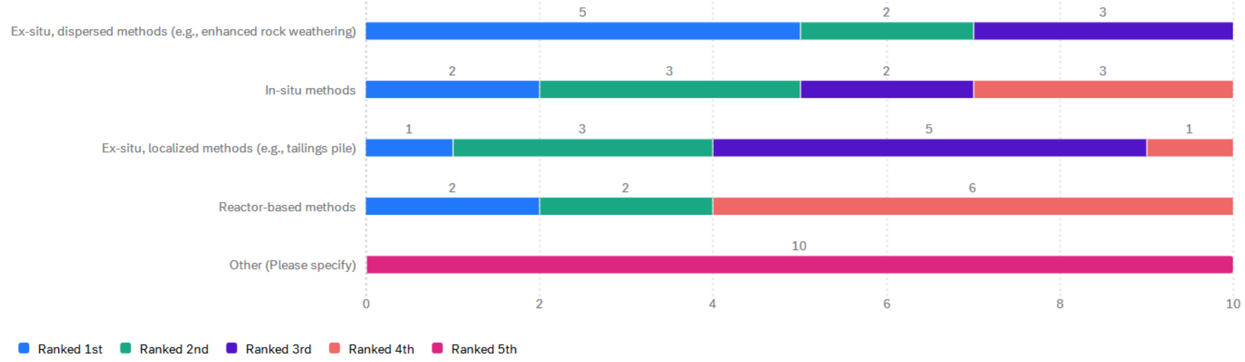


Experts noted durability, including both buried biomass and soil carbon, as being a major challenge for BiCRS. This can also extend to other carbon storage materials, such as bio-oil.

Mineralization Survey Responses

The following is a selection of the questions presented to respondents who self-identified as having mineralization CDR experience, along with charts illustrating responses. In a few cases, summaries of respondents' reasoning behind their answers are also included.

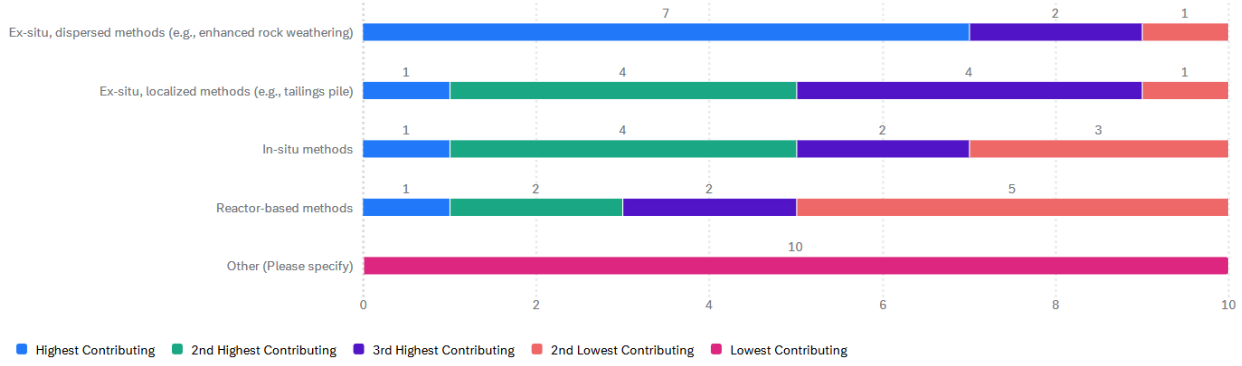
Which category of mineralization CDR do you believe will contribute the most to achieving the net-zero target by 2050? Consider economic viability in your selection.



Respondents highlighted the ease of deployment and significant theoretical potential of ex situ, dispersed methods (e.g., ERW) as justification for this method contributing most to net-zero targets by 2050. However, respondents also emphasized the difficulty with MRV in open systems. The substantial theoretical potential for ex situ, dispersed methods (i.e., ERW) may be overshadowed by the difficulty with MRV, unless innovative technologies or practices are developed that remove barriers to MRV. Specific challenges cited included issues with confirming whether charge balance of cations is from bicarbonate and not nitrate or other components, and that mass balance calculations will be difficult or impossible for MRV. Uncertainty remains for the scalability of localized vs. dispersed ex situ methods and whether these technologies can have a significant impact beyond an industry level (i.e., decarbonization of mining). Also highly mentioned were contained, reactor-based methods, due to their scalability and ease of MRV. Other respondents cited reactor systems as having a lower maximum potential due to other ex situ techniques likely becoming more technically and economically feasible at scale due to lack of significant CAPEX requirements and little change in total cost of reactor systems over the past 20 years.

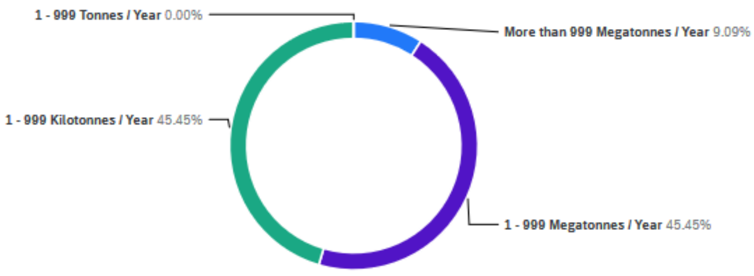
Respondents discussed the significant theoretical potential of in situ (geologic storage) mineralization technologies but emphasized that these techniques require significant infrastructure requirements and more site-specific constraints than other mineralization technologies. Moreover, the cost trajectory for these techniques largely depends on cost reductions of capture (e.g., from DAC or BiCRS), and thus the contribution to net-zero by 2050 will be closely tied to cost reductions and innovation from those technologies. There were differences in responses regarding the safety of these techniques, with some respondents citing the high efficacy and safety assured by mineralization and decades of carbon capture and storage experience, and others discussing the risks of high-volume subsurface CO_2 injection.

Which category of mineralization CDR do you believe will be the most scalable in the near-term future (2030)?



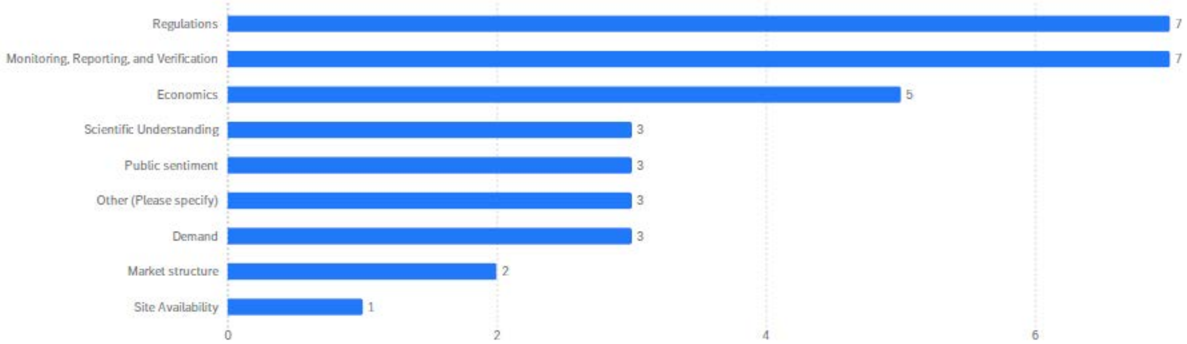
The TRL, scalability, and accessibility of ERW were highly cited as reasons why respondents selected their answers for near-term (by 2030) scalability. Additionally, the low implementation barrier and potential agronomic co-benefits were cited as drivers of early adoption of ERW methods. Resource requirements (reactive rocks and agricultural land) are abundant, and deployment methods (i.e., spreading on fields) can be integrated within existing practices. However, the uncertainty associated with potential risks of trace element leaching and surface water contamination from these methods may be a factor not captured by these results, in addition to the difficulties cited by respondents with MRV and quantification. For ex situ methods, increased mining industry interest and existing concentrated mineralization feedstocks (i.e., tailings piles) makes the ease of implementation by 2030 easier than other methods requiring new-build infrastructure. Respondents cited mineralization using industrial waste (i.e., steel slags and fly ash) as being readily implementable today, but with an eventual capacity/potential limit that may not be reached until beyond 2030 when existing waste feedstocks run out. Respondents emphasized that while in situ methods have high TRLs today, with multiple commercial operations ongoing, the long lag time of infrastructure deployment and permitting could reduce the scalability of these technologies by 2030.

What do you believe is the practical upper bound (net removal) for a single installation of a mineralization CDR project (consider the technology you believe most promising)? Please consider relevant factors such as availability and cost of renewable energy, feedstocks, financing, siting/space limitations, CO_2 offtake, etc.



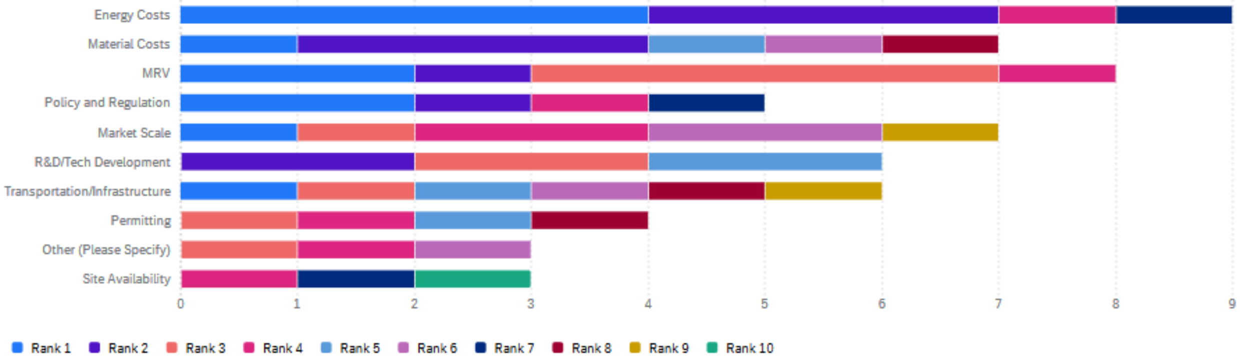
Most respondents indicated the likely upper bound for a single installation of mineralization CDR is between 1 and 999 kilotonnes/year or 1 and 999 megatonnes/year. The technology most cited as “promising” to reach this scale was ERW. Respondents believe that the restricting factors for this scale include the availability of suitable land for ERW, which may be overestimated in current models, feedstock and distribution network availability for dispersal, and limits from safety risks and MRV difficulties with single installations greater than the scale mentioned. For reactor and ex situ methods, the availability of existing mine tailings or other alkaline industrial wastes will limit the scale of a single installation. For in situ methods, respondents cited the availability of renewable energy, infrastructure, and permitting for large-scale projects as limiting factors to maximum scale. However, respondents cited the significant theoretical storage potential (gigatonne scale) of onshore and offshore basalts as possibly pushing the upper bound for single projects—or a network of projects—beyond the megatonne scale. Ultimately, across all technologies, project siting and space limitations were identified as the single largest limiting factor for scale of an installation.

In your opinion, what is (are) the most limiting factor(s) to global deployment for mineralization CDR? Select more than one if you deem their impact of similar magnitude.



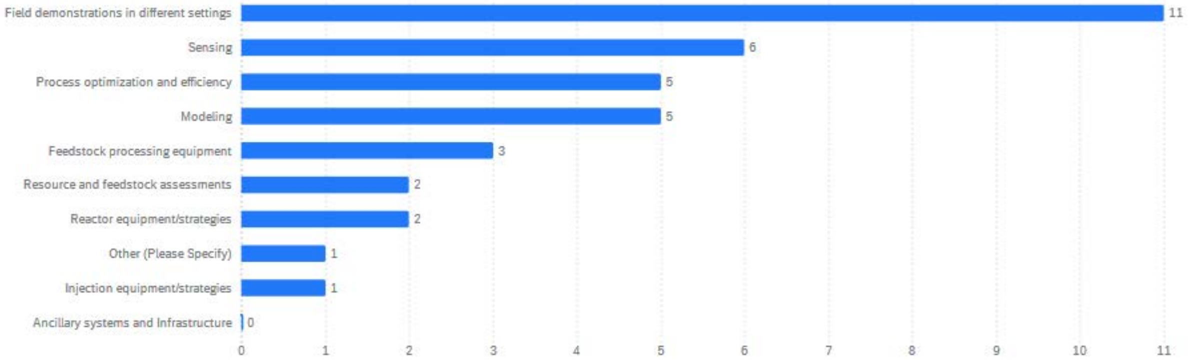
While respondents clarified that the limiting factors to global deployment of mineralization CDR depend on the mineralization technology employed, there are clear trends related to regulations and MRV that are crosscutting for all mineralization CDR technologies. Safety and health concerns related to potential trace metal leaching or contamination from ERW could prevent permitting/regulation of these technologies. Difficulties with accurate quantification of ERW could prevent acceptance of MRV and quality assurance of CDR produced by these methods. Delays in permitting Class VI CO_2 injection wells for all CO_2 storage could similarly delay in situ mineralization storage projects. Other concerns listed by respondents included quantification of co-benefits and defining how co-benefits should be addressed in these projects to reduce barriers to deployment and that, in general, the TRL for ex situ and ERW methods is still relatively low (demonstration phase), or the methods are too expensive.

What do you believe are the most sensitive economic drivers to bring down the cost of mineralization CDR (US$/tonne)?



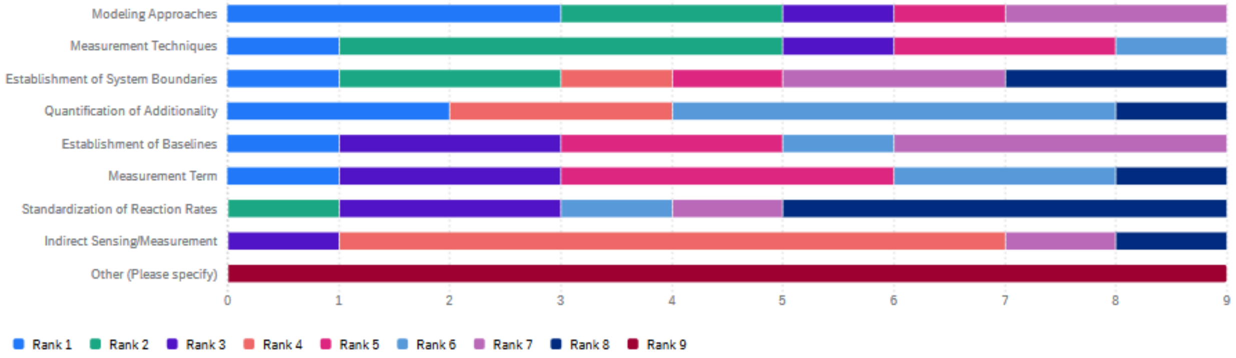
Most respondents cited high energy costs as the main driver to reduce the cost of mineralization CDR. Secondary cost drivers included material costs for construction or procurement of feedstocks, MRV costs, and costs associated with regulatory compliance. Other cost drivers specified by respondents included co-benefits that may not be captured in current cost estimates for these technologies—for example, agronomic co-benefits of ERW that could offset purchase of fertilizer (i.e., quicklime) or enhanced critical mineral recovery potential of ex situ or in situ mineralization methods.

What are the top areas where we should be directing the bulk of investments for mineralization CDR technology development?



Respondents significantly focused on field demonstrations as the avenue for accelerating mineralization CDR development and deployment. Given the low TRL of mineralization CDR technologies (excluding in situ), field demonstrations are needed to develop baselines for modeling, best practices for operation and MRV, and datasets to inform future deployments. This also ties into the next three most cited areas of investment: sensing, process optimization and efficiency, and modeling. Field demonstrations would provide significant testing of sensing methods, materials, and strategies that could reduce MRV costs and requirements. Demonstrating technologies in the field would furthermore lead to process optimization and efficiency improvements, while providing the necessary data to accurately model mineralization CDR processes. Other responses specified quantification of co-benefits, as this could directly lead to significant reduced costs or even revenue generation that could drastically shift the cost profile of mineralization CDR technologies.

Which aspect of the mineralization CDR process is the most uncertain in terms of Measurement, Reporting, and Verification?

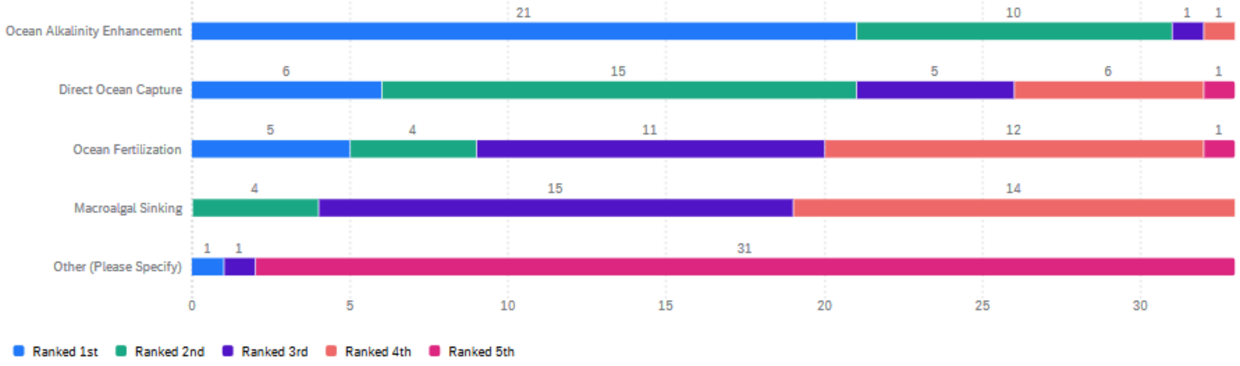


Respondents primarily cited modeling and measurement technologies as key factors for uncertainty within MRV. This may reflect earlier survey responses that emphasized developing modeling practices and measurement techniques (particularly for dispersed ex situ/ERW approaches) that can move toward broadly applicable MRV practices, rather than project- or site-specific practices. In addition, respondents emphasized in earlier responses that cheaper techniques like remote sensing or autonomous data collection could improve certainty by developing continuous data streams while reducing the cost of monitoring. Similarly, in situ mineralization techniques rely on reactive modeling techniques that suffer from lack of baseline conceptual models, standardized modeling approaches/tools, and uncertainty around implementing lab or field data in models.

mCDR Survey Responses

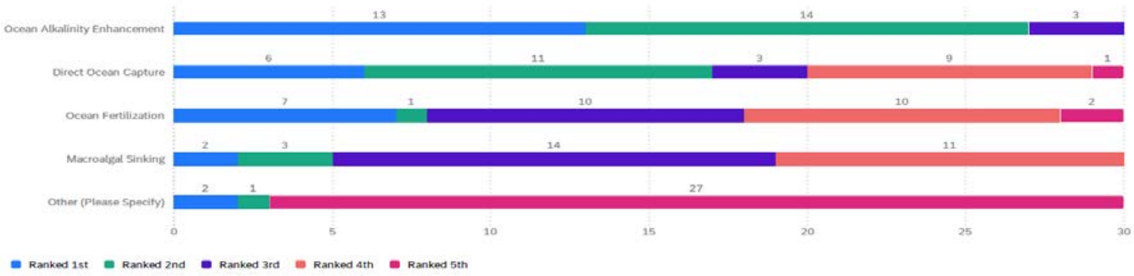
The following is a selection of the questions presented to respondents who self-identified as having mCDR experience, along with charts illustrating responses. In a few cases, summaries of respondents' reasoning behind their answers are also included.

Which category of mCDR technology will contribute the most to achieving the net-zero target by 2050? Consider economic viability in your selection.



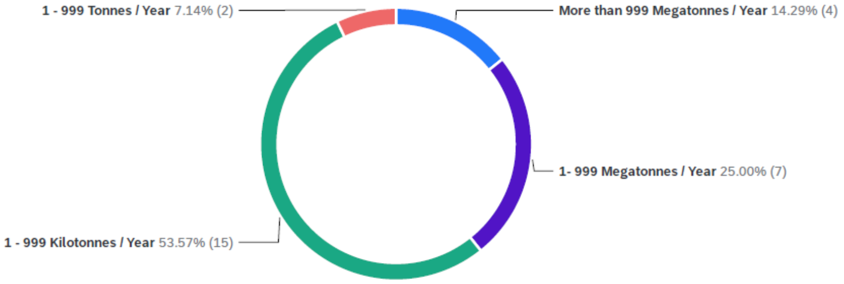
In a follow-on question asking respondents to explain the reasoning behind the order they chose and their relative confidence, responses were greatly varied. Abiotic methods such as OAE and DOC were both called out as being scalable, socially acceptable, and potentially lower cost. However, the risks of energy sourcing and MRV were factors decreasing confidence in these solutions. A few respondents called out the risks of biotic approaches being too great for them to be viable, such as MRV and environmental safety. The high proportion of “other” responses in the lowest-ranked category generally referred to restoration of coastal blue carbon ecosystems. Overall, many respondents indicated that more research was necessary to increase confidence across methods.

In your opinion, which type of mCDR technology will be the most scalable (operational) in the near-term future (by 2030)?



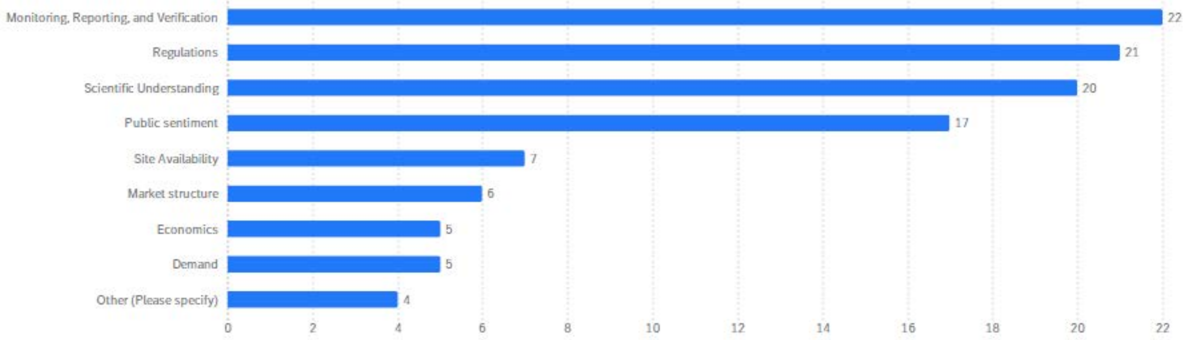
In the follow-on question asking respondents to explain their reasoning and relative confidence in their answer to the previous question (near-term future scalability), most respondents cited OAE and DOC as lower risk and higher TRL. Both methods are expensive, but respondents indicated that OAE may be cheaper than DOC, while DOC is likely to be more socially acceptable overall than OAE. Ocean iron fertilization was listed as potentially scalable but socially unacceptable. Coastal ecosystem restoration, the write-in, is most socially acceptable but potentially the least scalable. More economical competing use cases were listed as a factor limiting the scalability of macroalgal sinking. Note that MRV was listed as a scaling challenge for all methods. Overall, short-term scalability was sometimes evaluated based on social acceptance, cost, and differing aspects of technical readiness; respondents’ weighting and impression of these factors varied across methods.

What do you believe is the practical upper bound (net removal) for a single installation of a particular mCDR technology (consider the technology you believe most promising)? Please consider relevant factors such as availability and cost of renewable energy, financing, siting/space limitations, CO_2 offtake, etc.



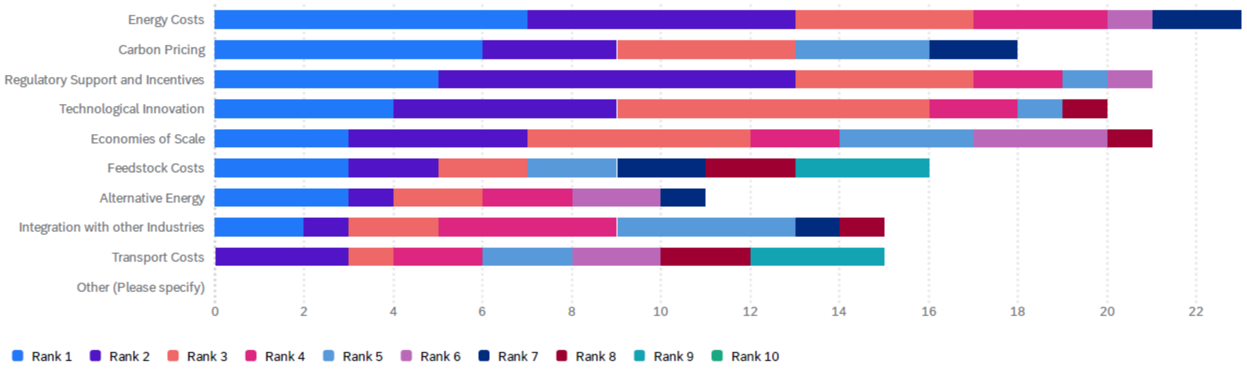
Regardless of method, more than half of respondents suggested that the upper bound a single installation could remove was 999 kt/yr, and an additional 25% suggested 999 Mt/yr. Accordingly, achieving CDR at scale would require many installations at different sites, and respondents sometimes listed siting and the number of sites as a potential limiting factor for scalability. Of the respondents, most selected OAE and DOC as the technology they considered most promising. Limiters cited include energy, transportation, social license, governance issues, infrastructure, environmental impacts, and feedstock availability.

In your opinion, what is (are) the most limiting factor(s) to global deployment of mCDR? Select more than one if you deem their impact of similar magnitude.



Most respondents indicated that MRV, scientific understanding, and public sentiment were the largest limiting factors for global deployment of mCDR. Of the entries listed in the “other” section (available technology, engineering efficiency, environmental impact, and technical feasibility), all could be attributed to limited scientific understanding. This reflects the earlier technological development level for these pathways. However, it should be noted that in a follow-on question, respondents stressed that while these factors are the most limiting, market structures and size will become important as these technologies commercialize.

What do you believe are the most sensitive economic drivers to bring down the cost of mCDR (US$/tonne)?



Here, most respondents shared concerns about energy availability and costs, regulatory support and incentives, and technological innovation—with issues related to carbon pricing and economies of scale also emerging as secondary concerns. Of the choices listed, respondents suggested that feedstock costs and transport costs were most likely to be of lowest concern. In a follow-on question, respondents also emphasized development choices, expressing the urgency of co-development of multiple technical pathways, renewable energy, and industrial integration as a high priority. In particular, parallel development of multiple CDR methods at once was suggested as a higher priority than focusing on a single technical pathway.

Respondent's opinion on the mCDR technology that holds the most potential for gigatonne-scale deployment by 2030 and the top two innovations that would help drive down costs:

While most respondents suggested that OAE was the most likely to deliver at scale, the second most comments suggested that no mCDR technology was likely to achieve the gigatonne scale by 2030, and that moving too quickly had the potential to limit social license. The top innovation that could drive down costs was overwhelmingly suggested to be models, measurement techniques, and new observing technologies that would improve MRV, although multiple other comments also suggested that improved membranes would also help drive down costs. Political will, energy availability, safe storage, environmental impacts, field studies, feedstock availability, and deployment efficiency were also mentioned at low frequencies.

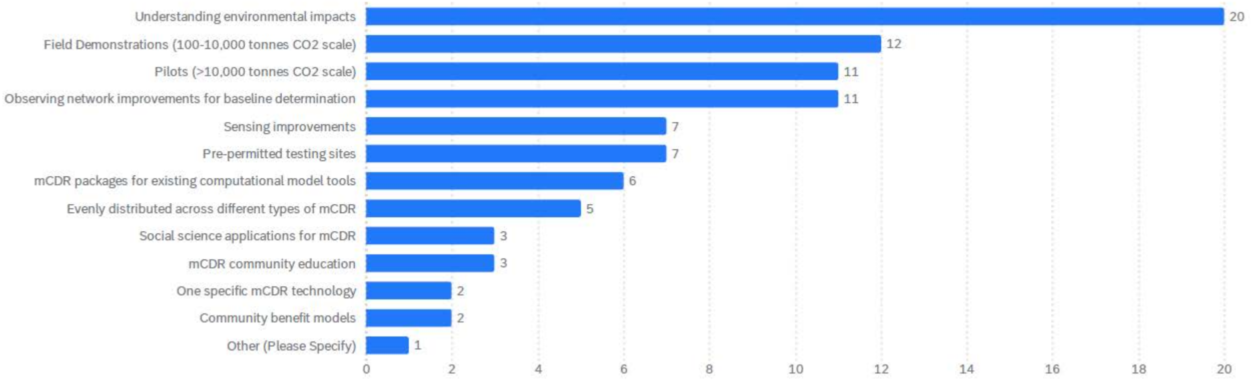
Do you believe the R&D challenges facing mCDR development are primarily in Basic Research needs or Applied Research needs?

and

Respondent's opinion on allocation of a fixed budget for mCDR RD&D to maximize return on investment:

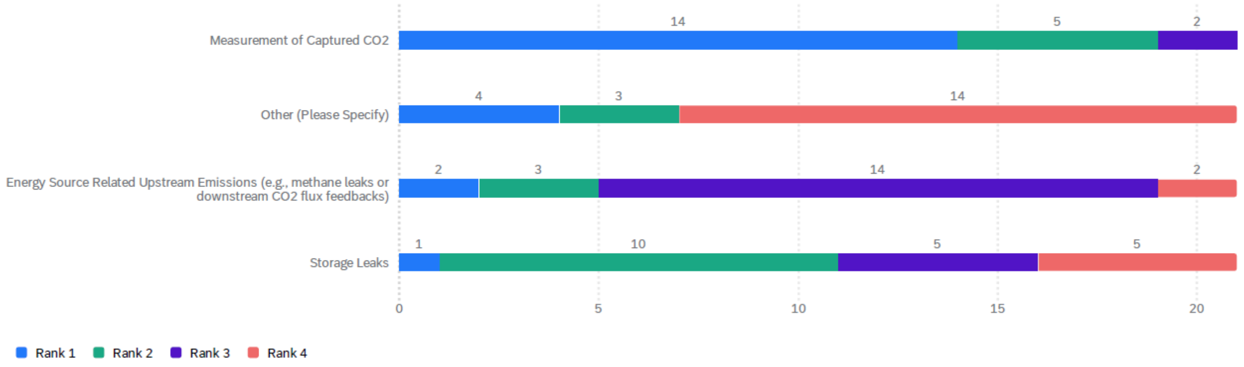
Here, respondents indicated that R&D challenges were both basic and applied, although more applied challenges emerged in response to this question. Accordingly, respondents' average opinions on allocation of a fixed budget for mCDR RD&D were evenly split between basic, applied, and deployment research, again weighted more heavily toward applied and deployment-based research options. Again, this reflects the mid-level technological readiness of these approaches, where the theory is promising but the "demonstration valley of death" remains. Eight respondents also indicated in the "other" category that spending should also support social sciences (e.g., governance, public engagement, messaging, decision-making under uncertainty, and human impacts/interactions), suggesting an average allocation of 5% (maximum 20%).

What are the top areas where we should be directing the bulk of investments for mCDR technology development? Please select 3.



Here, two-thirds of respondents suggested that understanding environmental impacts was an important priority. One-third of respondents suggested that field demonstrations, pilots, and observing network improvements should also be top priorities. Some respondents suggested spending on computational modeling development, but fewer than those that emphasized observational efforts. These answers align well with responses to previous questions, which noted that poor understanding of potential environmental impacts limited social license and political will—and accordingly limited deployment scale.

Which mCDR processes are the most challenging/uncertain in terms of Monitoring, Reporting, and Verification (MRV)?



Most respondents suggested that measurement of captured CO_2 was the most uncertain component of MRV, with storage leaks considered second most uncertain. Overall, upstream emissions were considered the least uncertain component of MRV for mCDR methods. Also mentioned in the "other" category were ecological and environmental impacts, durability, emissions related to material sources and transportation, and modeling of sea-air gas exchange.

What do you regard as the biggest challenge(s) that could prevent mCDR from becoming a mature CDR pathway with global climate impacts?

Here, respondents suggested five key factors that could prevent mCDR from maturing. More respondents listed social license as a primary inhibitor, which was related directly by multiple respondents to two other factors: environmental impacts and premature commercialization. Other concerns seen as limiting the field were investments in MRV and baselines and in capacity development.

Critical factors that were overlooked or not included in this survey for mCDR development and technology maturation:

Overall, respondents suggested a variety of different focuses that could benefit from additional attention, especially in an interdisciplinary context. While this survey focused on technological innovations, respondents suggested that more detail and concern about scale could be developed around social license, questions around carbon accounting (e.g., life cycle assessment, baselines, leakages, transport costs), economics of scale (e.g., competing ocean use cases, durability of carbon removed, separating the costs of deployment and MRV), environmental impacts, growing impacts of climate change, and international collaborations. This variety of mostly nonrepeating responses suggests that the survey overall captured the important consensus questions facing the mCDR field today.

A.4 Conclusion

This survey aimed to gather valuable insights from the broader CDR community, with the goal of vetting our assessments with external experts. We leveraged these insights to identify blind spots in our work, prioritize technological innovations, and maintain a balanced perspective across pathways. This information was integral to the development of a comprehensive and actionable report on the technological innovation opportunities for CDR intended to guide future efforts in carbon removal.

Appendix B. DAC Waterfall Chart: Methodology and Assumptions

B.1 Introduction

The solid sorbent DAC technology typically utilizes an amine-functionalized sorbent material, which is the most common alternative to alkaline solutions for DAC sorbents (20,54,242) . This technology separates CO_2 from the air through a temperature-vacuum swing adsorption/desorption cycle, as illustrated in Figure B-1. Lewatit VP OC 1065, a commercially available polymeric resin with primary amine groups, is believed to be similar to the sorbent materials used by Climeworks for their first-generation DAC (20). Because this material is readily accessible, it has become a benchmark for novel DAC sorbents developed in laboratories. However, fabricating amine sorbents with optimal pressure drop, air flow rate, CO_2 capacity, and desorption temperature for DAC remains a challenge (243). Figure B-1 shows the overall process flow of solid sorbent DAC system powered by electricity. Table B-1 shows the component-level information of a solid sorbent DAC system.

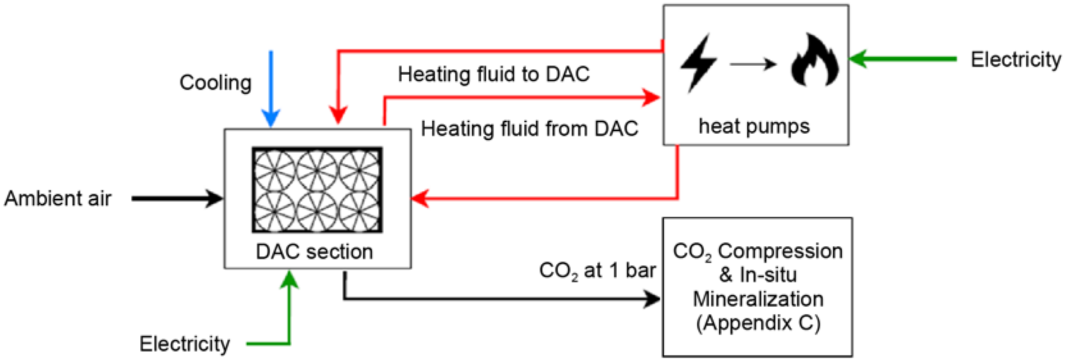


Figure B-1. Process flow diagram of the solid DAC system.

Adapted from (242).

Table B-1. Components of Solid Solvent DAC.

As referenced in (242).

Component	Parameter	Value
DAC section	Width of sorbent bed	1.43 m
	Height of sorbent bed	0.1 m
	Length of sorbent bed	0.0172 m
	Sorbent density	812.2 kg/m^3
	Bulk density	356.4 kg/m^3
	Internal porosity	0.22
	Feed gas velocity	0.028 m/s
	Particle size	7.5×10^{-4} m

Component	Parameter	Value
	Heat of CO_2 adsorption	70 kJ/mol
	Heat capacity of sorbent	1.5 kJ/kg-K
	Desorption temperature	110°C
	Regeneration energy (at 20°C, 50% relative humidity)	1.5 MWh/t-CO_2
	Cycle time	35 min
Sorbent	Sorbent capacity	1 mmol/g
	Sorbent lifetime	4 years
Heat pump	Lifetime	25 years
Fan	Capture rate	70%
	Power consumption	0.08 MWh_{el}/t-CO_2
	Pressure drop	1 mbar

B.2 Methodology

The techno-economic analysis calculation flow is illustrated in Figure B-2. It begins with regional variables such as temperature, relative humidity, and altitude. The productivity is highly sensitive to air temperature and relative humidity. As air passes through the contactor, the surface of sorbent rapidly equilibrates with the air temperature. While regional factors like wind speed, precipitation, and altitude also affect DAC performance, temperature and relative humidity are particularly influential in determining the kinetics within the air contactor. These regional variables significantly impact the CO_2 productivity (t-CO_2/yr-collector) and the system's overall electrical energy demand (MWh/t-CO_2), as shown by Eq. B-1 and B-2. The annual productivity per CO_2 collector has been estimated based on previous study (242). Here, the collector dimensions are 1.44 m (width) × 1.45 m (length) × 1.47 m (height), with 13 sorbent cells in each frame, and a total of 88 frames within the single collector. Productivity tends to be higher in regions with lower temperatures and relative humidity. Across a range of 1°C to 30°C and relative humidity levels between 5% and 100%, each collector can capture between 45.3 and 64.2 tons of CO_2 annually, with electricity consumption ranging from 1.35 to 2.69 MWh per ton of CO_2.

$$Productivity\left(\frac{t{-}CO_2}{yr{-}collector}\right) = a_0 + a_{10}T + a_{01}RH + a_{20}T^2 + a_{11}TRH + a_{02}RH^2 + a_{21}T^2RH + a_{12}TRH^2 + a_{03}RH^3 \qquad \text{Eq. B-1}$$

$$Electricity\ Demand\left(\frac{MWh}{t{-}CO_2}\right) = b_0 + b_{10}T + b_{01}RH + b_{20}T^2 + b_{11}TRH + b_{02}RH^2 + b_{21}T^2RH + b_{12}TRH^2 + b_{03}RH^3 \qquad \text{Eq. B-2}$$

Table B-2. Capital Costs for Solid Sorbent DAC Technology

	Coefficient		Coefficient
a_0	60.11	b_0	1.59
a_{10}	−0.1343	b_{10}	−0.01238
a_{01}	0.2973	b_{01}	−0.005352
a_{20}	−0.01372	b_{20}	0.0005591
a_{11}	0.008108	b_{11}	−0.0006398
a_{02}	−0.006948	b_{02}	0.0002529
a_{21}	6.41E-05	b_{21}	7.86E-07
a_{12}	−8.09E-05	b_{12}	6.19E-06
a_{03}	3.52E-05	b_{03}	−9.92E-07

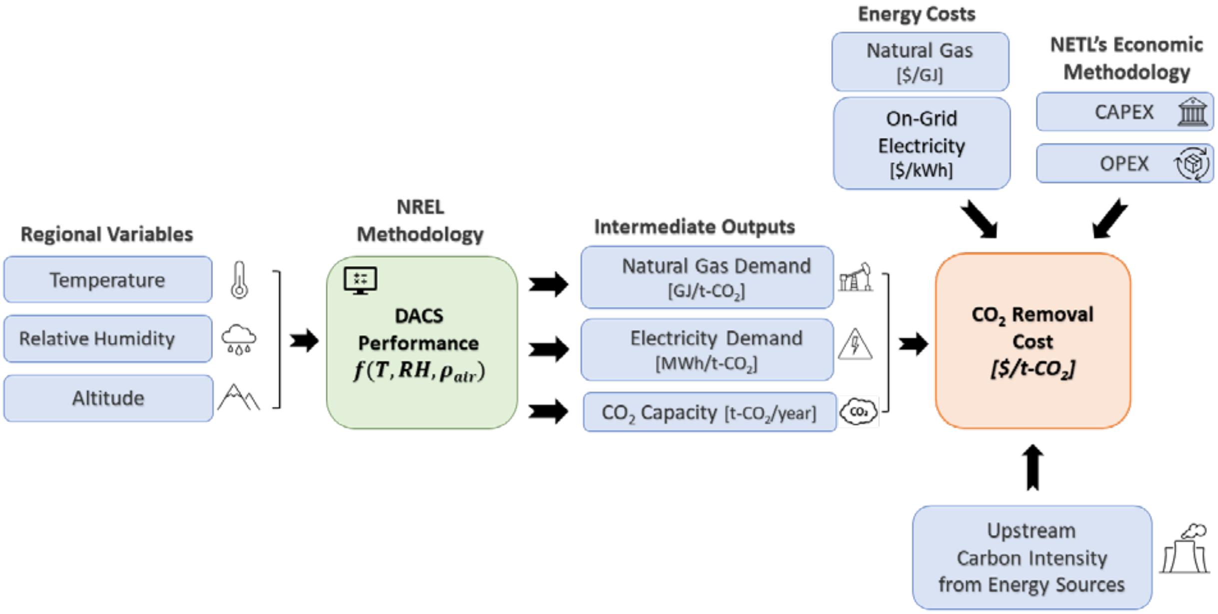


Figure B-2. Techno-economic analysis calculation flow

Capital Expenditure

The capital cost estimates are based on an AACE International Class 5 estimate, which includes an uncertainty range of ±50%. Due to the limited public information available for industrial-scale DAC systems, a sensitivity analysis was conducted on various process and cost parameters. Table B-3 illustrates the components of capital and operational costs for a solid sorbent DAC system. Other total plant cost categories include material handling, material preparation, compression, combustion turbine, accessories, cooling water system, and building and structures.

Table B-3. Capital and Operational Costs for Solid Sorbent DAC Technology.

As referenced in (62,242).

Capital Cost (M$)		Note
Instrumentation and control	14.48	Annual capacity: 100,000 t-CO_2/year
DAC system	91.27	
Other total plant cost	34.82	
Fixed Operating Cost (M$)		**Note**
Annual operating labor	3.51	-
Maintenance labor	1.07	
Administrative and support labor	1.14	
Property taxes and insurance	2.81	
Variable Operating Cost (M$)		**Note**
Maintenance material	1.6	-
Water	0.04	
Makeup and wastewater treatment	0.03	
DAC sorbent	0.42	
Waste disposal	0.09	

Levelized Cost of CDR

The techno-economic framework developed in this work is based on the National Energy Technology Laboratory's framework (244), adapting it for consistency with the recently published guidelines for the cost estimation of DAC technologies by the National Energy Technology Laboratory (61,62). The capital charge component of the non-energy levelized cost of CDR is determined by multiplying the total as-spent cost (TASC) of the plant by a fixed charge rate. TASC is calculated by taking the total overnight cost (TOC) of the plant and multiplying it by a TASC/TOC ratio. TOC represents the sum of the total plant cost and includes preproduction costs, inventory capital costs, and other expenses such as initial chemicals, land, owner's costs, and financing costs. In this study, TOC and fixed/variable operational costs are estimated as a portion of total plant cost for each DAC system(61,62).

The determination of the fixed charge rate and TASC/TOC ratio is outlined in (244) and is based on financial parameter assumptions common to the power industry. The product of the fixed charge rate and TASC/TOC ratio is referred to as the fixed charge factor. In these calculations, the fixed charge rate is 0.07 and the TASC/TOC ratio is 1.093. These values were derived for a plant with a 3-year construction period and have been applied to natural gas combined cycle cases in other National Energy Technology Laboratory studies (62).

The sum of the annual levelized capital costs, fixed operating and maintenance costs, and variable operating costs is then adjusted to the levelized CDR cost, as illustrated in Eq. B-3.

$$LCOR = \frac{(FCR)(TASC)+OC_{FIX}+(CF)(OC_{VAR})}{CF(F_{CO_2})} \qquad \text{Eq. B-3}$$

LCOR: Levelized cost of removal (\$/t-CO_2)
FCR: Fixed charge rate
TASC: Total as-spent cost (\$/year)
OC_{FIX}: Fixed operational cost (\$/year)
OC_{VAR}: Variable operational cost (\$/year)
CF: Capital factor (85%)
F_{CO2}: Net removal annual CO_2 capacity (t-CO_2/year)

The fixed operational costs for the plant are calculated based on the DAC system's varying performance and added to the capital charges as a portion of the total plant cost. Fixed operational costs include annual operating labor, maintenance labor, administrative and support labor, property tax, and insurance. Variable operating costs consist of maintenance materials, water, makeup chemicals, and waste disposal. The energy requirements for each DAC technology are influenced by regional parameters such as air temperature, relative humidity, and altitude. Electricity and natural gas costs are acquired from the U.S. Energy Information Administration's Annual Energy Outlook (245).

B.3 General Assumptions

Regional Conditions: California and Washington

Table B-4. Regional Conditions in California and Washington for DAC.

As referenced in (245).

	California	Washington
Regional condition (246)	T: 18°C, relative humidity: 52%, elevation: 883 m	T: 14°C, relative humidity: 70%, elevation: 518 m
Electricity cost, \$/GJ	52.6	17.2
Carbon intensity of electricity, g-CO_2/kWh	191	91
Annual CO_2 capture capacity, Mt/year	0.1	0.1
Capacity factor, %	85	85

Cost Reduction Through R&D Innovation

Regeneration energy can be reduced by using novel sorbent, catalytic support, better heat exchange system, or novel heating (e.g., microwave, joule heating, magnetic heating).

Sorbent lifetime can be extended by lower degradation over cycles or surface treatment for durability.

Cyclic time can be reduced by switching to novel sorbent that has higher reaction rate (kinetics), CO_2 adsorption capacity by different composition and structure, higher desorption rate, or faster regeneration process through novel methods (e.g., microwave, joule heating).

Novel sorbents potentially have higher CO_2 selectivity or higher kinetics (e.g., through higher specific surface area) during adsorption and desorption.

Table B-5. Assumptions for Each DAC Scenario Evaluated

Scenario		Note	Reference
Regeneration energy	Reference	Lewatit: 1.5 MWh/tCO_2 (at 20°C, 50% relative humidity)	(242)
	Moderate	Switching sorbent to APDES-NFC: 15% decreased	(247)
	Aggressive	40% electrical energy reduction by switching conventional conductive heating to microwave heating	(248)
Sorbent lifetime and cost	Reference	2 year, \$20/kg	-
	Moderate	3 year, \$7.6/kg	(20)
	Aggressive	4 year, \$2/kg	(20)
Cyclic time	Reference	Lewatit: 35 min	
	Moderate	43% decreased “adsorption half time” by switching sorbent to Tri-SBA-15 (20 min)	(247)
	Aggressive	85% decrease “adsorption half time” by switching sorbent to MAPS-MCF (5 min)	(247)
CO_2 capacity	Reference	Lewatit: 1 mmol/g	(240)
	Moderate	Switching to Purolite sorbent, 20% increase	
	Aggressive	Switching to LiX sorbent, 100% increase	(247)

B.4 Sensitivity Analysis

In Figure B-3, the tornado diagram presents a sensitivity analysis of factors influencing the Net CO_2 Removal Cost for carbon dioxide removal via a Direct Air Capture (DAC) system paired with in-situ mineralization. The baseline cost, estimated at \$1,148 per ton of CO_2 removed, reflects conditions in California, accounting for regional “non-technical variables” like ambient temperature, relative humidity, altitude, electricity cost, and the carbon intensity of electricity, as well as “technical variables” such as sorbent CO_2 capture capacity, cyclic time, regeneration energy demand, sorbent lifetime, sorbent cost, and in-situ mineralization. This baseline assumes California’s regional conditions and a sorbent with a 2-year lifetime, priced at \$20/kg, along with supercritical CO_2 in-situ mineralization.

Each variable was consistently adjusted by ±30% to observe its relative impact on the net CO_2 removal cost. Results indicate that the sorbent’s CO_2 capture capacity has the most significant impact within this ±30% range for our analysis, with costs ranging from \$961/t- CO_2 (+30%) to \$1,498/t- CO_2 (-30%). Cyclic time and regeneration energy demand also notably influence costs, exhibiting the next highest variability. Other factors, such as relative humidity, sorbent cost, carbon intensity of electricity, and electricity cost, have lesser impacts. Altitude, ambient temperature, and in-situ mineralization cost show comparatively minor effects within the ±30% variation range.

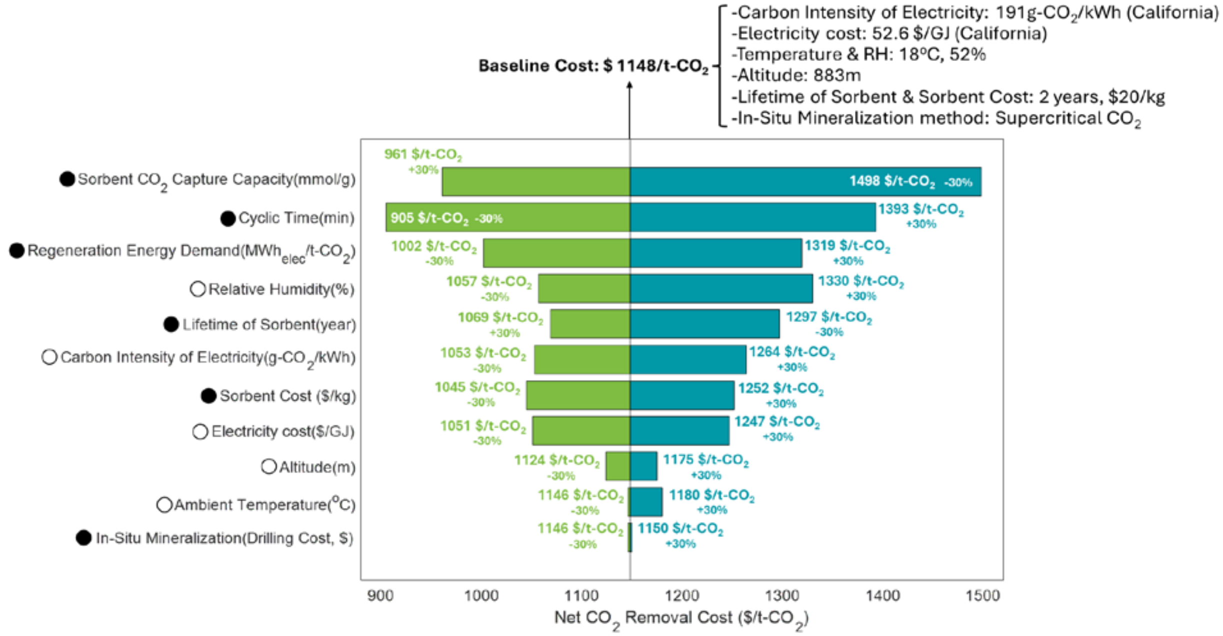


Figure B-3. Sensitivity analysis – Impact of variable variations (±30%) on Net CO_2 Removal Cost

Variables are indicated along the y-axis as technical with a closed circle (●) and non-technical with an open circle (○).

The sensitivity analysis emphasizes the importance of technical improvements on CO_2 capture capacity and regeneration energy demand to reduce CO_2 removal costs effectively, indicating that factors like altitude and temperature play a more limited role within the tested range. With all variables only being adjusted by ±30%, the carbon intensity of electricity ranged from 133.7 g/kWh (-30%) to 248.3 g/kWh (+30%), consistent with levels in states such as Oregon, New York, California, and South Dakota, which rely heavily on hydropower or nuclear power. In contrast, states like Utah and Wyoming, which depend on fossil fuels, have carbon intensities exceeding 700 g/kWh, which would make carbon intensity the dominant variable in the sensitivity analysis. Additionally, temperature ranged from 12.6°C (-30%) to 23.4°C (+30%), though some regions experience very cold or very hot ambient temperatures for much of the year.

Appendix C. Mineralization Waterfall Chart: Methodology and Assumptions

C.1 Introduction

This appendix serves to describe the purpose, scope, and assumptions behind techno-economic calculations made for CO_2 storage costs via mineralization, and present results of these calculations in combination with solid sorbent DAC costs to identify key areas for cost reduction through R&D innovation. The scope of this document covers two commercially and technically mature methods: $CO_2(aq)$ and $scCO_2$ injection. The first method, $CO_2(aq)$, describes the method developed by Carbfix in Iceland, where gaseous CO_2 is dissolved in the injection well via mixing at depth downhole, leveraging the hydrostatic pressure to maintain CO_2 in solution and avoid degassing (129,249). The second method, $scCO_2$, describes the method developed by Pacific Northwest National Laboratory in the Wallula Basalt Pilot Project, where CO_2 is injected in a pure phase as a supercritical fluid ($T > 31°C$, $P > 7.4$ MPa). Both methods are source-agnostic, meaning that CO_2 can be captured from any point source or CDR source (i.e., DAC) and conditioned for transport and storage. For the purposes of this section, CO_2 capture cost is considered from Appendix B, and thus only the levelized cost of storage is presented on a $/t$CO_2$ basis. Scenarios for DAC + in situ mineralization storage are modeled for Washington and California, as these locations may be feasible for coupled DAC + in situ mineralization (Section 5). The model was developed in close collaboration with technology developer Carbfix, collaborators at Rio Tinto, and staff from the Pacific Northwest National Laboratory. This appendix presents baseline assumptions and key model parameters used in the calculations, as well as results and interpretation of CO_2 storage costs via in situ mineralization.

C.2 General System Assumptions

The cost estimates presented here correspond to a theoretical, commercial-scale CO_2 storage system with a capacity to store 30 million metric tons of CO_2 over 30 years based on a hypothetical injection rate of 1 million metric tons per year that is commensurate with commercial hub-scale CO_2 storage projects by Carbfix (Coda Terminal) and existing Class VI-permitted $scCO_2$ injection wells (see Appendix C.4: $scCO_2$ System Assumptions). The techno-economic estimates are not tied to a specific reservoir but are constrained by conservative field-based assumptions for the maximum per-well CO_2 injection capacity for each technology. Field-derived specifications for CO_2 storage depend on the selected injection method, which in turn depends on reservoir conditions, injectivity of the well, water/brine availability, permitting, and other site conditions. Thus, it is assumed the hypothetical CO_2 storage reservoir for both cases has sufficient CO_2 storage capacity and injectivity to safely contain the 30-year storage capacity listed in Table C-1. Neither technology includes CO_2 transport, so it is assumed the DAC source is co-located with injection facilities and only short-range transport networks (i.e., from capture plant to injection well) are required. On-site compression is included for both technologies. No leakage or migration of CO_2 outside of the intended storage reservoir or caprock is assumed or included in cost estimates, in accordance with field observations from project reviews funded by DOE and the National Energy Technology Laboratory (250). Closure costs (i.e., plugging/cementing) are incorporated on a per-well basis, but do not include all of the post-injection site care financial responsibility costs associated with the Environmental Protection Agency's Underground Injection Control Class VI permit (see Appendix C.7: Notes). Water unit costs are representative of values for Washington. Capital costs and operation and maintenance costs for both the Washington and California scenarios are held constant. Regional assumptions (i.e., carbon intensity) are listed in Appendix B.

Table C-1. General Technical and Financial Assumptions

General Technical System Assumptions			
Parameter	**Unit**	**CO_2(aq)**	**$scCO_2$**
30-year storage capacity	tCO_2	30,000,000	30,000,000
Total project injection rate	tCO_2/yr	1,000,000	1,000,000
Storage efficiency (i.e., containment)	%	100%	100%
Injection well radius (inner diameter)	cm	16.51	16.51
Number of injection wells	#	20	2
Number of monitoring wells	#	9	9
Injection well depth	m	1,500	1,500
Monitoring well depth	m	1,500	1,500
Injection well lifespan	years	10	10
Monitoring well lifespan	years	10	10
CO_2 purity as received	%	99%	99%
Financial Assumptions and Results			
Item	**Unit**	**CO_2(aq)**	**$scCO_2$**
Cost of drilling	USD/m	$2,000	$3,000
Drilling cost per injection well	USD	$3,000,000	$4,500,000
Total injection well(s) drilling cost	USD	$60,000,000	$9,000,000
Closure cost per injection well	USD	$50,000	$50,000
Total injection well(s) closure cost	USD	$1,000,000	$200,000
Total injection well CAPEX	USD	$129,200,000	$30,200,000
Drilling cost per monitoring well	USD	$1,500,000	$2,250,000
Total monitoring well(s) drilling cost	USD	$13,500,000	$20,250,000
Closure cost per monitoring well	USD	$50,000	$50,000
Total monitoring well(s) closure cost	USD	$450,000	$450,000
Total monitoring well CAPEX	USD	$13,950,000	$20,700,000
Other capital as proportion of existing capital	%	25%	50%
Other capital costs	USD	$18,737,500	$14,900,000
Total other capital lifespan	yr	10	10
Discount rate	%	8%	8%
Levelized cost of listed capital	**USD/tCO_2**	**$13.96**	**$6.66**
Unit cost of water	USD/t	$0.10	NA
Water cost per tCO_2	USD/tCO_2	$2.71	NA
Total water cost	USD/yr	$2,705,013	NA
Unit cost of energy (WA)	USD/kWh	$0.06	$0.06
Unit cost of energy (CA)	USD/kWh	$0.19	$0.19
Operating and maintenance costs	USD/tCO_2	$1,873,750	$894,000
Levelized cost of operating and maintenance costs	**USD/tCO_2**	**$1.87**	**$0.89**

C.3 $CO_2(aq)$ System Assumptions

For the $CO_2(aq)$ method, a conservative injection rate of 50,000 metric tons of CO_2 per year per well was assumed based on site characterization and reservoir modeling of Carbfix's flagship commercial-scale "Coda Terminal" CO_2 mineral storage hub (251). Note that the injection rate used in this model presents a conservative estimate of per-well injectivity assuming 40-kg/s injection rates, whereas field injectivity tests at the Coda Terminal site indicated feasible injection rates of up to 70 kg/s. It is assumed that CO_2 is delivered at >99% purity and atmospheric pressure before being compressed to 2.5 MPa for injection in a gaseous state, with a separate CO_2 and water pipe that mix when sufficiently deep for complete dissolution (i.e., >2.50 MPa) (129,249). Energy requirements assume pumping for the water intensity of approximately 27 tH_2O/tCO_2 (249).

Table C-2. Aqueous System Assumptions

Parameter	Unit	Value
Injection rate	tCO_2/yr/well	50,000
Water efficiency factor (% CO_2)	%	3.7%
Water intensity	tH_2O/tCO_2	27.05
Henry's Law constant	(mol/L)/MPa	0.336
pCO_2 injected	MPa	2.50
Compression requirements	kWh/tCO_2	75.00
Pumping requirements	kWh/tCO_2	23.00

C.4 $scCO_2$ System Assumptions

For the $scCO_2$ method, a conservative injection rate of 500,000 metric tons of CO_2 per year per well was assumed based on existing active Environmental Protection Agency Underground Injection Control Class VI permits (252) (CO_2 injection rate ranges from 300,000 to 1.0 million metric tons/year) using this injection method, because no mineralization-specific $scCO_2$ has been conducted apart from the 1,000-metric-ton pilot-scale test conducted by Pacific Northwest National Laboratory. It is assumed that the DAC facility supplies 100,000 metric tons of CO_2 per year, with other CO_2 sources filling in the remaining per-well capacity. CO_2 is assumed to be received at atmospheric pressure in this scenario (i.e., CO_2 sourced via DAC) and subsequently compressed to supercritical conditions ($T > 31°C$, $P > 7.38$ MPa) for injection, utilizing a single-train five-stage compressor system (253).

Table C-3. Supercritical System Assumptions

Parameter	Unit	Value
Injection rate	tCO_2/yr/well	500,000
kWh required per tCO_2 compressed	kWh/tCO_2	100.36
Gas constant	kJ/kmol-K	8.31
CO_2 temperature at compressor inlet	K	313.15
Molar mass of CO_2	kg/mol	44.01
Isentropic efficiency of compressor	%	0.75
Average CO_2 compressibility [a]	%	0.995
Average ratio of specific heats for CO_2 [a]	%	1.277
Average CO_2 compressibility [b]	%	0.985
Average ratio of specific heats for CO_2 [b]	%	1.286
Average CO_2 compressibility [c]	%	0.970
Average ratio of specific heats for CO_2 [c]	%	1.309
Average CO_2 compressibility [d]	%	0.935
Average ratio of specific heats for CO_2 [d]	%	1.379
Average CO_2 compressibility [e]	%	0.845
Average ratio of specific heats for CO_2 [e]	%	1.704

[a] Corresponds to a pressure range of 0.1–0.24 MPa and an average temperature of 356 K in the compressor.
[b] Corresponds to a pressure range of 0.24–0.56 MPa and an average temperature of 356 K in the compressor.
[c] Corresponds to a pressure range of 0.56–1.32 MPa and an average temperature of 356 K in the compressor.
[d] Corresponds to a pressure range of 1.32–3.12 MPa and an average temperature of 356 K in the compressor.
[e] Corresponds to a pressure range of 3.12–7.38 MPa and an average temperature of 356 K in the compressor.

C.5 $scCO_2$ Enhanced Critical Mineral Recovery Assumptions

This section describes assumptions for the “disruptive innovation” included in Section 5, $scCO_2$-enhanced critical mineral recovery. While this technology has previously focused on ex situ mineralization techniques (112), in situ technology is currently under development at Pacific Northwest National Laboratory through the Advanced Research Projects Agency – Energy MINER program (254). In this scenario, it is assumed that $scCO_2$ is injected with a ligand suitable for enhanced mineralization and selective metal extraction. It is assumed that any additional CAPEX associated with surface mineral processing facilities are out of scope of this techno-economic assessment and would be included in a separate assessment for surface facilities. However, additional costs associated with injecting the selected ligand and for additional water usage to “flush” the fluid into the formation would require additional fixed operating expenses and variable operating expenses for the ligand and water usage, respectively, which are included in the scenario presented here. Assuming a reservoir of 1.0-km^3 volume of pure olivine (3,200-ppm nickel) with sufficient injectivity and storage capacity to accept long-term injection, and assuming 5% of the reservoir can be dissolved with a carbonation efficiency of 60%, we estimate that roughly 110 kg CO_2 could be mineralized per kilogram of nickel produced (assumes 100% nickel recovery efficiency). These assumptions represent a theoretical scenario of injecting into a pure olivine volume and thus represent a theoretical maximum for potential enhanced critical mineral recovery with associated uncertainties regarding the volume accessible for dissolution, carbonation efficiency, and nickel recovery rates – all of which are under further research through the MINER program. Transferring this finding to the specific injection rates applied to this techno-economic analysis in Table C-1, we estimate that approximately 272,727 metric tonnes of nickel could be produced over the 30-year lifetime of the project. Given the commodity price of nickel at the time of writing of $16,627.50 per metric tonne, we estimate a levelized nickel revenue of \$151.16/tCO_2 (255). Inherent to this estimate is the uncertainty in the nickel commodity price due to market fluctuations. Considering the 2024 minimum and maximum spot price of nickel, we include the uncertainty in potential nickel revenue based on these values which changes the estimated levelized nickel revenue to a range of \$140.92/tCO_2 - \$193.39/tCO_2.

Table C-4. scCO_2 Enhanced Metals Recovery Assumptions for the Disruptive Innovation Case

Parameter	Unit	Value
Nickel in olivine (Tamarack case) [a]	ppm	3,200
Total volume	km^3	1.0
Volume dissolved	%	5%
Carbonation efficiency	%	60%
Nickel recovery	%	100%
CO_2-Ni recovery ratio	kg CO_2/kg Ni	110
Ni commodity price (BASE) [b]	USD/tNi	\$16,627.50
Ni commodity price (MAX) [c]	USD/tNi	\$21,272.50
Ni commodity price (MIN) [d]	USD/tNi	\$15,501.60
Additional fixed OPEX	USD/tCO_2	\$6.00
Additional variable OPEX	USD/tCO_2	\$1.50
Levelized nickel revenue [e]	USD/tCO_2	\$151.16

[a] Nickel in olivine from Tamarack, Minnesota, coarse-grained olivine deposit (256,257).

[b] Nickel spot price as of July 12, 2024 (time of writing).

[c] Nickel spot price as of May 21, 2024 (maximum spot price).

[d] Nickel spot price as of July 25, 2024 (minimum spot price).

[e] This value is presented here as revenue (+), while in Section 5 it is presented as a negative cost.

C.6 Results

Results for the techno-economic modeling indicate a baseline levelized cost of storage of \$24.64/tCO_2 for the CO_2(aq) method and \$13.70/tCO_2 for the scCO_2 method in Washington. In California, the techno-economic model indicates a levelized cost of storage of \$37.87/tCO_2 for the CO_2(aq) method and \$27.14/tCO_2 for the scCO_2 method. Key differences include the additional capital cost required for the injection well requirements needed for the CO_2(aq) method to meet the targeted annual injection rate and the additional energy cost requirements for the scCO_2 method due to the additional compression requirements needed to condition CO_2 for supercritical injection. Spatial differences between Washington and California are dominated by the substantially higher energy costs for the California scenario.

C.7 Notes

While the model assumes sufficient CO_2 storage capacity to accommodate all injected CO_2, there may be additional costs related to land and pore space access because the area of review for the CO_2(aq) method (with 20 injection wells) would likely be greater than the scCO_2 method (with only two injection wells). Moreover, some general system assumptions may not capture site-specific conditions that could impact costs significantly for each method. For example, the assumed injection depth of 1,500 m for both methods may not capture the cost savings that may be associated with shallower injections that are possible when utilizing the CO_2(aq) method, but not the scCO_2 method, because the CO_2(aq) method can theoretically inject at depths <800 m (generally assumed minimum depth to maintain scCO_2 conditions). However, to avoid uncertainty related to Class VI permitting requirements (i.e., minimum depth to underground sources of drinking water) that are site-specific, the 1,500-m injection well depth assumption is appropriate. The assumption for total number of monitoring wells is also largely site-dependent and will vary depending on the existence of leakage pathways (e.g., legacy boreholes, faults/fracture systems, fracturing of caprock) and nature of the trapping mechanism. For this model, nine monitoring wells (smaller diameter) are assumed for both methods under consideration, but the actual number in the field will vary significantly by site and verification objectives. The base value of nine monitoring wells was taken from (99) and represents a conservative estimate compared to the six monitoring wells to be drilled for the Coda Terminal (258). The costs presented for the levelized cost of storage estimate do not consider costs associated with financial responsibility assurances for post-injection site care under the Environmental Protection Agency's Underground Injection Control Class VI program. However, these costs may add up to $33,672,785 to the overall project cost (259).

Appendix D. CDR Startup Companies Evaluated in the Investment Landscape

Figure 2 in this report illustrates the investment landscape for CDR startup companies. The companies included in this analysis and visualization are provided below:

DACS

280 earth
Aeon Blue
Aerleum
Aircapture
Airhive
AirMyne
Arbon
Capture6
Carbominer
Carbon Collect
Carbon Engineering
CarbonCapture
Carbyon
Clairity Technology
Climeworks
CORMETECH
Direct Carbon
Emissol
Feather Fuels
Flow Aluminum
Freshean
Fugu (Energy Production)
GigaDAC
Global Thermostat
GreenCap Solutions
Greenlyte
Heimdal
Heirloom
Holocene
Hydrocell
Innosepra
Ionada
Jeevan
Mission Zero Technologies
Neg8 Carbon
NeoCarbon
NGK Insulators
Noya
Octavia Carbon
Origen
Parallel Carbon
Phlair
Planet Savers
Prometheus Fuels
ReCarbn
Removr
RepAir
Skytree
Soletair Power
Spiritus
Sustaera
Svante
Terrafixing
Thalo Labs
Travertine
Ucaneo
Vallidun
Verdox
WindCapture Technologies
Yama
ZeoDAC

Mineralization

44.01
8 Rivers
Advanced Cooling Technologies
Arca
Atlas Materials
Blue Skies Minerals
Carbfix
Carbon Cure
Carbon GeoCapture
Carbon Upcycling
Carbonaught
CarbonBuilt
Carbonfuture
Cella
CO2 Lock
Cquestr8
Debergium
EDAC Labs
Eion
Everest Carbon
Exterra Carbon
Flux Carbon
Green Minerals
Green Sequest
Holy Grail Carbon
InPlanet
MCI Carbon
Metalplant
Neustark
O.C.O Technology
Partanna
RockFarm
Silicate
Undo
Veolia UK
Verde Agritech

BiCRS

1point8
3R-BioPhosphate
Aces High BioChar
Airex Energy
All Power LAbs
Amata Green
BC Biocarbon
Bio365
Biochar Innovations
Biochar Life
Biochar Life
Biochar Now
Biochar Solutions
BioCIRC
Carba
Carbo Culture
Carbogenics
Carbonex
Char Technologies
Charm Industrial
Circular Carbon
Cotierra
Dowman
Dutch Carboneers
EarthSpring Biochar
Gaia Refinery
Gekka
Glanris
Grassroots Biochar
Groupe Bordet
High Plains Biochar
Husk
InterEarth
Klimate.co
Locoal
Mash Makes
Myno
Northeastern Biochar Solutions
Novocarbo
Organilock
Orsted
Ozen Plus
Phoenix Biomass Energy
Pacific Biochar
Planboo
Proton Power
Pure Biochar
PyroCCS Qualterra
Reverse Carbon
Soil Reef
Sonnenerde
Standard Biocarbon
Stockholm Exergi
SymSoil
Takachar
TorrCoal
Vaulted Deep
Wakefield Biochar

mCDR

Aquaponics Iberia
Aquarry
ARC Marine
Atmocean
Banyu Carbon
Blue Dot Change
Blusink
Brilliant Planet
Brineworks
Captura
CarbonBlue
Carboniferous
Crew Carbon
Ebb
Lillianah Technologies
Limenet
Lithos Carbon
Ocean-based Climate Solutions
Phykos
Planetary
Pronoe
Running Tide
Seafields
Vycarb