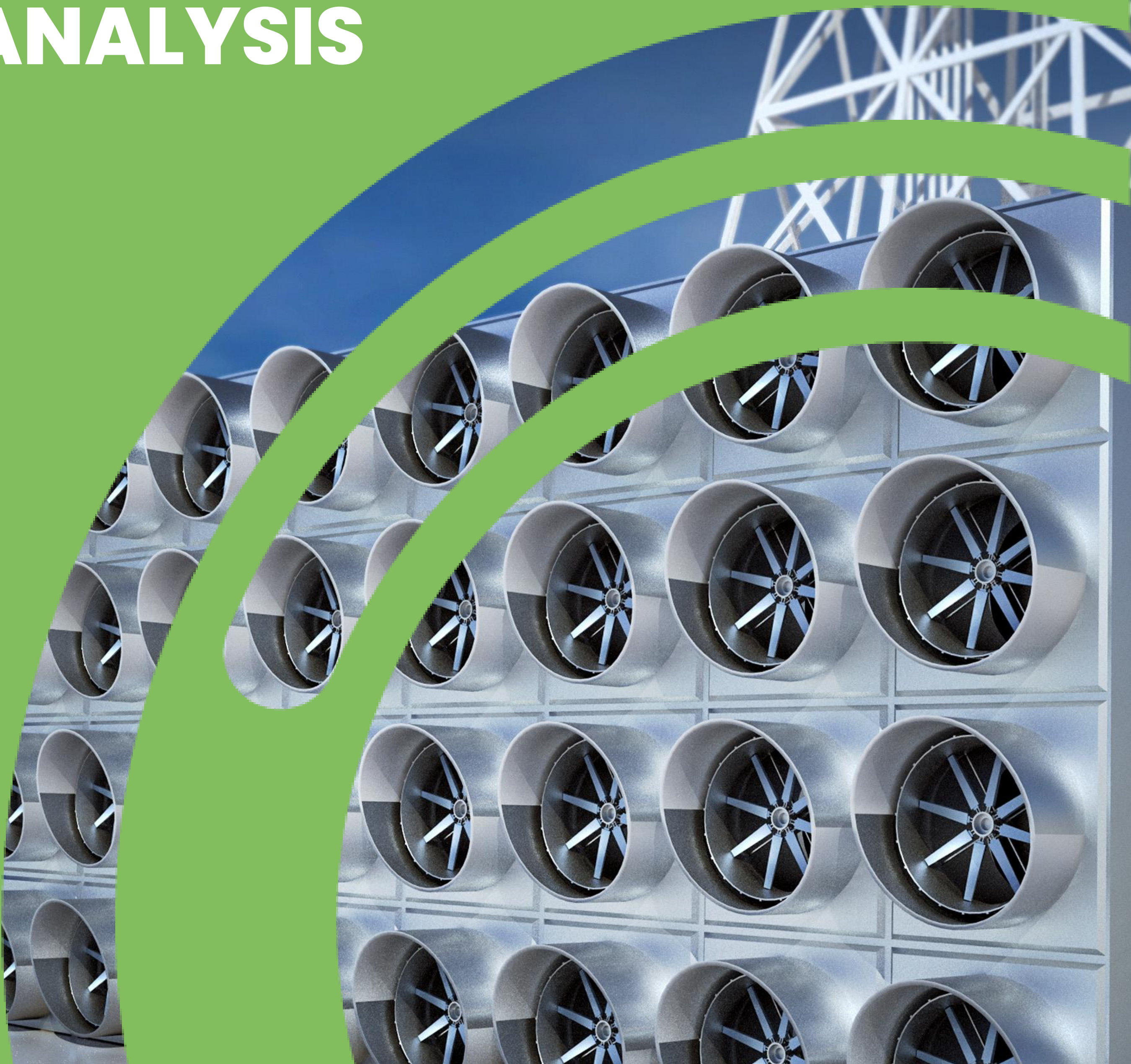
CARBON DIOXIDE REMOVAL MISSION

AUGUST 2022

1ST EDITION

CARBON DIOXIDE REMOVAL TECHNOLOGY ROADMAP: INNOVATION GAPS AND LANDSCAPE ANALYSIS



Contents

Abbreviations

BECCS	bioenergy with carbon capture and storage
BiCRS	biomass with carbon removal and storage
BioCCS	biomass with carbon capture and storage
CCS	carbon capture and storage
CCUS	carbon capture, utilization, and storage
CDR	carbon dioxide removal
CO_2	carbon dioxide
CO_2e	CO_2 equivalent
DAC	direct air capture
GHG	greenhouse gas
GJ	gigajoule
Gt	gigatonne
IPCC	Intergovernmental Panel on Climate Change
J	Joule
kJ	kilojoule
KOH	potassium hydroxide
kt	kilotonne
LCA	life cycle analysis
MI	Mission Innovation
MJ	megajoule
MOF	metal-organic framework
Mt	megatonne
MW	megawatt
NaOH	sodium hydroxide
PV	photovoltaics
RD&D	research, development, and demonstration
t	tonne (metric ton)
TEA	techno-economic analysis
TRL	technology readiness level
wt	weight
WtE	waste to energy

Preface

This Innovation Roadmap presents an overview of the current status, innovation needs, and research efforts in Mission Innovation (MI) Carbon Dioxide Removal (CDR) Mission member countries for three CDR approaches: direct air capture with storage, enhanced mineralization, and biomass with carbon removal and storage.

The Roadmap was authored by members of the CDR Mission (http://mission-innovation.net/missions/carbon-dioxide-removal/). It draws on a review of recent literature, a survey of CDR Mission members, and input from mission stakeholders and subject matter experts. Innovation needs and other potential opportunities compiled by the authors are intended for consideration and discussion by CDR Mission members. The document is designed to assist and inform members in identifying opportunities for collaboration that accelerates research, development, and demonstration (RD&D)—and ultimately for accelerating responsible large-scale deployment—of CDR technologies. References are provided throughout the Roadmap for readers to explore topics in further depth.

CDR Mission members are concurrently developing an Action Plan that builds on this Roadmap to articulate specific activities to be led by mission members that address priority innovation needs in the near-, mid-, and long-term.

The Roadmap concentrates on technical challenges, needs, and efforts. Non-technical challenges are introduced in the document and CDR Mission members recognize their critical importance for CDR deployment, but they are not the focus of this Roadmap.

The Roadmap focuses primarily on technologies and systems for the 'atmospheric carbon dioxide (CO_2) capture' portion of engineered and hybrid CDR approaches. Technology challenges and innovation gaps associated with CO_2 transport, storage, and use in products are essential aspects of CDR systems but are not covered in depth in this document. Carbon dioxide transport, storage, and use are examined by other international fora such as the Technical Group of the Carbon Sequestration Leadership Forum (CSLF) and the IEA Greenhouse Gas R&D Programme (IEAGHG).

The CDR space is rapidly evolving. The Roadmap provides a snapshot given current understanding and circumstances. CDR Mission members will continue to monitor the progress of relevant technology development and adjust priorities commensurate with changing needs.

Summary in Brief

- Carbon dioxide removal (CDR) refers to human activities that deliberately **capture CO_2 from the atmosphere and securely store the captured CO_2 in a manner intended to be permanent.** For a CDR project to be net negative, on a life cycle basis more CO_2e must be removed than is emitted.
- CDR is a **necessary component of a broad portfolio of climate change solutions.** In the near term CDR can further deep decarbonization efforts. CDR is needed to achieve economy-wide net-zero emissions commitments by counterbalancing emissions from the hardest to decarbonize sectors in the mid-term, and decrease atmospheric concentrations of CO_2 in the long term—gradually reversing some aspects of climate change.
- Current global **deployment of net negative technological CDR is practically zero.** A few dozen pilot-scale direct air capture operations are capturing about 11,000 tonnes[1] of CO_2 per year, and commercial-scale facilities capturing biogenic CO_2 exist but are not yet generating net-negative emissions.[2]
- The CDR Mission aims to **enable CDR technologies[3] to achieve a net reduction of 0.1 gigatonnes of CO_2 per year by 2030.** Climate models, such as those reported by the Intergovernmental Panel on Climate Change, indicate several gigatonnes of CO_2 removal annually will be needed by 2050.
- For the purposes of this Roadmap, CDR refers **to engineered and hybrid removal approaches**, with a focus on direct air capture with storage, enhanced mineralization, and biomass with carbon removal and storage.
- Atmospheric CO_2 capture for **short-term duration storage products** (e.g., synthetic fuels which are combusted) **is not considered CDR** because it does not result in the storage of CO_2 in a manner intended to be permanent.

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1 11,000 tonnes is 0.00001 gigatonnes. Several gigatonnes of CDR will be needed by 2050. 1 gigatonne (Gt) is the equivalent of 1 billion tonnes. For perspective, a gigatonne is approximately equivalent to one year of emissions from 250 million gasoline-fueled vehicles.

2 Net CO_2 emissions from the few commercial-scale currently operational facilities that store biogenic CO_2 are still positive, due to the CO_2 emissions from the production process (CDR Primer 2021).

3 The CDR Mission is currently focused on technological and hybrid approaches including direct air capture with storage, enhanced mineralization, and biomass with carbon removal and storage. Natural ecosystems and ocean technologies also offer promising pathways but are not in the scope of this Roadmap.

Direct air capture with storage

- **Direct air capture (DAC)** technologies include **near-commercial processes** that are being deployed today at pilot-scale (technology readiness level (TRL) in the 5-8 range) **and emerging technologies** that involve novel approaches at early stage TRL (<5).
- Research, development, and demonstration (RD&D) on DAC technologies in the TRL 7-8 range, plus learning-by-doing from increased deployments, have the potential to deliver near-term improvements in cost and performance, reduce negative impacts, and increase co-benefits. RD&D on DAC technologies in the TRL 5-7 range will help prove technologies work in different environments and assist in scale up to commercial size facilities. In the longer term, RD&D on DAC technologies at TRL <5 can accelerate development of novel approaches. Gigatonne scale removals may require breakthroughs enabled by investment in **RD&D across a wide range of approaches and TRLs.**
- Key innovation opportunities for DAC systems include materials that **can capture CO_2 faster, with longer material lifetimes, and by using less energy and scalable systems design that reduce capital and operating costs.** Other important technical opportunities include better understanding of co-benefits, local temperature and humidity effects on DAC performance, and ability to scale up manufacturing supply chains.
- Technology opportunities for DAC system deployment include substantially **reducing capital costs, generating co-products such as water, minimizing energy requirements, and/or integrating low-cost, low-carbon heat and electricity** with minimal trade-offs for resource consumption and competing uses for the energy.
- Given the nascency of DAC, exploring and **demonstrating a diversity of early DAC technologies** will enable technological learning that can drive down costs.

Enhanced mineralization

- Enhanced mineralization pathways that remove CO_2 from the air using rocks on earth's surface (surficial mineralization) are in the **early stages of development** (TRL <5). Currently there are no surficial mineralization projects beyond demonstrations generating net removals, although significant RD&D efforts are underway.
- Mineralization provides **naturally permanent storage of CO_2**, potentially eliminating some of the energy requirements and logistics steps. Surface mineralization does, however, involve potentially energy-intensive gathering, crushing, transportation, and dispersion of crushed minerals.
- Promising sources of **rocks for mineralization are prevalent across the globe.** Waste materials from industrial or mining operations can also be used.
- Key technology challenges to surficial mineralization include **kinetics of carbonation in rocks, energy and land use, monitoring CO_2 uptake, and system logistics.**

- Notable innovation opportunities to accelerate deployment include characterizing **mineralization rates** across different mineral types and environmental conditions, developing **remote sensing technologies** which could detect the amount of CO_2 removed by mineralization projects, and **understanding the benefits and risks.**

Biomass with carbon removal and storage

- Biomass with carbon removal and storage (BiCRS) refers to **approaches that use land or water-based biomass**—which naturally takes CO_2 from the atmosphere or seawater while growing—in combustion or other conversion processes combined with carbon capture and storage (bioCCS) or used to create bio-based products **for the purpose of permanently sequestering the CO_2.**
- There are several different BiCRS approaches and pathways, with technological development **ranging from early-stage research** (TRL <5) **to commercial stages of deployment** (TRL >9).
- BioCCS facilities are **cumulatively sequestering about 2 to 3 million tonnes of CO_2 per year**, with about 25 million tonnes of CO_2 per year in additional bioCCS facilities in planning or development stages. However, when considering the full life cycle, these operations are not yet producing net negative emissions.
- **Biomass feedstock production, including plant and algae, is energy intensive** and can include activities such as seeding, fertilizer and herbicide production, harvesting, and transportation to processing facilities. Use of biomass residues—such as agriculture and forest residues—tend to have the lowest cost, environmental impact, and impact on food and fiber production.
- Key challenges for high TRL approaches include **diverse biomass feedstocks, conversion efficiency, capture systems** that accommodate biomass sources, and generating net negative life cycle emissions. For low TRL approaches, key challenges include **proving technical performance** for a range of feedstock types and the **ability to develop and scale up** promising systems beyond niche applications.
- Key innovation opportunities include conversion processes that **accommodate heterogeneous biomass feedstocks**, optimization of biomass **feedstocks to maximize carbon removal** (rather than optimizing for energy content or products), **measuring upstream emissions** such as those associated with land use change and crop management, and **supply chain logistics** for biomass resources, facilities, markets, and storage.

Crosscutting

- **RD&D efforts across a wide range of pathways and TRLs** are important for developing a broad portfolio of technologies as a foundation for a large-scale global CDR industry in the mid and long terms.
- Many technological CDR pathways **require large amounts of energy per tonne of CO_2 removed**, presenting a crosscutting opportunity to reduce energy requirements

across the life cycle (including system logistics) and/or increase availability of responsible, low-cost, low-carbon energy sources appropriate for integration with the unique siting flexibility of many CDR systems.

- **Sustainable land use presents a challenge** across different approaches, depending on factors such as energy sources, feedstocks, supply chain, and capture method.
- Each CDR approach faces non-technical constraints, such as **social acceptability**, long term and low-cost **financing**, and **demand certainty**. Community engagement and consideration of environmental justice for affected communities will also be essential.
- **Robust accounting methods** are needed to quantify greenhouse gas (GHG) emissions from cradle-to-grave operations, incorporate CDR in national inventories and provide mechanisms for international market integration/transferability, and understand effects on factors such as water consumption, land use, biodiversity, food security, and ecosystem impacts.
- Life cycle analysis (LCA) provides a holistic perspective of the potential environmental impacts of a product or process throughout the entire lifetime. This includes the extraction of raw materials through the end-of-life. An **LCA determines whether a project that captures CO_2 from the atmosphere is a net CO_2e remover or emitter** on a cradle-to-grave basis over the lifetime of the project and identifies opportunities for improvement.
- Technical and analytical challenges of applying LCA to engineered and hybrid CDR approaches include, for example, the lack of consistent analysis boundaries, high-quality data, LCA standards for CDR, and reference projects. Innovation opportunities include **development of consistent cradle-to-grave system boundaries, harmonization of variables** (e.g., land, process, temporal), and **remote sensing** techniques to measure carbon cycle impacts.

Landscape Analysis

- As the importance of CDR in achieving climate goals has become clear in recent years, there has been a **proliferation of CDR initiatives and projects in the public and private sectors.**
- CDR Mission member government policies and programs are **accelerating deployment of later-stage CDR technologies and strategically investing in RD&D** for the next generation of CDR technologies. Government efforts are complemented by innovation and investment in the private sector, which has blossomed in recent years. Yet, more public and private innovation and investment are needed.
- The CDR Mission is continually identifying key stakeholders and **pursuing opportunities for collaboration** to advance Mission goals and amplify impact.
- Common interests and priorities across CDR Mission member governments and key stakeholders will be identified in a **forthcoming Action Plan.**

1 Introduction

Carbon removal is an essential tool in the suite of climate actions. The world simply cannot meet global climate goals without carbon removal. Alongside dramatic emissions cuts, the global community will need solutions to remove billions of tons of CO_2 from the atmosphere every year to limit the impact of climate change (IPCC 2022 - SPM).

Slashing emissions today is critical for making progress toward Paris Agreement goals.[4] But decarbonization alone is insufficient. CDR is necessary to counterbalance emissions from sectors that are hard to completely decarbonize, and to eventually reduce the concentration of CO_2 in the air. The choice of CDR methods will vary by country, and deployment must be sustainable and manage non-technical constraints, including political preferences and social acceptability. While CDR is not a substitute for emissions avoidance or reductions,[5] it can serve multiple roles in the near-, mid-, and long-terms (IPCC 2022 – chp 12):

1. As a complement to decarbonatization efforts by further reducing net GHG emission levels in the near term

What is CDR?

Carbon dioxide removal refers to anthropogenic activities that deliberately remove CO_2 from the atmosphere and durably store it in geological, terrestrial or ocean reservoirs, or in products (IPCC 2022 - TS).

For the purposes of this Roadmap, CDR refers to engineered and hybrid removal approaches, with a focus on direct air capture with storage, enhanced mineralization, and biomass with carbon removal and storage.

What is Net Negative?

To qualify as net negative, a CDR project must:

- Physically remove CO_2 from the atmosphere.
- Store the removed CO_2 in a manner intended to be permanent.
- Remove and permanently store more CO_2e on a life cycle basis than is emitted to the atmosphere (Tanzer and Ramirez 2019).

If CO_2 captured from the air is re-released, this is equivalent to delayed emissions.

What is not CDR?

Atmospheric CO_2 conversion for short-term duration storage products (e.g., synthetic fuels which are combusted) is not considered CDR because it does not result in storage of CO_2 in a manner intended to be permanent.

Natural CO_2 uptake not directly caused by human activities (e.g., unaltered mineral outcrops) is not considered CDR.

Carbon capture and storage (CCS) that captures CO_2 from a concentrated stream of flue gas from fossil-based power and industrial facilities and stores the captured CO_2 is important for reducing emissions, but it is not removing CO_2 from the air and therefore not CDR. However, CCS may be part of a CDR approach if atmospheric CO_2 that is captured via plants during photosynthesis is then stored geologically or in durable products. For example, CCS integrated with biomass-based combustion facilities and pulp and paper mills are considered CDR and have the potential to generate net negative life cycle emissions.

[4] The Paris Agreement's central aim is to strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius.

[5] Avoiding emissions (e.g., renewable energy and energy efficiency) and reducing emissions (e.g., point source capture and sequestration and sustainable aviation fuels) are generally the most economic, commercially-ready, and efficient methods for deep emissions reductions. It is critical that CDR efforts do not distract from efforts to avoid or reduce emissions or create a false impression that decarbonization is not important if emissions can be removed from the air.

2. As a counterbalance for GHG emissions from the sectors that are the hardest to decarbonize (e.g., aviation and agriculture) in the mid-term
3. As a tool to address legacy emissions by achieving and sustaining net negative GHG emissions in the long term

While the roles for CDR solutions address different markets and needs and will depend on different sets of regulations, they are not in conflict with each other. CDR represents the same set of technologies regardless of the role. Development of such technologies mutually reinforce all roles for CDR.

Figure 1 illustrates the potential contribution of CDR approaches.

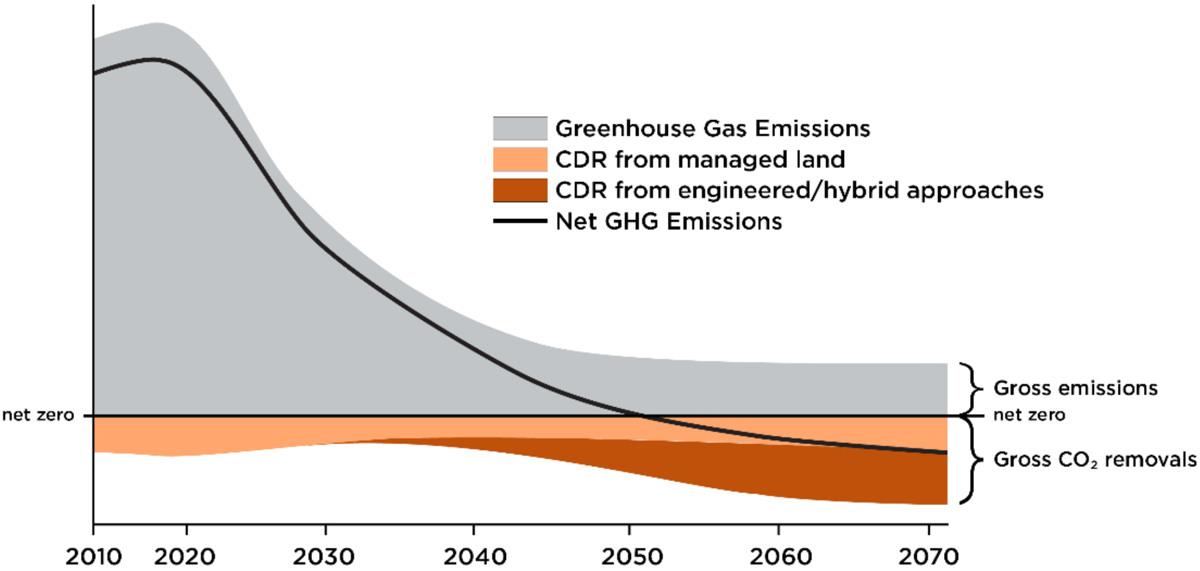

Figure 1. Stylized illustration of global greenhouse gas emissions curve and CDR to reduce net GHG emission levels in the near term, counterbalance residual emissions to help reach net zero GHG emissions in the midterm, and achieve and sustain net negative GHG emissions in the long term; CDR from managed land (e.g., afforestation, reforestation, improved forest management) shown in light orange in the figure is currently not within the scope of the CDR Mission (Source: Adapted from IPCC 2022 – chp 12).

The Intergovernmental Panel on Climate Change (IPCC) has reported modelling results for a range of emissions scenarios. All scenarios that limit global warming to no more than 1.5 °C include CDR (nature-based and technological solutions) (IPCC 2018a).[6] Several billion tonnes (gigatonnes) of removal are anticipated to be needed (IPCC 2022). For perspective, a gigatonne is about 3% of annual global emissions. The specific amount of CDR required is directly proportional to the ability (or inability) to reduce emissions in line with temperature targets—fewer emissions reductions will require a greater need for CDR.

The current level of engineered CDR deployment—led by forward-looking governments and companies conducting demonstration-scale projects—collectively totals on the order

[6] Most integrated assessment models (IAMs) and IPCC pathways include few CDR approaches—such as bioenergy with carbon capture and storage and managed land—yet the total quantity of removals from nature-based and technological approaches are relevant for understanding the magnitude of the scale-up challenge for CDR more broadly.

of a few thousand tonnes of net CO_2 removed per year. While these vanguard entities are setting the foundation for this rising sector, the global industry is six orders of magnitude less than the scale of removal likely needed.

Recognizing the herculean challenge of accelerating CDR deployment to meet the required pace and scale needed, Mission Innovation (MI) launched an initiative called the CDR Mission to accelerate international collaboration in developing CDR approaches. The CDR Mission's focus is to enhance the systems that lead to negative emissions through an emphasis on secure CO_2 storage and/or conversion into long-lived products in a manner intended to be permanent.

Considerations for Scale-up of CDR

Widescale CDR deployment depends on several feasibility and sustainability indicators. Cost, technology effectiveness, and life cycle impacts are key considerations that the CDR Mission is focused on. This does not imply that mission members perceive these factors to be more important for scale-up than the others, but rather these factors are essential and fit within the broader MI framework. For more discussion on scale-up factors, see IPCC 2018a.

Cost, including financial incentives, market development, and business models

Technology effectiveness, including the rate at which operations can remove emissions and facilitate performance at large scales and multiple locations

Energy and other resources associated with scaled-up CDR technologies facing increasing competition for energy, land, water, biomass, and other resources

Environmental–ecological impacts, including life cycle emissions, co-benefits and trade-offs

Geophysical–institutional resources, including subnational and global geophysical/geochemical resources, workforce expertise, and policy frameworks

Storage frameworks, including secure transport, risk and liability, permitting, monitoring, reporting, and verification for a defined time period

Socio-cultural factors, including community acceptance to ensure that CDR is deployed in a just and responsible manner and helps attain the United Nations Sustainable Development Goals

The Need for a Mission

Governments, companies, and organizations are making significant efforts to meet their Paris Agreement goals, appropriately emphasizing deep decarbonization. CDR provides an essential tool to help meet their emissions targets. The breadth of CDR approaches offers an opportunity to tailor removal solutions to a region's unique resources, capabilities, and public needs. On the other hand, the technologies and mechanisms across CDR approaches are diverse and at different stages of maturity,

Importance of Public Engagement

Social understanding and support of CDR technologies is necessary to enable the speed and scale of deployment necessary to achieve global climate goals. Perceived risks and benefits, distributive concerns, trust in developers and governing institutions, and public input in decision-making are all factors critical to social support.

Robust public engagement throughout project development—starting with initial research and planning—will be conducive to a project's acceptance and long-term success. Key pillars of engagement are transparency and equity in every phase of a project. Alignment with sustainable development objectives and maximizing co-benefits can further encourage social support, enable faster action, and support the design of equitable deployment that protects human rights.

leading to challenges in understanding the advantages and disadvantages, and developing and responsibly scaling up a CDR industry. Challenges include reducing the energy and other resource requirements, improving the economics of each pathway, accurately and independently quantifying reductions and removals via life cycle analyses (LCAs), and evaluating co-benefits and trade-offs of potential project sites and pathways.

The Mission brings forward the world's first public-private coordinated approach to CDR technology innovation. Through collaborative projects on research, development, and demonstration (RD&D), the CDR Mission will not only accelerate cost and performance improvements but also help industry, investors, governments, and the public gain a better understanding of CDR technologies and impacts. This knowledge will inform decision-making about domestic policies and resources on climate approaches and bolster the private sector's confidence to make further investments to mature and commercialize these technologies. The Mission is helping ensure proper attention is given to understanding CDR opportunities and addressing challenges in a coordinated and cohesive manner.

Mission Purpose and Scope

There are many different CDR approaches, including land-based biological, ocean-based biological, geochemical, and chemical approaches (IPCC 2022). The Mission currently prioritizes the following land-based biological, geochemical, and chemical approaches (commonly referred to as engineered and hybrid approaches): direct air capture (DAC) with storage, enhanced mineralization, and biomass with carbon removal and storage (BiCRS). For each of these approaches, the captured CO_2—whether it is pure or mineralized—can be either geologically sequestered or stored in the form of long-lived products, in a manner intended to be permanent. The Mission is not currently focused on ocean-based approaches (e.g., blue carbon management, ocean fertilization) or entirely nature-based CDR concepts

Public-Private Coordination

Governments, research institutions, innovators, and private investors must work together to achieve the ambitious targets for CDR. Government RD&D funding gives scientists opportunities to evaluate and improve potential technologies and prove they will work. Deploying these technologies will require supportive government policies and skilled entrepreneurs and businesses who know how to take promising technologies and bring them to market at scale. Government support will contribute to predictability, traceability, and accountability.

The recent influx of private capital (e.g., US$650 million for a DAC company in April 2022) and corporate CDR purchases (e.g., US$925 million commitment from Frontier Fund in April 2022) underscores the need for public-private engagement on challenges such as:

- Independent standards to help ensure CDR outcomes are robust, equitable, and safe.
- Certainty in funding since the private sector alone is unlikely to provide sufficient resources in the mid- to long-term that are needed for CDR to reach gigatonne scale.

Private investment in CDR deployments will help drive innovation and learning-by-doing. However, government policies and support—beyond early-stage RD&D—will help catalyze commercial scale deployments to accelerate learning, which then the private sector can apply to new projects.

such as afforestation, improved forest management, or wetland restoration, but recognizes the importance of these approaches.[7]

The high-level goal of the CDR Mission is to enable CDR technologies to achieve a net reduction of 100 million tonnes (0.1 gigatonnes) of CO_2 per year globally by 2030. The CDR Mission aims to catalyze an emerging global CDR industry by increasing RD&D of CDR approaches, harmonizing LCAs and techno-economic analyses (TEAs), and facilitating near-term demonstrations and advancements toward responsible deployments.

In keeping with the MI focus on accelerating RD&D of high-potential technologies, the CDR Mission aims to catalyze the CDR technologies and pathways that are ready for responsible, wide-spread deployment. The Mission also investigates promising nascent approaches, aiming to reduce costs, increase scale, and enhance co-benefits. To reach the levels of carbon removal needed, the emerging CDR industry will need to concurrently a) deploy and scale mature technology pathways, while b) continuing research, development, and demonstration of earlier-stage technologies and pathways that will be needed for gigatonne scale removal.

7 Subject to member interest and capacity, the Mission could explore some of these topics in the future.

2 Opportunities and Challenges

2.1 Direct Air Capture with Storage

Direct air capture (DAC) refers to any process or technology that captures CO_2 directly from ambient air using a CO_2 capture medium that is regenerated for re-use. The captured CO_2 is then securely stored geologically or in long-lived products (locked away in a manner intended to be permanent), in a process known as direct air capture with storage.

Overview of Direct Air Capture Approaches

Near Commercial and Pilot-Scale Technologies

DAC processes that have been deployed at pilot and demonstration scales commonly start with fans to move ambient air through contactors. The contactors apply a chemical or physical process that separates the CO_2 from other molecules in the air. Chemical processes, which are currently the most developed DAC approaches, fall into two main classes of technologies: solid sorbents and aqueous-based solvents. Sorbents usually contain amines that react with CO_2 molecules to form carbamate (including carbamic acid) and/or bicarbonate bonds, while solvents commonly contain hydroxide groups that react with CO_2 to form carbonates and/or bicarbonates.

After the CO_2 from the air has been chemically captured in the contactors, the CO_2-laden material undergoes temperature, pressure, moisture, power supply, and/or chemical swings to release the CO_2 in a concentrated stream, and the sorbent/solvent is regenerated for re-use. The released CO_2 is then compressed and geologically sequestered or durably stored in the form of long-lived products, which is defined in this Roadmap as securing the CO_2 in a manner intended to be permanent.[8]

In DAC systems that employ solid sorbents, amines are usually appended onto very high-surface-area (up to 6,000 m^2/g) porous materials to facilitate the capture of dilute CO_2 concentrations in the air. Promising support structures to use as solid sorbents include resins, alumina, silica, activated carbon, cellulose, covalent-organic frameworks (COFs), and metal–organic frameworks (MOFs). The bond that forms between amines and CO_2 can be broken at relatively low temperatures (~100°C) (McQueen 2021, Sanz-Perez 2016), thus enabling the pairing of solid-sorbent-based DAC systems with low-carbon energy resources such as geothermal, solar thermal, heat pumps or low-grade waste heat. The source of heat must be higher than the required process regeneration temperature to allow for reasonable rates of heat transfer.

In DAC systems that use liquid solvents, a hydroxide such as KOH or NaOH reacts with CO_2 in air to form a carbonate (e.g., K_2CO_3 or Na_2CO_3) that then reacts with calcium hydroxide

8 If the removed CO_2 is re-released, it is equivalent to delayed emissions.

($Ca(OH)_2$) in a causticizer to form calcium carbonate precipitates, which can be recovered and calcined at very high temperatures (up to 900°C) to release the captured CO_2 (McQueen 2021, Sanz-Perez 2016). Liquid solvents are globally available commodity chemicals, can be prepared on a large scale, and are relatively inexpensive, compared to solid sorbents.

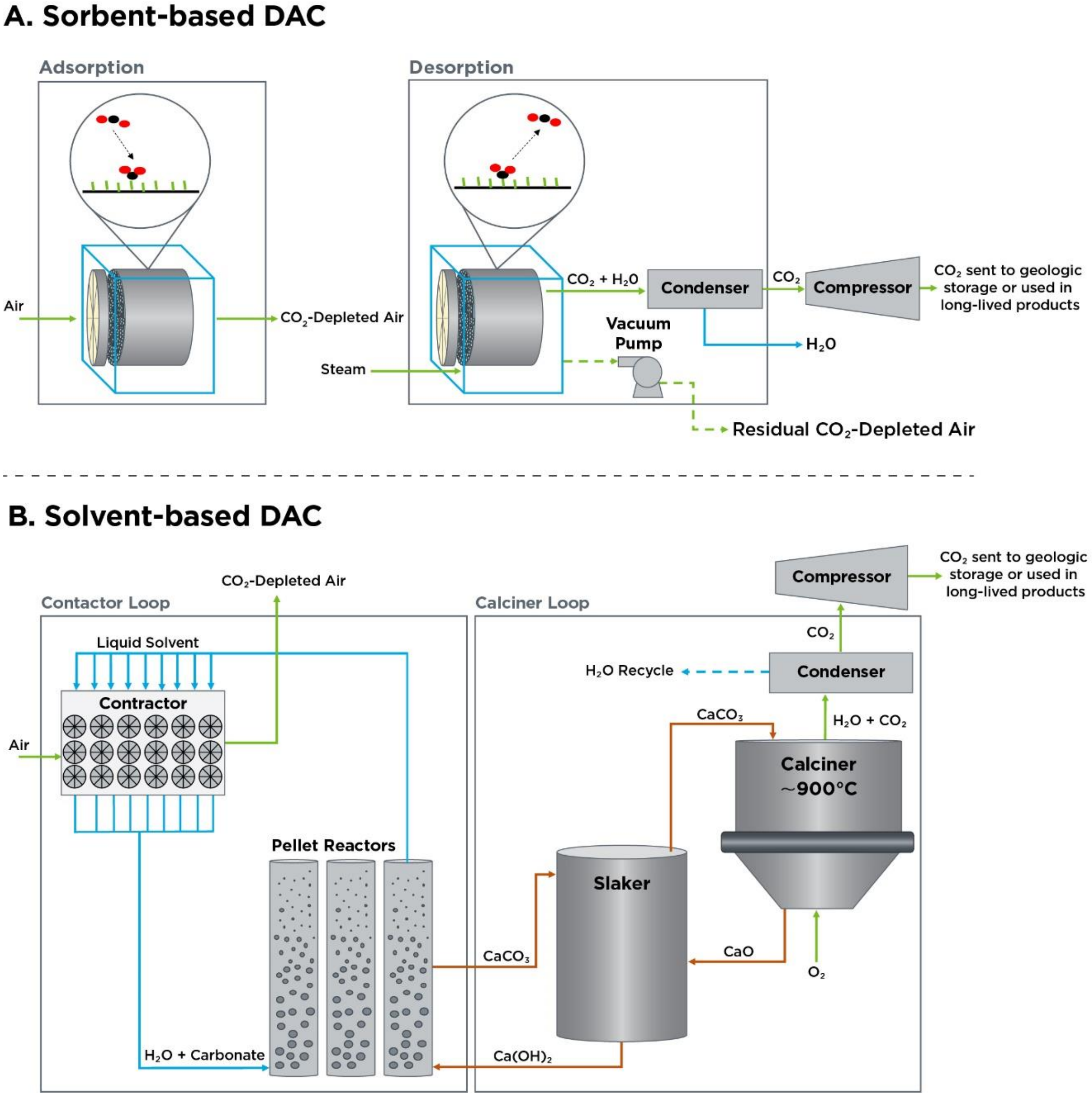

Figure 2. CO_2 capture directly from the air via (A) sorbent- and (B) solvent-based approaches. Note that energy flows are not shown in this simplified process schematic but are also an important aspect of DAC processes and life cycle analyses.[9] (Adapted from McQueen 2021).

9 For solvent-based DAC, the calciner in particular requires substantial energy. This could be provided by low-carbon electric heating or by combustion of natural gas or potentially biomass thereby combining DAC with BiCRS.

Emerging Technologies

Besides advancements to the near-commercial suite of DAC technologies, numerous research organizations and innovative companies are exploring breakthrough DAC technologies:

- **Integration with Existing Airflow Equipment.** Since a significant amount of energy must be expended to flow large volumes of air across contactors, an active area of research couples existing airflow systems (e.g., cooling towers, wind turbines, moving vehicles, and heating, ventilation and air conditioning (HVAC) units) with DAC technologies (Baus 2022, Dong 2021).[10] For example, integrating sorbent or solvent-based DAC units with cooling towers is being explored to reduce the energy expenditure associated with air flow over the contactors.[11] Additionally, coupling DAC with HVAC units could reduce the carbon footprint associated with building construction and operation, while enhancing indoor air quality.[12] Another emerging development is a fan-less DAC technology retrofitted onto commercial trains that is equipped with temporary CO_2 storage units, where regenerative braking energy can be used to regenerate the CO_2 capture sorbent.[13]
- **Passive Direct Air Capture (PDAC).** There could be significant cost and energy savings if DAC could be performed without fans (Shi 2020a, Shi 2020b).[14] For example, mechanical trees are being developed that capture CO_2 passively (without fans) using a moisture swing whereby CO_2 is captured under dry conditions and released under humid conditions.[15] Another design includes a PDAC approach whereby metal oxides/hydroxides (MgO and/or $Ca(OH)_2$) are spread onto large area trays to react directly with the CO_2 in air to form carbonates which are regenerated using a calcination process.[16] (The details of mineralization are explained in the Enhanced Mineralization section.) Another area of research uses $Ca(OH)_2$ particles to passively capture CO_2 in the form of $CaCO_3$ over a period of hours to days. The hydroxide capture medium is then regenerated using acids and bases produced by an electrolyzer, ultimately resulting in a pure stream of CO_2.[17]
- **Direct Conversion into Long-lived Products.** Directly converting CO_2 from air into functional materials with long lifetimes (e.g., construction materials, carbon fibers, ceramics) can satisfy the requirements of high-quality CDR while establishing revenue generation streams to offset the costs of removal (Zuraiqi 2022).[18] Additionally, CO_2 captured from the air could be directly incorporated into concrete materials (e.g.,

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[10] For example, see Urban Sequoia for more details.
[11] See Noya for more details.
[12] See Soletair Power for more details.
[13] See CO_2Rail for more details.
[14] See CO2CirculAir for more details.
[15] See Carbon Collect for more details.
[16] See Heirloom for more details.
[17] See Parallel Carbon for more details.
[18] See Carbon Cantonne and SkyNano Technologies for more details.

cement, aggregates, demolition waste) to enhance material properties and store CO_2 that has been removed from the atmosphere.[19] (This concept is further explained in the Enhanced Mineralization section.)

- **Co-product Generation.** Co-products can provide a revenue stream offsetting some of the cost of DAC, as long as the separation of CO_2 from the co-product does not require significant energy inputs or incur other major costs. For example, some sorbent-based processes can generate water as a co-product by extracting humidity from the atmosphere along with CO_2.[20] On-demand, high-purity water can be valuable particularly in densely populated, arid environments.
- **Low Temperature DAC.** Heat required to regenerate sorbents or solvents is the main driver of energy use in most DAC processes. The thermodynamics of adsorption are more favorable at lower temperatures, although kinetics are typically slower. Recent research suggests the overall temperature differential required to regenerate sorbents can be significantly reduced when DAC is performed at low temperatures (around -20°C) (Rim 2022). Energy savings have been demonstrated from DAC operations in colder climates.[21]
- **Novel Regeneration Swings.** Another route to minimize heating requirements is to employ regeneration methods which could be powered directly by renewable electricity (e.g., electrochemical, microwave).[22] For example, researchers are developing a solvent-based DAC process based on an electrochemical separation method that has the potential to reduce energy requirements.[23] Another research area involves electrodes which are coated with redox active molecules that possess a strong binding affinity for CO_2. At a particular voltage, the modular electrolyzer stack can capture CO_2 from air, and when the voltage is switched the CO_2 is subsequently released. No additional heating would be needed for this process.[24] Instead of relying on the co-development of renewable electricity infrastructure as DAC is scaled up, some designs directly incorporate wind turbines[25] and solar photovoltaics[26] into the modular DAC process flow units.

Potential Scale of Direct Air Capture

The deployment of large-scale DAC technologies has the potential to capture CO_2 from the atmosphere at rates of one to tens of Gt CO_2/yr (CDR Primer 2021, IEAGHG 2021, IPCC 2022). There are currently 19 demonstration or small-scale DAC plants in the world (IEA 2021) with a total capture capacity of about 11,000 tonnes of CO_2 per year, where about

[19] See Brimstone and Neustark for more details
[20] See Carbon Capture and Avnos for more details.
[21] For example, see Climeworks and TerraFixing for more details.
[22] See RepAir, Holy Grail, and RedoxNRG for more details.
[23] See Mission Zero Technologies for more details.
[24] See Verdox for more details.
[25] See Carbon Blade for more details.
[26] See AspiraDAC for more details.

half of the captured CO_2 is geologically stored (IEAGHG 2021). The other half is used for food, beverage, or agricultural applications, which may result in CO_2 being released into the atmosphere over short time scales and would not satisfy the durable storage requirements of CO_2 removal. Additional direct air capture capacity units totaling more than 1 Mt CO_2/yr are in advanced stages of development, although not all DAC facilities are expected to result in net CO_2 removals. One study found that if the global DAC removal capacity can reach 2 Mt CO_2/yr by 2025, then by assuming 20-30% scale-up rates 190-1,400 Mt CO_2/yr can be achieved by 2050 (Mulligan 2020).

Status of Pilot-Scale Direct Air Capture

Cost

- The levelized cost of DAC projects varies significantly (Realmonte 2019, Young 2022) and is currently reported in the range of US$350-$700+ per net tonne of CO_2 removed (Evans 2017, Gertner 2019, IEAGHG 2021, McQueen 2021, Ozkan 2022b).[27] The estimates are highly dependent on factors such as the scale of the project, location, purity of CO_2 captured, financial assumptions, the type of capture technology employed, the type of energy used to power the process, local conditions like climate, and other factors.
- The cost of compressing and storing supercritical CO_2 fluid in subsurface pore spaces is about US$10-20/t CO_2 (CDR Primer 2021, NASEM 2019), however, the cost varies across geographic, geologic, and institutional settings due to regional differences such as transport mode and distances, scale of operation, monitoring assumptions, permitting, and reservoir geology (Smith 2021).

Energy use

- DAC systems typically need a large amount of energy, roughly 5–10 GJ/t CO_2 removed (Baker 2020, Mulligan 2020, NASEM 2019), with an energy mix of 60-80% heat (for CO_2 release and sorbent/solvent regeneration) and 20-40% electricity (for fans, vacuum pumps, and process units) (IEAGHG 2021, NASEM 2019).[28] Assuming an energy requirement of 10 GJ/t CO_2, DAC would require about 10% of the total annual U.S. energy consumption to scale to a capture rate of 1 Gt CO_2/yr (Mulligan 2020).
- Sorbent-based approaches require heat energy of about 1–6 GJ/t CO_2 (which is dependent on the strength of the physical or chemical interaction between the sorbent and CO_2) and electrical energy of roughly 1–2 GJ/t CO_2, while solvent-based technologies require about 5–8 GJ/t CO_2 of heat and roughly 1–2 GJ/t CO_2 of electricity (McQueen 2021, Ozkan 2022b). Novel regeneration swings could reduce the amount of heat energy required to release the captured CO_2.

[27] Costs of DAC with durable storage are variable and uncertain, as the technology has yet to be deployed at large scale. It should be noted that wider estimate ranges (beyond $1000/t$CO_2$ removed) have been mentioned in the literature (Realmonte 2019, Young 2022).

[28] Some reports have noted that their DAC processes require slightly larger amounts of energy, between 10-14 GJ/tCO_2 (Deutz 2021, Young 2021).

- Based on these energy requirements, sorbent-based and solvent-based approaches require about 180 MW and 310 MW of power, respectively, to capture 1 Mt CO_2/yr (assuming closer to the higher end of the energy requirements and a capacity utilization factor of 90%) (Baker 2020).

Land use

- From a techno-economic standpoint, DAC can be sited nearly anywhere there is access to low-cost and low-carbon energy and in proximity to geologic storage sites or other durable end-uses for captured CO_2 (e.g., construction materials, ceramics). DAC located near sources of waste heat could reduce burdens on the energy system. However, the sensitivity of overall DAC performance to different ambient conditions (e.g., hot and humid vs. cold and dry) is an important consideration during the initial planning and development of large-scale projects (Rim 2022). CO_2 partial pressure decreases at higher elevations which may also pose constraints on the feasibility of siting DAC plants.
- The land area footprints for sorbent-based DAC plants (not considering energy source or compression equipment) capturing 1 Mt CO_2/yr are estimated to range from 0.1-2 km^2 (Baker 2020, Beuttler 2019, Lebling 2022a, Ozkan 2022b). For solvent-based DAC, the land area requirement for a 1 Mt CO_2/yr facility is estimated to be about 0.5 km^2 (Lebling 2022a, Ozkan 2022b).
- The total land area, including land use for energy generation outside the facility fence line, depends largely on the source of heat and power. Natural gas energy source requires 1,400 m^2/MW (34% capacity factor), nuclear requires 2,500 m^2/MW (90% capacity factor), solar PV requires 120,000 m^2/MW (28% capacity factor), and wind energy requires 240,000 m^2/MW (28% capacity factor) (Stevens 2017). With today's technology, a DAC plant capturing 1 Mt CO_2/yr would require up to about 20 km^2 of additional land area if powered entirely by PV (Baker 2020). These estimates highlight that regardless of the DAC process, the size of the overall plant could become limited by the land area required for the energy source.

Water use

- Operating a DAC process can consume a significant amount of water, or conversely, it could produce water, depending on the process. In solid sorbent processes, the water usage is highly variable. Processes that incorporate the use of steam condensation for the regeneration of solid sorbents may contribute to water being lost to the environment at a ratio of 1.6 t H2O/t CO_2 (NASEM 2019). Some DAC sorbent systems produce water on a net basis, which is highly dependent on the climate where the plant is located and the method of heating employed (steam condensation vs. indirect heating) (Lebling 2022b).
- Significant amounts of water (1-7 tH2O/t CO_2) are typically lost to the environment in the form of evaporation during the air contacting step in liquid solvent-based DAC processes. The amount of water lost is similar to the amount of water required to manufacture a tonne of cement or steel and the extent of water lost to the

environment will increase with a higher temperature or lower relative humidity of the plant site (Keith 2018, Lebling 2022b).

Direct Air Capture Technological Challenges

Examples of DAC Companies

Climeworks, a Swiss company, has developed a solid sorbent DAC technology. The company has deployed 15 DAC demonstration plants (of which some are powered solely by renewable energy). In a partnership with Carbfix, Climeworks has developed a facility in Iceland that is currently capturing and storing CO_2 at a capacity of 4,000 tCO_2/yr. Climeworks announced a partnership with 44.01, a company that has developed an in-situ mineralization technology, for the capture and storage of CO_2 in geologic formations in the Middle East. In April 2022, Climeworks announced that it raised $650 million in its latest round of equity funding. In June 2022, Climeworks revealed plans to develop a new DAC facility (called Mammoth) capable of removing 36,000 tCO_2/yr and is expected to be operational by 2024.

Global Thermostat, a U.S. company, has developed a solid sorbent DAC technology. The company has constructed two plants with a capacity of 2,000 tCO_2/yr and is partnering with ExxonMobil. In July 2021, Global Thermostat announced a partnership with engineering firm Black & Veatch to construct a 100,000 tCO_2/yr DAC plant, supported by $2.5 million in U.S. DOE cost-share funding.

Carbon Engineering, a Canadian company, has developed a liquid solvent technology for DAC. Carbon Engineering is partnering with Oxy Low Carbon Ventures and 1PointFive to deploy a 1 $MtCO_2$/yr plant in the Permian basin of the United States, and the facility could be operational in 2024. The project currently plans to use the captured CO_2 for enhanced oil recovery applications, which contribute to overall emissions reductions (decarbonization). Using Carbon Engineering's technology, Oxy Low Carbon Ventures and 1PointFive plan to deploy 70 to 135 DAC plants, each with a capture capacity of 1 $MtCO_2$/yr, with downstream geologic sequestration and enhanced oil recovery applications.

Cost for DAC is a central barrier to greater deployment. To this end, important technological challenges for DAC systems include (but are not limited to) sorbent/solvent materials CO_2 loading capacity and rate, supply chain for materials, and energy use.[29]

- **Material performance.** CO_2 loading capacity (also called working capacity, which depends on the absorption and desorption capacity of the material) and sorbent/solvent lifetime are important parameters driving operating costs. These costs can be reduced with sorbent/solvent materials that have higher CO_2 capture capacities and longer-term stability in air.
- **CO_2 capture and desorption kinetics.** The rate of CO_2 capture affects the capture-regeneration cycle time and therefore the overall operating efficiency of the DAC plant. Local temperature and humidity of the DAC plant site affect the reaction rates and complicate efforts to optimize absorption and desorption rates.
- **Material supply.** The ability to sustainably scale-up sorbent materials (e.g., amines and support structures) manufacturing is a supply side challenge; advanced developments in recycling and reuse of sorbents may mitigate this challenge.

[29] Technology challenges associated with CO_2 compression, transportation, and injection for geologic storage or utilization in durable products are also important considerations for DAC system development and scale up but are not the focus of this roadmap since these topics are well examined in other documents, such as the Carbon Sequestration Leadership Forum Technology Roadmap.

- **Energy use.** Large energy inputs, such as requirements for air contacting and sorbent/solvent regeneration, are currently necessary to release the captured CO_2 and regenerate the capture materials.
- **Systems.** To result in the efficient removal of CO_2 from the atmosphere, DAC plants will need to be integrated with low carbon energy sources and durable storage and/or utilization mechanisms. Additionally, the costs of performing DAC can be offset by process designs enabling the generation of co-products or even the direct conversion of air-captured CO_2 to valuable products.

Significant breakthroughs in the performance of DAC can be made by reducing energy requirements of air contacting and sorbent/solvent regeneration, electrifying all energy inputs for straightforward integration with renewable electricity, and tapping into existing chemical/manufacturing supply chains for process scale-up.

Equipment

Solid sorbent units are typically modular by design, which may increase siting flexibility, consistency and standardization, and lower investment risks (Lackner 2022). Furthermore, learning rates tend to decrease with unit size because of fewer opportunities for iterative improvement as the technology is developed (Sweerts 2020). Sorbent-based contactor units can be stacked in a modular fashion to increase plant size, depending on the scale of the desired CO_2 capture application. For example, solid sorbent DAC units can be designed so that the repeat module has a capacity of about 50 t CO_2/yr (McQueen 2021). However, these systems usually rely on a vacuum swing regeneration to extract excess air from the contactor, requiring large cross-sectional areas and thicker process equipment units that increase costs.

To regenerate the CO_2-laden liquid solvents, process units downstream of the air separation unit are required, as depicted in **Figure 2B** (e.g., pellet reactor, slaker, calciner). Since the capture and regeneration steps take place in different types of reactors, the minimum feasible unit size of liquid solvent DAC technologies is expected to be larger when compared to sorbent-based DAC technologies. However, the liquid-solvent DAC plants can be constructed based on an architecture of repeatable modular units, such as air contactors, and central processing facilities, to achieve economies of scale.

Given the nascency of DAC, a diversity of approaches will be required to achieve gigatonne scale deployments, and it will be important to consider how factors such as unit size and advanced manufacturing methods will play a role in reducing overall process costs. The cumulative capacity and number of projects are two critical metrics which should be prioritized to drive learning-by-doing and cost reductions of DAC.

Opportunities to address the main challenges for sorbent-based approaches and solvent-based approaches are outlined below in **Table 1** and **Table 2**, respectively. Opportunities for earlier-stage emerging approaches are outlined in

Table 3. For more details on each opportunity shown below, please refer to sources provided in the right-hand column.

Table 1. Key Technology Challenges and Innovation Gaps for Solid Sorbent DAC Technologies[30]

Technology Challenge Area	Innovation Gap	Sources for Further Detail
Material Performance	• Novel materials with high CO_2 capture flux (>3.5 mol CO_2/ min*m^3), such as functionalized MOFs, zeolites, activated carbon, silica materials, carbon nanotubes, porous organic polymers, and carbon molecular sieves	McQueen 2021, Ozkan 2022b, Siegelman 2021, Sinha 2016,
	• Advanced support structures with increased interactions with CO_2 (i.e., increase space velocity)	DeWitt 2018, McQueen 2021, Siegelman 2021
	• Materials that have minimal loss of CO_2 loading capacity in the presence of heat and oxidizing components (>1 year of continuous cyclic operation)	Azarabadi 2019, Feric, 2021, Nezam 2021, Ozkan 2022b
CO_2 Capture and Desorption Kinetics	• Minimization of the fluid boundary diffusion resistance (mass transfer limitation) and the internal diffusion resistance at the pore level (kinetic limitation)	DeWitt 2018, McQueen 2021
	• Engineered materials with pore sizes that span many scales (hierarchical) so that a low pressure drop (large pores) can be achieved for facilitating mass transport while also maintaining a high surface area (small pores)	McQueen 2021
	• Optimization of the effect of temperature and humidity on CO_2 capture rates	Deng 2021, Kong 2022, Rim 2021
Material Supply	• Manufacturing scale-up that is low cost and minimizes energy demand and environmental impact	Deutz 2021, McQueen 2021, Ozkan 2022b
Energy Use	• Optimization of base strength to minimize system energy requirements for regeneration (e.g., vacuum and temperature)	McQueen 2021
	• Reduction of pressure drop across the contactor through shallow contactor design and optimized sorbent packing in the contactor arrays	Ozkan 2021, Sanz-Perez 2016
	• Lower specific heat capacity and higher thermal conductivity of sorbent materials	McQueen 2021, Realff 2021
Systems	• Plant siting (e.g., effects of local climate, altitude, resources, proximity to storage opportunities)	CDR Primer 2021, Lebling 2022a, Okzkan 2022b
	• Integration with low-carbon energy supply	CDR Primer 2021, Deutz 2021, Lebling 2022a, Ozkan 2022b

[30] The technology challenges presented in the table have been obtained from a literature review conducted by the authors of the roadmap, and augmented based on input from CDR mission members and other subject matter experts.

Table 2. Key Technology Challenges and Innovation Gaps for Liquid Solvent DAC Technologies[31]

Technology Challenge Area	Innovation Gap	Sources for Further Detail
Material Performance	• Novel solvent chemistries with high CO_2 capture flux (>0.5 mol CO_2/min*m^3)	Brethome 2018 Diederichsen 2022, Keith 2018, Liu 2020a, Prajapati 2022, Simeon 2022, Voskian 2020
	• Advanced packing materials with increased interactions between base chemistry and CO_2 (i.e., increase space velocity)	DeWitt 2018, McQueen 2021, Sanz-Perez 2016
	• Solvents that maintain their CO_2 loading capacity with low degradation rates in the presence of heat and oxidizing components	Azarabadi 2019, Feric2021, Nezam 2021, Ozkan 2021
CO_2 Capture and Desorption Kinetics	• Faster kinetics (instantaneous reaction vs. fast pseudo first order); Reaction constant > 10^{10} cm^3/mol*s, liquid-phase mass transfer coefficient < 10^{-3} m/s	McQueen 2021
	• Reduced liquid-phase diffusion resistances by enabling thinner coating of liquid solvent in the reactor (i.e., reactor design)	Brethome 2018, McQueen 2021
Material Supply	• Manufacturing scale-up (for non-globally available commodity chemicals) that is low cost and minimizes energy demand and environmental impact	McQueen 2021, Ozkan 2022b
Energy Use	• Optimization of base strength to minimize system energy requirements for regeneration	McQueen 2021, Sanz-Perez 2016
	• Reduction of pressure drop across the contactor through shallow contactor design and other design optimizations	Ozkan 2021, Sanz-Perez 2016
	• Lower specific heat capacity and higher thermal conductivity of solvent materials	McQueen 2021, Realff 2021
Systems	• Plant siting (e.g., effects of local climate, altitude, resources, proximity to storage opportunities)	CDR Primer 2021, Lebling 2022a, Okzkan 2022b
	• Integration with low-carbon energy supply	CDR Primer 2021, Deutz 2021, Lebling 2022a, Ozkan 2022b

[31] The technology challenges presented in the table have been obtained from a literature review conducted by the authors of the roadmap, and augmented based on input from CDR mission members and other subject matter experts.

Table 3. Key Technology Challenges and Innovation Gaps for Emerging DAC Technologies[32]

Technology Challenge Area	Innovation Gap	Sources for Further Detail
Energy Use	• Integration of DAC with existing airflow infrastructure to minimize additional energy inputs (e.g., HVAC units and cooling towers)	Baus 2022, Dong 2021, Erans 2022
	• Passive transport of ambient air to reduce energy requirements of forced airflow	Ozkan 2022a, Ozkan 2022b, Shi 2020a, Shi 2020b
	• Novel desorption approaches (e.g., electro-swing, microwave-swing, steam-swing, moisture-swing) to reduce heating requirements and improve energy efficiency of regeneration	Ellison 2021, Hemmatifar 2022, McGurk 2017, Ozkan 2021, Ozkan 2022a, Shi 2020a, Shi 2020b, Voskian 2019, Zhu 2021
	• Identification and development of materials that can capture CO_2 at low temperatures (e.g., -20 °C) and be regenerated under mild conditions (e.g., 25 °C) while maintaining a high CO_2 working capacity	Kong 2022, Rim 2022
Systems	• Co-product generation (e.g., capturing the humidity in air) to create an additional revenue source	Lebling 2022b
	• Direct conversion of air-captured CO_2 into long-lived products	Zuraiqi 2022

Direct Air Capture Projected Costs

Current reported costs for DAC plus storage are high, but companies developing DAC technologies forecast substantial cost reductions in the next few years. Design improvements and declining manufacturing costs could reduce costs of current DAC approaches to about US$200–$300/net-t CO_2 removed by 2024 (CDR Primer 2021, Gertner 2019, IEAGHG 2021).[33] On the other hand, a recent techno-economic study suggest that the costs of DAC may only reach ~US$200–$300/net-t CO_2 removed sometime between 2050 and 2075 (Young 2022).[34] Other forecasts estimate that by 2050 costs may be as low as

[32] Challenges and innovation gaps for emerging approaches identified in this table may also be applicable to sorbent and/or solvent approaches. In other words, the scope of the tables are not mutually exclusive. The technology challenges presented in the table have been obtained from a literature review conducted by the authors of the roadmap and augmented based on input from CDR mission members and other subject matter experts.

[33] The Carbon Engineering and Oxy Low Carbon Ventures large-scale DAC facility in the U.S. has estimated costs of a 0.5 $MtCO_2$ first-of-a-kind facility to be US$300-430/t CO_2, but would eventually drop to US$125-150/t CO_2 with more deployments.

[34] The four DAC processes that were examined include KOH absorption paired with regeneration via lime looping, KOH absorption coupled with regeneration via bipolar membrane electrodialysis, solid sorbent DAC employing a temperature vacuum swing adsorption process, and ambient weathering of MgO paired with a calcination regeneration process.

US$46–$164/net-t CO_2 stored, if approximately 0.5 Gt CO_2/yr cumulative capacity is reached (Larsen 2019). The Carbon Negative Shot initiative (United States) aims to reduce the cost to US$100/net-t CO_2e by 2032 of any approach that will measurably remove CO_2 from the air and durably store it at meaningful scales; the cost target includes separation, transport, sequestration, and monitoring.[35] Assuming these goals are met, employing DAC to remove one gigatonne of CO_2 would cost about US$100 billion (Mulligan 2020, NASEM 2018).

In addition to RD&D investments, deployment is critical to facilitate experiential learning to drive down costs. Learning-by-doing could facilitate the cost reductions of current DAC approaches by an order of magnitude within the next decade, following a similar cost trajectory to PV modules in the early 2000's (Lackner 2022). If the scale of DAC installed capacity increases to 1.5 Mt CO_2/yr, learning-by-doing could drive down costs to $100 per tonne assuming a learning rate of 20% (Lackner 2022). Before opportunities for further cost reductions can be fully understood, DAC systems will need to be tested at scale and under real environmental conditions (Mulligan 2020, NASEM 2019).

Summary

RD&D on current process designs (plus learning-by-doing from increased deployments) have the potential to deliver near-term improvements in cost and performance and result in more tonnes removed in the short term. RD&D on pilot scale DAC technologies will help prove technologies work in different environments and assist in scale up to commercial size facilities. Gigatonne scale removals may also require substantial technology breakthroughs enabled through investment in RD&D on novel materials and processes beyond the approaches that are deployed at small scale today. In the longer term, RD&D on advanced materials with long-term stability, engineered systems that enhance capture kinetics, and paradigm-shifting designs that reduce energy use provide opportunities for step-change technological improvements.

Technological innovations are but one of several important aspects that will enable large-scale DAC deployments. Addressing non-technical barriers, such as financing (from hard to decarbonize industries in particular), demand certainty, incentive policies, and community engagement will be especially critical for near-term deployments. In addition, deployments of increasingly larger-scale DAC plants and development of enabling business models and regulations will facilitate learning-by-doing.

Technological advancements and analysis can address not only technology challenges outlined herein but also can help address non-technical barriers to DAC. This includes informing policies for responsible storage in a manner intended to be permanent or CO_2 transport infrastructure, access to low-carbon energy, efficient use of water resources, quantification of co-benefits, and collection of accurate data for understanding life cycle impacts. Public policy will be required to value the emissions reductions and removals

[35] https://www.energy.gov/fecm/carbon-negative-shot

that DAC enables, overcome financing barriers related to upfront capital needs and development timelines, and enable the creation of viable long-term markets.

2.2 Enhanced Mineralization

Enhanced mineralization is the acceleration of the natural reaction of CO_2 from ambient air with alkaline minerals to form stable carbonates, storing the CO_2 in a manner intended to be permanent.

Overview of Enhanced Mineralization Approaches

Enhanced mineralization emulates and accelerates natural carbonation processes, making use of chemical potential energy available in rocks by exposing minerals that were far from equilibrium with the atmosphere and hydrosphere (NASEM 2019). Mineralization processes naturally occur at the following locations: Earth's surface where silicate rocks are exposed to the atmosphere, in the subsurface through the percolation of CO_2 rich water into reactive rock formations, and in the ocean through formation of dissolved bicarbonates that have the potential to precipitate as solid carbonates. Some enhanced mineralization processes involve the regeneration of the alkaline minerals for re-use, similar to recycling a solvent or sorbent in a DAC process. The Roadmap focuses on surficial mineralization processes, also referred to as enhanced rock weathering, which expose CO_2 in the atmosphere to pulverized minerals typically dispersed over land in thin layers at atmospheric temperature and pressure conditions (**Figure 3**).[36] These pulverized minerals enhance naturally occurring silicate weathering processes, which remove CO_2 from the atmosphere through mineralization reactions between the CO_2 in the air that is dissolved in water and sources of alkalinity that leach out from the silicate materials and rocks rich in calcium and magnesium.

[36] Surficial enhanced mineralization processes are the focus of this section since it is land-based (ocean-based approaches are currently not part of the CDR Mission) and does not involve processes for concentrating CO_2, which is included in the DAC section. Other mineralization approaches include *in-situ* and *ex-situ*. *In-situ* describes approaches for reacting CO_2-rich (concentrated) fluids with naturally occurring minerals deep (800-1000 m) below the earth's surface for permanent storage. *In-situ* mineralization could be coupled with DAC as mentioned under Emerging Technologies in the DAC section. *Ex-situ* mineralization involves the use of alkaline minerals that are placed in a reactor and exposed to concentrated streams of CO_2 in high temperature and/or pressure conditions. *Ex-situ* mineralization processes can also be used to capture and store CO_2 from fossil fuel combustion point sources, however, such processes are usually not considered removal since the CO_2 is not being removed from the atmosphere. *Ex-situ* mineralization can be used to durably store CO_2 from a source such as DAC that captures CO_2 from the atmosphere and produces an effluent stream containing a high concentration of CO_2. For example, DAC systems where CO_2 from the air is concentrated to only about 10%–20% purity are then reacted with alkaline minerals. By increasing the concentration of CO_2 from 400 ppm to 10–20 wt.%, significantly less energy is required than going from 400 ppm to 95 wt.% (Kelemen 2020, Wilcox 2017). If high pressure conditions are required to facilitate mineralization, these additional energy-intensive steps need to be accounted for on a techno-economic and life cycle basis.

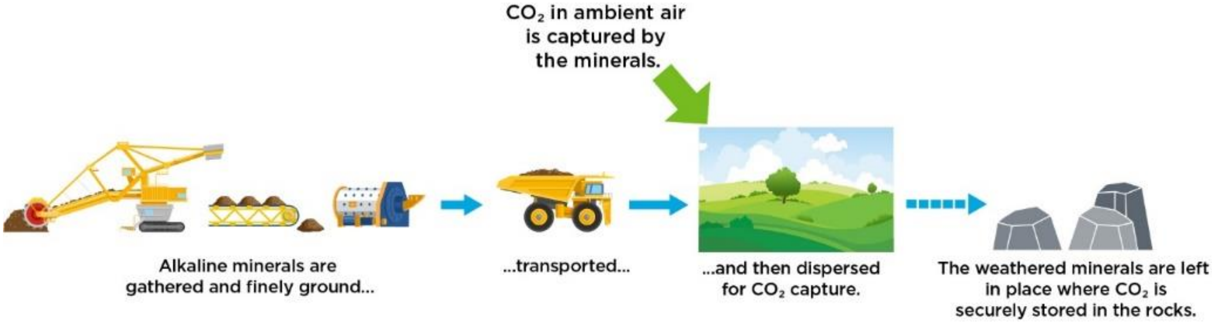

Figure 3. Diagram outlining potential surficial mineralization steps (Adapted from Spence 2021).

The most promising sources of alkalinity for CDR come from rocks containing a high concentration of Mg^{+2} and Ca^{+2} ions, which can be found in silicate minerals (e.g., olivine, wollastonite, and serpentine), mafic/ultramafic rocks (e.g., basalts, peridotites, and serpentines), and waste materials from industrial or mining operations (e.g., steelmaking slags and mine tailings) (CDR Primer 2021). Such mineral sources are prevalent across the globe. Materials other than wastes would need to be mined and ground (activities that entail their own carbon footprints, as well as land impacts) before being used to capture CO_2 directly from the air.

Mineralization provides secure storage of CO_2 and since carbonates possess a lower energy state than CO_2, mineralization proceeds favorably from a thermodynamic perspective. Additionally, these reactions allow the capture and storage to occur in a single step, potentially eliminating the logistics and energy requirements of transporting CO_2 from the capture to storage site. Early research suggests that the application of finely ground rock dust to agricultural soils has co-benefits such as improved soil quality and increased crop yields (Beerling 2018, Mulligan 2020, Vienne 2022), in addition to CO_2 removal, although rock dust can produce negative air quality and health impacts. Mineralization is most effective in warm, humid conditions (Strefler 2018). For example, calcium hydroxide ($Ca(OH)_2$) reacts rapidly with CO_2 and this rate is highly dependent on the presence of water.

Potential Scale of Enhanced Mineralization

Currently, there are few companies performing surficial mineralization at the field scale. Since no comprehensive life cycle analysis has been made publicly available, the current scale of surficial mineralization net removal is estimated to be about zero.

The deployment of surficial mineralization solutions appears to have a large-scale CO_2 removal potential. Solid industrial alkaline wastes, such as steelmaking slags and mine tailings, are produced at rates with a theoretical storage capacity of up to 1.5–3 Gt CO_2/yr, though the sluggish rates of mineralization may limit these values (Kelemen 2019, Renforth 2019). In addition, while estimates vary, 0.5–2.0 Gt CO_2/yr or more could theoretically be removed via the application of basalt powders to 10%–50% of global cropland (Sandalow 2021a). The theoretical capture capacity of olivine is about 1 tonne of CO_2 per 1 tonne of rock (Schuiling 2006), though complete carbonation may take hundreds of years as the

rate of capture from air greatly depends on the particle size (Kelemen 2020). For other rock types, such as basalt, this ratio can be as low as 1 tonne of CO_2 per 4 tonnes of rock (Mulligan 2020, NASEM 2019).

Mineralization using magnesite has the potential to remove at least 2–3 Gt CO_2/yr. There are about 8.5 Gt of magnesite in reservoirs around the world, of which only 30 Mt/yr are currently mined (Bray 2020). To remove 1 Gt CO_2/yr (assuming a 20 μm particle size and 90% carbonation achieved), this approach would require about 7,000 km^2 of land area (McQueen 2020) and one quarter of the worldwide magnesite reserves (Kelemen 2020),[37] highlighting that feedstock and resource availability do not appear to be limiting factors for this process. However, it should be noted that current mining operations would need to be scaled up by a factor of around 30 to achieve this level of CO_2 removal. Other than magnesite, other sources of alkalinity such as CaO, Na_2O, or industrial wastes could be explored as mineralization feedstocks.

Altogether, with favorable policies and support, surficial mineralization could remove about 1 Gt CO_2/yr from the atmosphere by 2035 and 10 Gt CO_2/yr by 2050 (Sandalow 2021a). However, this would involve the mining, grinding, and transportation of rocks on the Gt scale as well, and so—similar to other CDR approaches—impacts and trade-offs would need to be carefully considered.

Status of Enhanced Mineralization Technologies

Surficial mineralization pathways are in the early stages of development. The main steps include mineral acquisition, mineral processing (e.g., crushing, grinding and/or pre-treatment), transportation, carbonation, stirring and monitoring.[38] Few concepts have developed beyond TRL 4, although some may have progressed to TRL 6 and above (Zevenhoven 2022 – in press). Potential costs for surficial mineralization pathways range from roughly US$50–500/t CO_2, although this estimated cost range is preliminary given the lack of large-scale deployments (Mulligan 2020). Costs are mainly dependent on the differences in feedstock material composition and process requirements as well as the reactivity of selected minerals, energy source for regeneration (if a cyclic process is employed), and duration of the exposure to air (Kelemen 2019, McQueen 2020, NASEM 2019). For example, because of differences in alkalinity, enhanced weathering applications that use dunite cost an estimated US$60/t CO_2, while those that use basalt cost an estimated US$200/t CO_2, assuming a particle size of 20 μm (Sandalow 2021a, Strefler 2018).

Crushing and grinding rocks can also be a significant driver of costs and energy use. Using current methods, creating surface areas on the order of 1–10 m^2/g requires 10–100

[37] Repeated cycles of CDR, separation of CO_2, and re-use of MgO, could provide a sink for ~1 Gt CO_2 per cycle

[38] *Ex situ* mineralization processes are more mature and have reached demonstration phase of development. Costs for *ex situ* processes are estimated at roughly \$70–\$300/tCO_2-stored (CDR Primer 2021, Kelemen 2019, NASEM 2019). The costs could be further reduced through the conversion of alkaline-containing solid and CO_2-containing gaseous waste streams to produce valuable products for use in building/construction materials, and some companies are actively incorporating this technology into their processes with rates of hundreds of MtCO_2/yr expected by 2030.

kWh/t-rock, though technological breakthroughs could allow for greater surface areas of around 10–100 m^2/g but at much higher energy use of ~100–500 kWh/t-rock (Kelemen 2020). The optimal particle size for the kinetics of enhanced mineralization processes is roughly 10–100 μm, though increasing the specific surface area is more important to maximize the contact between CO_2 and the inorganic mineral (Kelemen 2020, Strefler 2018). Creating ultrafine particles (<10 μm) significantly increases energy and cost requirements associated with grinding, and may pose health risks (accidental inhalation of the particles) (Strefler 2018). For example, grinding olivine particles from a size of 120 μm to 4 μm requires an additional 150 kWh/t rock (Turri 2019). Findings from field studies suggest that particles in the size range of 100–1000 μm may be sufficient to remove CO_2 from atmospheric conditions, as long as the specific surface area of the rocks are greater than 1 m^2/g (Project Carbdown 2022). Spreading particles less than 100-200 μm in size may be difficult. Costs associated with applying mine tailings for enhanced mineralization involve additional crushing and grinding steps (~US$10/t of rock), transportation (US$0.05/km/t of rock), distribution (US$12–14/t of rock), and stirring (US$2/t of rock) (Kelemen 2020, Sandalow 2021a, Strefler 2018). Additional costs would arise from collecting and calcinating the rocks for regeneration and re-use (for cyclic processes), as well as applying robust monitoring, reporting, and verification.

Due to the favorable carbonation thermodynamics, the energy required to capture CO_2 from the air via enhanced mineralization is minimal (<0.05 GJ/t CO_2 captured, though 5–8 GJ/t CO_2 is required if the minerals are regenerated in a continuous cycle) (McQueen 2020, McQueen 2022). The continuous cycle pathway involves cyclic calcination and weathering (e.g., MgCO3-MgO), with subsequent CO_2 storage or utilization.[39]

Examples of Enhanced Mineralization Projects in the Private Sector

The Future Forest Company, a U.K. company, is exploring an enhanced weathering approach whereby basalt powders are crushed and spread over forest floors. The company plans to deploy pilot-scale projects to examine the effectiveness of the approach.

Carbin Minerals, a Canadian company, has developed a technology that enhances CO_2 mineralization rates of mine tailings and enables the collection/extraction of metals that are needed for the clean energy applications.

greenSand, a Dutch company, is sprinkling olivine powder on soil to mineralize CO_2 and nourish the soil at a cost reportedly around US$50/t CO_2.

Enhanced Mineralization Technological Challenges

Key technology challenges to CO_2 mineralization include kinetics of carbonation in rocks, energy and land use, monitoring CO_2 uptake, and system logistics.

The rate of mineralization is the primary challenge, as nature-based carbonation reactions typically occur on geological timescales (Kelemen 2019). In research efforts to accelerate rates, scientists have uncovered mechanisms of mineralization reactions,

[39] Although the continuous cycle pathway resembles a process similar to DAC pathways, it is included in this section because its challenges and innovation opportunities are aligned with mineralization pathways.

though further research is required to determine suitable combinations of rocks and reaction conditions for CDR applications (NASEM 2019, Li 2022, Zhong 2021). There is limited understanding of the effects of pressure, temperature, pH, surface area, and particle size for different rocks and materials (Kelemen 2019, Kelemen 2020).

The energy use for large-scale surficial approaches could be a limiting factor, as crushing and grinding rocks to a fine powder is energy-intensive. Innovative systems integration could allow for the pairing of processes that result in the production of crushed alkaline powders with CO_2 mineralization reactions. Energy requirements could also be reduced by optimizing particle sizes of the feedstock and the dispersed rock (CDR Primer 2021, Kelemen 2020, Sanna 2013).

In a surficial mineralization process, the land area required to remove 1 Gt CO_2/yr is estimated to be around 150,000 km^2 (assuming a 10 cm thick layer of tailings and a concentration of 3 wt.% labile Mg in mine tailings) (Kelemen 2020). For context, 150,000 km^2 is about the size of Tunisia. The land area required could be reduced to roughly 1,500-15,000km^2 (roughly the size of Qatar) by using a cyclic process in which the tailings are regenerated after being in contact with the air for a certain period (Kelemen 2020, McQueen 2022). However, doing so introduces an energy-intensive calcination step.

A better understanding is needed of the environmental impacts from the use of chemical additives, water consumption, releasing CO_2-containing solutes (including asbestos fibers) and/or metals (especially nickel and chromium) into ecosystems. This includes the end-of-life environmental impacts and long-term stability of the particulate minerals, as the carbonated minerals make their way into waterways or get buried in soil.

Another significant technology barrier to the deployment of large-scale mineralization is the difficulty with monitoring CO_2 uptake attributable to an enhanced mineralization project (Kelemen 2020, Sandalow 2021a), which can hinder the ability to generate verifiable credits in carbon markets. There are also uncertainties regarding the permanence of CO_2 removal via surficial mineralization pathways, as soil inorganic carbon (SIC) losses have been demonstrated to take place on decadal timescales (Kim 2020) and are highly dependent on environmental conditions (e.g., humidity, pH, temperature, soil-water content) (Ferdush 2021, Zamanian 2021). A few measurement techniques have been proposed, including total inorganic carbon (TIC) (Erans 2020, Paulo 2021), dynamic closed chambers (DCC) (Luther-Mosebach 2016), and eddy covariance (EC) (Prytherch 2021). TIC measurement allows for the detection of carbonation by characterizing the solid-phase products of mineralization, while DCC and EC techniques are aimed at monitoring CO_2 fluxes over large areas. There is a need for pilot-scale

Carbon Drawdown Initiative

Project Carbdown is conducting initial field scale experiments in Europe to develop a low-cost, scalable and accurate measurement, reporting, and verification technology to study the CDR potential of applying basalt powders to croplands. In 2021, 27 tons of Eifelgold basalt were applied to 0.7 hectares of cropland, which revealed the following 10 key parameters and conditions affecting the removal quality: annual rainfall, soil temperature, soil pH, rock dust size, rock surface area, rock application rate, soil type, irrigation, secondary minerals/clay formation, and rock type.

experiments that incorporate these monitoring technologies to accurately measure baseline CO_2 fluxes and the resulting effect of enhanced mineralization. The results will help in determining the feasibility of large-scale enhanced mineralization processes and identifying which parameters (e.g., weathering time, stirring tailings, layer thickness, water sprinkling) can improve CO_2 capture performance.

System logistics—including mining/gathering, crushing facilities, transportation, and dispersion of crushed minerals—represents another significant challenge. This includes logistics of distributing optimal mineral resources so that crushed alkaline powders can be dispersed efficiently and effectively.

Specific innovation gaps that, if addressed, could help overcome the main challenges are outlined in **Table 4**. The right-hand column provides relevant sources with more detailed information about each of the gaps.

Table 4. Key Technology Challenges and Innovation Gaps for Enhanced Mineralization Technologies[40]

Technology Challenge Area	Innovation Gap	Sources for Further Detail
Mineralization Kinetics	• Rate limiting step of mineralization for various alkaline minerals (i.e., mineral dissolution vs. CO_2 transport)	Sandalow 2021a
	• Optimal reaction conditions (e.g., temperature, humidity, pH, time, stirring, thickness, water sprinkling)	Erans 2020, Kelemen 2019, NASEM 2019, Zhong 2021, Kelemen 2020
	• Effect of mineral properties (e.g., size, shape, crystallinity) on mineralization reaction thermodynamics and kinetics, including the determination of rate constants	Li 2022, Mulligan 2020, NASEM 2019, Paulo 2021, Sandalow 2021a
	• Dosage requirements (mass per land area) for achieving large-scale CO_2 removal	McQueen 2020, Sandalow 2021a
	• Extraction efficiency of Mg^{+2} and Ca^{+2} from silicate-bearing minerals which pose transport limitations via surface passivation	CDR Primer 2021, Gadikota 2020, Sandalow 2021a
	• Enhanced mass transport of CO_2 via sparging, improved stirring, and/or increasing the chemical potential gradient via elevated CO_2 partial pressure	CDR Primer 2021, Gadikota 2020, Gunnarsson 2018
	• Pre-treatment methods to improve reaction rates	Meng 2021, NASEM 2019, Sandalow 2021a
Energy Use, Land Use, and	• Optimal particle size of feedstock and dispersed rock	CDR Primer 2021, Kelemen 2020, Sanna 2013

[40] The technology challenges presented in the table have been obtained from a literature review conducted by the authors of the roadmap and augmented based on input from MI CDR members and other subject matter experts.

Environmental Impacts	• Reduced energy demand for rock mining, grinding and pre-treatment	Kelemen 2020
	• Prevention of particulate matter, hazardous components in minerals and industrial wastes from entering the environment	Sandalow 2021a
	• Reduced energy demand during metal oxide regeneration and recovery	McQueen 2020
Monitoring of CO_2 Uptake	• Methods for measuring groundwater flux of CO_2 and atmospheric CO_2 flux	Kelemen 2020, Sandalow 2021a
	• Improved understanding of each mineralization approach, including potential mechanisms and sources of CO_2 re-release	Ferdush 2021, Kim 2020, Zamanian 2021
Systems	• Co-located rock source and dispersal location to minimize transportation distances	McQueen 2020, Sandalow 2021a
	• Enhanced CO_2 content of mineralized products which can be sold to offset removal costs	Sandalow 2021a, Woodall 2019
	• Degradation rate of materials employed for repeated cycles of enhanced mineralization	Kelemen 2020
	• Mapping global mineralization resources (rocks, ultramafic bodies) and potential dispersal locations	Sandalow 2021a

Summary

Enhanced mineralization provides secure storage of CO_2, allowing the capture and storage to occur in a single step. Surficial mineralization approaches potentially eliminate some of the logistics steps and energy requirements, such as for transporting CO_2 from the capture to storage site. Surface mineralization does, however, involve other potentially energy intensive and complex logistics steps such as gathering, crushing, transporting, and dispersing crushed minerals. The slow speed of mineralization is a key limiting factor.

The most promising sources of rocks for mineralization contain a high concentration of Mg^{+2} and Ca^{+2} ions, which are prevalent in rocks across the globe. Waste materials from industrial or mining operations also represent prime source candidates for mineralization.

Surficial mineralization pathways are in the early stages of development. Few concepts have developed beyond TRL 4. As such, the current scale of surficial mineralization net removal is estimated to be about zero, although significant research, development, and demonstration efforts are underway. Mineralization approaches have large-scale CO_2 removal potential, with estimates varying widely but on the order of several gigatonnes of CO_2 removed annually.

Key technology challenges to CO_2 mineralization include kinetics of carbonation in rocks, energy and land use, monitoring CO_2 uptake, and system logistics. Notable opportunities to address enhanced mineralization challenges are shown in **Table 4** and include, for example:

- Understanding mineralization rates across the different mineral types by collecting experimental data according to a set of standardized conditions (e.g., temperature, pressure, particle size, pH).
- Reducing energy use by selecting rock and/or tailing sources that are rich in alkalinity, low in toxic metal concentration, easily accessible, and possess a small particle size (~100 μm).
- Considering dispersal locations with regard to the location of source rock and/or tailing sources for logistics.
- Developing remote sensing technologies which could allow for on-demand quantification of CO_2 mineralization and monitoring of the fate of the CO_2 over long periods of time.
- Studying the agronomic benefits and risks (including LCA) associated with introducing fine particulate matter containing heavy metals and identifying methods for minimizing negative impacts.
- Mapping potential mineral resources and candidate deployment locations globally.

The performance of mineralization pathways improves with increasing CO_2 concentration. The integration of DAC processes with mineralization steps could provide an opportunity to reduce the energy expenditure typically associated with DAC (i.e., CO_2 from the DAC flue stream does not need to be high concentration) while forming carbonates as long-lived products.

In addition to technological innovations, non-technical challenges are substantial. These include, but are not limited to, availability of land, long term and low-cost financing, and demand certainty. Community engagement will also be essential for surficial mineralization, as it is for other CDR processes.

2.3 Biomass Carbon Removal and Storage

Biomass carbon removal and storage (BiCRS) refers to approaches where biomass (plant- and algae-based material) naturally removes CO_2 from the atmosphere or seawater via photosynthesis, and the removed CO_2 is deliberately stored in a manner intended to be permanent.

Overview of BiCRS Approaches

There are several different BiCRS approaches, with technological development ranging from early-stage research to commercial stages of deployment that generate marketable energy products (**Figure** 4).

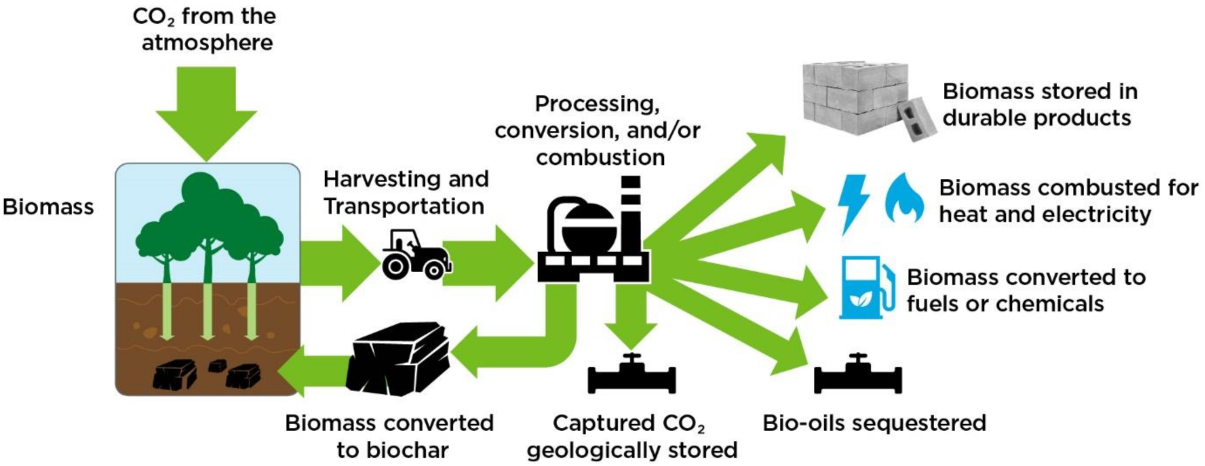

Figure 4. Overview of BiCRS steps; potential feedstock sources include biomass residues, energy crops, and algae; pathways with products shown in blue which involve combustion of biomass (e.g., heat and electricity) or conversion to short-lived end use products (e.g., fuels and chemicals) require capture and secure storage of CO_2 emissions (Adapted from EFI 2022)

For the purposes of this Roadmap, BiCRS processes include[41]:

- Approaches that capture and permanently remove biogenic CO_2 by combustion or conversion of biomass (e.g., into heat, electricity, hydrogen, or liquid fuels), where the resulting CO_2 emissions are captured and stored. These processes are termed BioCCS.
- Approaches that durably store carbon from biomass in long-lived products.
- Approaches that sequester carbon from biomass without generating marketable products other than CO_2 removals.

To be considered net negative, the BiCRS pathways must demonstrate net negative greenhouse gas emissions on a life cycle basis, and the removed CO_2 must remain securely stored or locked away in products.

The optimal technology pathway depends upon the type of feedstock and desired use (e.g., pathways designed to maximize production of electricity, creation of products, removal of CO_2).

BioCCS

The idea of combining bioenergy production with CCS was first proposed about 20 years ago and is often cited as a key carbon removal technology in integrated assessment models reported by the IPCC (Smith 2016, IPCC 2018a). Several routes are suitable for the conversion of biomass into final energy products or chemicals in combination with CCS. **Figure 5** below shows a range of pathways, with pathways leading to liquid or gas products most suitable for CCS integration. A well-known BioCCS approach is 'bioenergy with carbon capture and sequestration', or BECCS, where biomass is combusted to

[41] In addition to seeking to overcome technical challenges associated with these BiCRS pathways, within scope of the CDR Mission are topics for proper evaluation of BiCRS processes related to sustainable development (e.g., not in conflict with the United Nations Sustainable Development Goals) such as availability of biomass considering energy/food/water and other land and resource uses.

produce electricity in a facility where the CO_2 is captured and stored underground. Examples of BioCCS pathways that are currently available include:

- Combusting biomass with CCS for electricity generation, including co-firing biomass with existing coal-fired power plants fitted with CCS.
- Combustion of municipal waste with biomass, fitted with CCS and deliverance of heat and power to nearby communities.
- CCS fitted to pulp and paper mills where waste from pulp and paper production already is burnt for energy purposes.
- Converting biomass to hydrogen via gasification, with CCS integrated after the hydrogen and CO_2 are separated.
- Converting biomass to liquid fuel, with CCS for the fermentation process.
- Integrating biogas (gas resulting from the decomposition of organic matter such as municipal waste under anaerobic conditions) collection systems with CCS.

BioCCS can be integrated into industrial metallurgical plants such as iron and steel, aluminum, and silisium/ferrosilisium, which use carbon to reduce metal oxides whereby CO_2 is formed. Partly or fully replacing fossil carbon with biomass (e.g., in the form of biochar) and fitting CCS to the emission points can potentially result in net negative emissions. The availability of biomass to produce biochar is limited, however, compared to the global need for metal oxides reduction.[42]

Bio-based marketable products

Biogenic CO_2 can be stored in biochar and in a number of long-lived products such as building materials. Performance of some novel products are still unproven but may provide benefits; it is unclear how well bio-based CO_2 utilization into marketable products will scale.

Biochar can be used as heating fuel (e.g., replacement for fossil coal) or applied to soil (rather than combusted). In the latter use, biochar can act as a long-lived product that can increase soil carbon sequestration leading to improved soil fertility. The permanence of CO_2 stored in biochar varies between a few decades and several centuries, depending on soil type and biochar production temperatures (IPCC 2018a). Biochar is generated from pyrolysis of wood chips, plant residues, algae, manure or other agricultural residues. The chemical and physical characteristics of biochar vary depending on the feedstock, pyrolysis conditions, cooling, and storage environment.

Bio-sequestration without products other than CO_2 removal

In addition to geologic storage of CO_2 separated from biomass, and utilization of CO_2 in marketable bio-based products, there is a third potential pathway for BiCRS. If the primary goal is the removal of CO_2, rather than producing marketable commodities (e.g.,

[42] A possible future alternative for reducing metal oxides is hydrogen.

electricity, heat, fuels), the biomass could be converted directly into a form well suited for geologic storage. For example, gasification or fast pyrolysis can convert biomass to bioliquids or bio-oils which can then be directly injected underground in depleted oil fields without the need for CCS units or further processing. Benefits of this approach include avoiding capital and operating costs associated with CCS or further conversion into products (Sandalow 2021a, Schmidt 2018), and more straightforward geologic injection permitting in some regions compared to permitting required for the injection of compressed CO_2.

Feedstock

Biomass feedstock can come from biological residues (also called 'waste biomass' and includes agriculture residue, logging residue, black liquor from pulp and paper production, municipal solid wastes, sewage sludge, manure), purpose-grown energy crops (e.g., switchgrass, willow), and algae cultivation. The use of biomass residues in the forest sector and pulp and paper industry presents the potential for net negative emissions using BioCCS. Gasification of black liquor could provide feasible options for integrating CCS. Biological residues tend to have the lowest cost, environmental impact, and impact on food and fiber production (Sandalow 2021b).

Depending on the source, biomass feedstock supply may involve several energy intensive activities such as tilling, seeding, fertilizer and herbicide production and application, harvesting, and transportation to processing facilities (NASEM 2019). Feedstock production also has implications on land use change. It is important to incorporate these factors when calculating net emissions of BiCRS pathways in life cycle analyses to assess overall environmental impacts (Torvanger 2018; see also Section 2.5). On a life cycle basis, currently deployed large-scale facilities that convert biomass to electricity or products—while lower-carbon than fossil-based electricity or products—still emit more CO_2e than they remove, and so are not yet considered to be a net removal process (CDR Primer 2021). Several factors affect a project's ability to be net negative (depending on the pathway), such as emissions associated with biomass feedstock production, emissions associated with energy requirements for conversion and point source capture, and re-release of emissions when CO_2 is stored in short-lived products (e.g., fuels).

Conversion

Biomass conversion into energy carriers—such as electricity, heat, or fuel—or bioproducts (e.g., building materials, biochar) can be broadly divided into four categories (**Figure 5**):

- **Thermochemical** pathways involve controlled heating and decomposition of biomass into liquid, gaseous, and solid products. Thermochemical conversion technologies, such as gasification, pyrolysis, and hydrothermal liquefaction, are well suited to carbon-negative configurations and are promising candidates for additional RD&D (NASEM 2109).

Two examples of thermochemical pathways

Gasification coverts biomass to "syngas" (hydrogen and carbon monoxide), which can then be burned to produce electricity or catalytically or biologically converted to liquid fuels. Alternatively, the syngas can undergo a water-gas shift reaction to form hydrogen and CO_2, and the hydrogen can be separated leaving a CO_2 stream for capture and sequestration.

Pyrolysis entails heating biomass in the absence of oxygen to produce liquid (bio-oil), gaseous, and solid (biochar) products. Bio-oils can be turned into liquid fuel products or injected into depleted oil reservoirs, and the biochar provides a sequestration pathway.

- **Mechanical/chemical** pathways include densification[43], which involves applying pressure to mechanically densify the material, and extraction methods using a solvent to chemically separate oils from biomass feedstocks.
- **Thermo/biochemical** pathways include enzymatic hydrolysis, which is an intermediate step in the conversion process prior to fermentation. Hydrolysis produces high sugar yields, but the resulting mixture must be capable of supporting fermentative organisms while they produce biofuels.
- **Biochemical** pathways rely on living microorganisms—often yeast or bacteria—to process biomass into hydrogen, fuels, or chemicals. This includes anaerobic digesters that process sewage sludge and produce various end products including methane. Many biofuel production facilities built to date are based on fermentation, producing both biofuel and a high-purity stream of CO_2 for carbon capture and sequestration or utilization. Biofuel with CCS is deployed at several corn ethanol facilities.

[43] For more information on densification processes, see Pampuro et al. 2020 https://www.sciencedirect.com/science/article/abs/pii/S0016236119319726

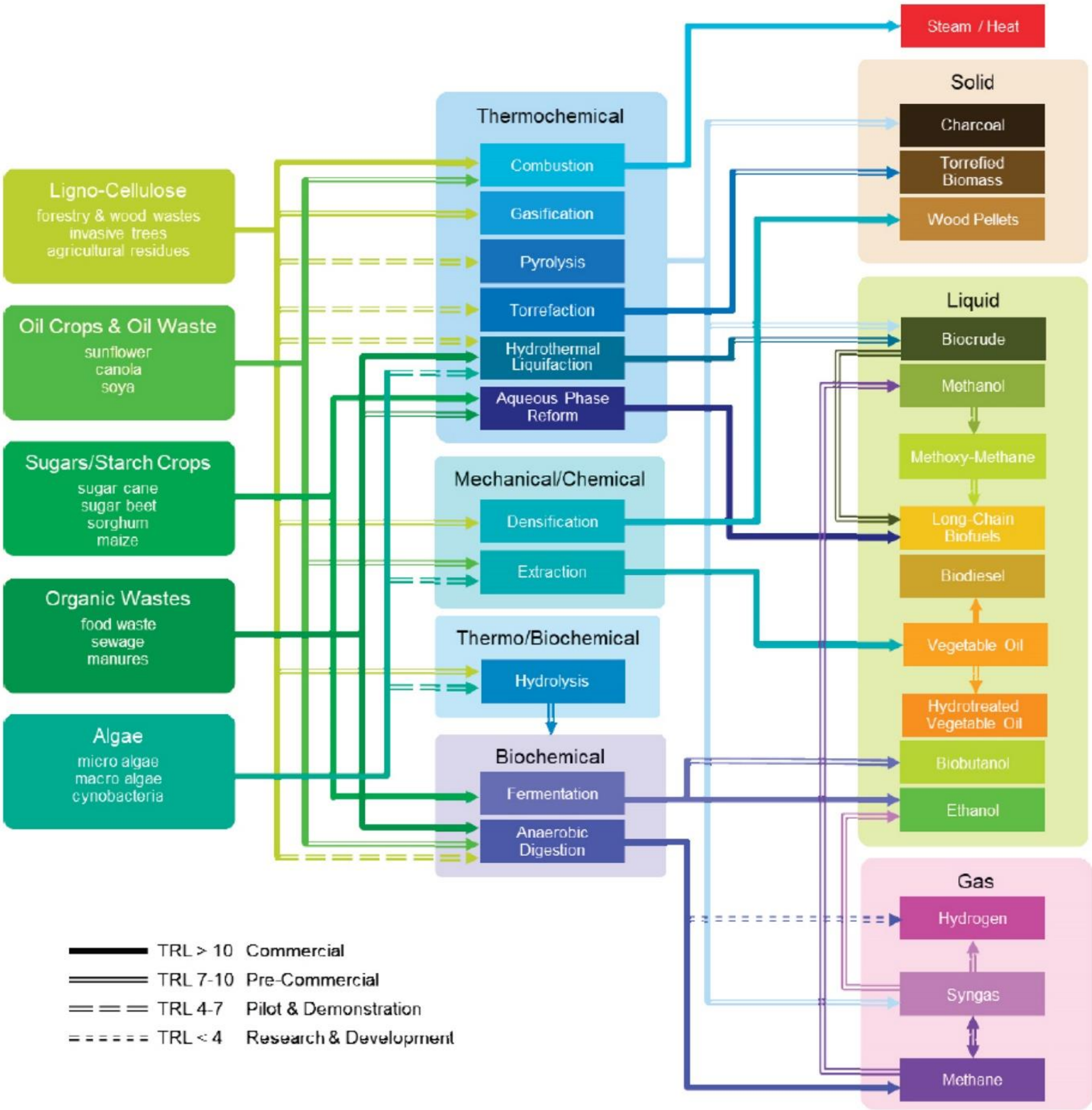

Figure 5. Biomass conversion pathways and TRLs[44,45] (Source: NASEM 2019).

**Products include marketable energy materials (e.g., heat, ethanol) as well as materials that may have more value if sequestered directly instead of consumed (e.g., charcoal, biocrude). Additional emerging product concepts that have uncertain conversion pathways include biofiber entombment in concrete (Sandalow 2021b).*

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44 For more detail on TRL definitions and associated description of biomass conversion technology status, see Table 4.7 of NASEM 2019.

45 The pathways and connectors shown here are notional. Additional connections between technology categories are possible but not all potential interactions are shown in the figure.

Potential Scale of BiCRS

Globally, facilities employing biomass with CCS are cumulatively sequestering approximately 2.5 million metric tons of CO_2 per year (Mt CO_2/yr), although on a life cycle basis the operations do not yet net result in negative emissions.[46] BioCCS facilities with an additional cumulative capacity of about 25 Mt CO_2/yr are currently in planning or development stages.[47] Facilities that currently sequester biogenic carbon include several ethanol plants in the United States. Some waste-to-energy plants in northern Europe, where burning municipal solid waste and producing electricity and heat as byproducts is a mature industry, have plans for CO_2 capture and storage.

Example BiCRS Deployments

- In the United States, a corn ethanol facility owned by Archers Daniels Midland has captured about 2.4 MtCO_2 from their fermentation process since 2017 and injected the CO_2 into a geologic saline formation.
- In the United Kingdom, a Drax facility converted most of its coal-fired units to biomass wood pellets over the past decade and is currently piloting CCS technologies. At full scale the facility could geologically store 16 MtCO_2/yr, although net life cycle emissions of the process are uncertain at this time (EFI 2022).
- In Japan, the 50 MW Mikawa Power Plant was converted from coal to biomass (mostly palm kernel shells) and captures about 50% of CO_2 emissions from a CCS demonstration at the facility.
- Charm Industrial, based in the United States, converts biomass into bio-oils from a fast pyrolysis unit and then ships the liquids for injection into salt caverns for sequestration.

The global potential for BiCRS is about 5 Gt CO_2/yr by 2050, considering limited biomass feedstock availability based on moderate gains in feedstock and conversion productivity and land and resource limitations for food security, biodiversity, and other sustainability factors, rather than technical feasibility alone (Smith et al. 2016, Sandalow 2021b).[48] More aggressive estimates of the potential scale of BiCRS are 15+ Gt CO_2/yr by 2050 (NASEM 2019).[49] The range of estimates also vary based on assumptions of costs, financial incentives, and other policies (EFI 2022).

[46] On a life cycle basis, the process- and up- and downstream emissions are larger than the sequestered biogenic CO_2.

[47] See Global CCS Institute facilities database for more information https://co2re.co/. Summary data reported by Sandalow 2021b.

[48] For comparison, the U.S. National Academy of Sciences reports the potential global carbon removal rate to be 3.5–5.2 GtCO2/yr for BECCS given current technology and at a cost of less than US$100/tCO2 (NASEM 2019). Fuss et al. 2018 estimates the CO_2 removal potential from BECCS to be from 1.2–5.2 GtCO2/yr to upwards of 31 GtCO2/yr.

[49] For context on the scale of BiCRS, Sweden has developed an implementation plan for net negative biomass pathways to achieve up to 10 MtCO_2/yr (0.01 GtCO_2/yr) by 2045.

Status of BiCRS technologies

Cost estimates for BiCRS approaches range from US$15–$400+ per tonne of CO_2 stored.[50] The wide range of estimates is largely based on geographic location and the diversity of technologies employed. For instance, biochar pathways and biofuels produced via fermentation that generate high-purity CO_2 streams as a byproduct tend to have lower costs per tonne of CO_2 captured, although life cycle CO_2e emissions of biofuel production with CCS are still positive (CDR Primer 2021).[51] At the other end of the cost range, an emerging approach of fast pyrolysis[52] and geologic injection of bio-oil is reported to currently be about $600 per tonne of CO_2 sequestered.[53]

BiCRS Technological Challenges

Many technology elements required for BiCRS are already mature and commercially available at scale today in global supply chains, such as technologies in pathways noted as commercial in **Figure 5**. Challenges to the broader deployment of these pathways include higher costs of bio-based fuels and products that compete with fossil-based sources, as well as non-technical challenges to BiCRS such as potential impacts to food security and biodiversity (see page 36). Opportunities remain for technological improvements in mature processes such as drying, gasification, and biomass boilers. Meaningful improvements to conversion efficiency, waste handling, and capital cost reductions are possible through RD&D investments and additional learning-by-doing. In addition, several pathways and technologies that are currently less mature have the potential to play important roles in BiCRS and require further development. Important technical challenge areas include:

- **Feedstocks.** Lignin constitutes about 30 percent of the weight and 40 percent of the energy content of biomass. Organisms are unable to rapidly metabolize lignin for fermentation (NASEM 2019). Increasing the rate of carbon uptake of biomass feedstocks—including foliage, roots, and enhancements to soil carbon sequestration—poses significant technical challenges.
- **Conversion.** Heterogeneous biomass inputs present difficulties for conversion heat balances, processing times, and overall conversion system optimization. Cellulosic biomass contents can foul ash-handling systems, especially systems originally

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50 Based on estimates from Langholz et al. 2020, Baker et al. 2020, Fuss et al. 2018, and DOE 2022 (not yet published). For comparison, IPCC 2022 (chapter 12) estimates US$15-400/t$CO_2$ for BECCS and US$10-345/tCO2 for biochar, and IPCC 2018a reports US$50-$250 per tonne of CO_2 sequestered from BECCS pathways.

51 All fuels that include carbon that are combusted will inevitably generate CO_2. The LCA of CO2e emissions from bioethanol with CCS can be significantly improved using fertilizer based on low-emissions hydrogen, electrified machinery charged with renewables, and other emissions-reduction techniques in the supply chain.

52 Fast pyrolysis involves higher temperatures and generates a greater proportion of liquid products than slow pyrolysis, which uses lower temperatures and solid biochar is the primary product.

53 https://www.fastcompany.com/90677039/this-startup-keeps-co2-out-of-the-air-by-injecting-bio-oil-underground

designed to handle coal ash. Equipment requirements for conversion drive high capital costs, and modular designs with lower upfront costs are currently less developed. Tar removal from biomass pyrolysis and gasification processes can also create operational challenges that increase maintenance requirements and costs.

- **Capture.** Many of the carbon capture technologies have been developed for coal power plant scale deployment, which are significantly larger than most BioCCS facilities. When bioenergy owners analyze their operations for potential CCS opportunities from biomass combustion, facilities are often seen as too small to justify the cost. Carbon dioxide capture equipment increases capital costs and energy use, and products from the combusting or conversion of biomass feedstocks can lead to fouling residues in the capture equipment. This applies to CO_2 capture, not only from boilers, but for other processes as well (e.g., pyrolysis).[54]
- **Utilization with long-term carbon removal.** Bio-based products create a revenue stream for facilities but lack the process efficiency to generate products that are low enough cost or otherwise differentiable from mature fossil fuel-based products with established value chains. Improvements in efficiency and driving down costs may come at the expense of reduced removal (Fajardy 2018); bio-products that re-release some of the captured CO_2 may have difficultly becoming net negative CO_2e on a life cycle basis.
- **Systems.** The logistics of transporting biomass to conversion facilities located near CO_2 storage and near energy markets is a significant challenge to systemwide scale-up. Co-locating biomass resources, conversion facilities, and storage location would limit the need for long distance biomass movements but also limits biomass supply and facility siting options.

Table 5. Key Technology Challenges and Innovation Gaps for BiCRS Approaches[55]

Technology Challenge Area	Innovation Gap	Sources for Further Detail
Biomass Feedstocks	• Biomass—including plant and algae—optimized for life-cycle carbon removal, such as plants that increase soil carbon, plants that are optimized for conversion treatments, or plants that are more efficient at pulling CO_2 from air; genetic modification of crops to enhance carbon uptake and durability, including heat and/or salt tolerant species for production in marginal environments; understanding how biomass optimization for carbon removal affects agricultural productivity, sustainability, and biodiversity	Jansson 2021, Babson and Hsu 2022, EBTP 2020

[54] This challenge is most applicable to biomass combustion processes. It is less relevant for biochemical processes such as fermentation and anaerobic digesters.

[55] The technology challenges presented in the table have been obtained from a literature review conducted by the authors of the roadmap and augmented based on input from MI CDR members and other subject matter experts.

	• Cultivation of macroalgae in marine waters at large scales while minimizing ecological risks	Silverman-Roati 2021
	• Continuous biomass production systems such as fixed algae production and microbial mats	Kang 2019, Vigneron 2018
	• Optimal biomass densification, pre-treatment, and formation techniques that convert a variety of biomass feedstocks into a standardized drop-in fuel replacement for coal	NASEM 2019, Pampuro et al. 2020
Conversion Technologies	• Pyrolysis among different feedstocks and process designs, including development of modular systems optimized for generating biochar and bioliquid for direct injection	Sandalow 2021b, Laird et al. 2009
	• Gasification of woody or cellulosic biomass for conversion to H_2 or carbonaceous fuels, including gasifier designs built to accommodate biomass ash and heterogeneous feedstocks	Lacey 2018
	• Supercritical water gasification to convert biomass to syngas without drying and with high reaction rates and H_2 yield	Hu et al. 2020, Okolie 2019
	• Use of high temperature working fluids (>1,100°C) from conversion of biomass to heat that can create >60% electric conversion efficiencies (compared to under 40% efficiencies in conventional biomass power plants)	NASEM 2019
	• Metabolic engineering of microbes and bacteria to more selectively convert biomass to products in biochemical pathways	Joshi 2022
Capture Technologies	• Energy- and cost-efficient integration of biomass conversion with CO_2 capture	EBTP 2020
	• Optimization of BioCCS facilities for variable feedstocks, capacity, and biomass availability to reduce capital costs and energy consumption	NASEM 2019
	• Catalysts for removal of tar from bio-based gas products	Guan 2016
	• Extraction of valuable materials—including critical minerals—from residues of municipal solid waste	Gutiérrez-Gutiérrez 2015
Utilization	• Quantification of biochar carbon sequestration permanence and understanding how biochar soil amendments affect agricultural productivity, water use, and albedo	NASEM 2019, Smith 2016
	• Development of advanced construction techniques and new application areas for long-lived products	Sanchez 2020, Winchester 2020

	• Development of long-lived, high-value products, including bio-based chemicals, biofiber concrete, and other materials that enhance performance and durably store carbon – considering performance, life cycle analysis, techno-economics, and environmental trade-offs	Sandalow 2021b, Simon 2021
	• Use of biomass in the process industry, e.g., biochar or bio-hydrogen as reductants in combination with CO_2 capture to realize CDR	EBTP 2020
Systems	• Assessment of supply chain logistics for network configuration considering biomass resources (e.g., biological residues and municipal solid waste), transport, land use, water consumption, impact on biodiversity, processing facilities, product markets, and suitable geologic storage	Sandalow 2021b, NASEM 2019, Negri 2021
	• Cascading use of wood and biomass-based products	IPCC 2019
	• Availability of biomass in competition with other uses, especially in the context of increasing intensity and frequency of climate-driven drought, extreme precipitation events, and changing water availability globally	Soimakallio et al. 2022
	• Assessment of removal capacity as compared to alternative uses of land, e.g., re/afforestation	Forster 2020

Measurement of life cycle emissions also presents an important challenge to BiCRS projects. Carbon dioxide at the capture and storage sites are straightforward to measure, but life cycle emissions from biomass production and use and other impacts are more difficult to quantify (See Section 2.5).

Non-technical challenges, while not the focus of this Roadmap, present significant barriers to large scale deployment of BiCRS. An illustrative list of important non-technical challenges include:

- Gaining public acceptance and social license to operate large scale BiCRS systems.
- Lack of financial and policy incentives for carbon removal, such as carbon removal credits, robust emissions trading programs, tax credits, and regulations (e.g., see Schenuit et al. 2021).
- Certifying removal from BiCRS projects in a manner that is transparent, permanent, verifiable, and widely accepted.
- Limited availability of low cost capital for early-mover BiCRS facilities, which likely have high capital costs.
- Governance and coordination challenges such as sharing scientific and commercial sensing data; clarity of roles, responsibilities, and benefits across supply chains (e.g., see Torvanger 2018).

- Secondary effects from the process of growing, transporting, refining, and converting feedstocks into biofuels, including biodiversity, food security, water usage, ecosystem impacts from fertilizer runoff, noise, and air pollution across the life cycle, and environmental justice of siting additional combustion energy systems in already-affected communities.

Summary

There are many different BiCRS approaches and pathways, with technological development ranging from early-stage research (TRL <5) to commercial stages of deployment (TRL >9).

Of the BiCRS processes, those involving combustion or conversion of biomass combined with CCS (bioCCS) are the most prevalent by a wide margin. Facilities employing biomass with CCS are cumulatively sequestering approximately 2.5 Mt CO_2/yr, with about 25 Mt CO_2/yr additional bioCCS facilities in the planning or development stages, although current large scale bioCCS operations do not yet produce net negative emissions. Other BiCRS processes include creation of bio-based products or converting biomass for the primary purpose of sequestering carbon rather than generating marketable products.

Biological residues such as agriculture husks and forest slash tend to have the lowest cost, environmental impact, and impact on food and fiber production.

Energy use is concentrated in the conversion steps, with feedstock production also involving energy intensive activities such as tilling, seeding, fertilizer and herbicide production and application, harvesting, and transportation to processing facilities.

Key challenges for commercially available BiCRS approaches include innovations in biomass feedstocks, conversion, capture, and system logistics to convert the end-to-end process from a net emitter to net negative. For lower TRL approaches, key challenges include proving technical performance and the ability to scale up promising systems beyond niche applications.

For all approaches, robust accounting methods are needed to understand GHG emissions from upstream operations. Other important challenges to scaling up deployment include considerations for factors such as water consumption, land use, biodiversity, food security, and ecosystem impacts.

2.4 Storage options for removed CO_2[56]

[56] The technology challenges and innovation gaps associated with CO_2 storage and/or use in products are outside the scope of this document. As noted earlier, the main goals of this report are to summarize the status of and identify the main gaps and challenges associated with steps for removing the CO_2 from the air, since CO_2 disposition and conversion are examined by other international fora such as the Technical Group of the Carbon Sequestration Leadership Forum (CSLF) and the IEA Greenhouse Gas R&D Programme (IEAGHG). This section provides a high level overview.

Once CO_2 has been successfully captured from the air, there are two main pathways which can be employed: geologic storage and storage in long-lived products (locked away in a manner intended to be permanent).

Geological storage systems like oil and gas fields and deep saline formations have an estimated storage volume collectively ranging from about 1,675 Gt CO_2 to more than 10,000 Gt CO_2—far more than total anthropogenic emissions that need to be removed (IPCC 2018b). While geologic storage sites are broadly distributed globally—with the largest known fields in the Americas, Europe, and Australia-New Zealand— siting projects in proximity to suitable injection sites is an important cost consideration (Pilorge et al. 2021). For BiCRS, several regions have both high biomass potential and high CO_2 storage potential, including North America, Europe, and Southeast Asia (Sandalow 2021b).

Captured CO_2 could allow for the creation of valuable products (e.g., construction materials, ceramics) which result in net negative emissions. This could provide companies with a pathway to generate marketable products which can offset some of their original process costs. For example, some innovative businesses are developing technologies to use CO_2 to make synthetic limestone for use in building materials.

2.5 Life cycle analysis and techno-economic analysis

Life cycle analysis (LCA) is a methodology where emissions (e.g., greenhouse gas emissions) are inventoried and environmental impacts (e.g., global warming) are characterized for the cradle-to-grave evaluation of a product or process. By design, LCA provides a holistic perspective of the potential environmental impacts of a product or process throughout the entire lifetime. This includes the extraction of raw materials through the end-of-life. To understand the net impacts of a CDR pathway, an LCA considers not only the emissions of the CDR removal process itself, but also the emissions associated with the upstream (e.g., energy resources, materials, water, land use) and downstream operations (e.g., CO_2 transportation, conversion, product use, storage). An LCA determines whether a project that captures CO_2 from the atmosphere is a net CO_2 remover or emitter on a cradle-to-grave basis. Two International Organization for Standardization (ISO) standards provide the principles and framework (14040) and requirements and guidelines (14044) for conducting an LCA (ISO 2006a, ISO 2006b). A separate standard, ISO 14067, focuses specifically on the reporting of the carbon footprint for products (CFPs) (ISO 2018). It is largely based on ISO 14040/14044, but with a narrower focus on potential impacts related to climate change. Not only can LCA be used to help determine the net CO_2e removal of a CDR approach, but it can also help with the assessment of potential tradeoffs with other environmental impacts. Even though the approaches for LCA are codified in the ISO standards, we recognize the need to establish specific guidance for the subjective elements in those standards to harmonize data and methods to allow for consistent assessments of CDR approaches. Using ISO standards is voluntary unless required by jurisdictional authorities. It is important to consider not only the full life cycle effectiveness of a project, but also to understand clearly what the

documented measurement, reporting, and verification plans are to ensure the CO_2 removal has the intended climate effect over long periods of time.

There are no universally accepted approaches to or boundary limits and baselines for CDR processes (Terlouw et al. 2021). Technology and analysis challenges of applying LCA to engineered CDR approaches, which limit comparability within a single approach or across multiple approaches, include the following (summarized in **Table 6**):

Lack of consistent LCA boundaries. LCAs need consistent system boundaries (cradle-to-grave) that consider upstream (e.g., feedstocks, supply chain) and downstream processes (e.g., CO_2 fate, waste management). This is especially important for CDR since the implication is long-term, durable storage. For BiCRS this includes growing, harvesting, transporting, and processing the biomass and separating and handling the CO_2 that is eventually stored underground. Boundaries should also consider both temporal and geographic factors. For example, the LCA for enhanced mineralization projects involving alkaline industrial wastes should incorporate temporal availability of industrial waste tailings, since these industries may reduce in size as they also tend to be heavy CO_2 emitters. The location of a CDR operation and the timing of deployment may evolve over the development cycle and both items can have significant impacts on the data that is used in the analysis. The LCA boundaries should consider the potential direct and indirect land use change implications as well, although specifying system boundaries can be difficult because of insufficient data to perform the analysis in a specific way.

LCA boundaries should also consider temporal factors, including time differences between emissions and removal. CDR impacts the carbon cycle on timeframes of decades to centuries, where land and ocean sinks may become sources of CO_2 as atmospheric concentrations change over time (IPCC 2021, Keller et al. 2018).

When captured CO_2 is stored in long-lived products, the system provides more than one function to the society due to the double role of CO_2 as emission and feedstock. This issue raises the potential for double counting of the removed CO_2, and system expansion of the analysis can help avoid this pitfall (Müller et al. 2020, Raadal and Modahl 2022).

Lack of high-quality data available. Since many CDR pathways involve low TRLs, limited data are available to provide input for conducting the LCAs. As a result, there is high uncertainty with parameters required to assess many CDR processes, and these uncertainties can compound and lead to large error margins. There are also challenges connected to gathering data due to lack of guidelines. The results of LCA must convey the uncertainty, and sensitivity analyses can identify specific parameters driving the overall results. Anticipated key parameters affecting the results of the analysis include the amount and carbon intensity of the energy used, both as electricity and heat, as well as allocation for processes that produce more than one product (Liu 2020b, Terlouw 2021), avoided processes (e.g., using municipal solid waste for hydrogen generation avoids emissions from its incineration (Amaya-Santos et al. 2021)). Key uncertainties and assumptions need to be documented transparently such that LCAs deliver appropriately informed assessments of the actual emissions reduction potential.

Lack of LCA standards specific to CDR. As an assessment framework, LCA is governed by ISO standards 14040 and 14044; however, those standards are generic and do not offer guidance for specific technology applications, nor do they provide any of the data necessary to complete a study. In addition, the Policy and Action Standard of the Greenhouse Gas Protocol specifies methods relevant to evaluating removal capacity.[57] The scope and level of detail should be consistent among studies and articulated in LCA standards.[58] This includes identification of key parameters that must be included and recommended data sources for inputs. Mechanisms should also be developed to guide decisions on when to adjust accounting protocols as scientific understanding changes. These mechanisms would ultimately provide greater clarity to the market on how and when factors may change.

Considerations for scale up. The required material and energy inputs for a process per unit product evolve as deployment expands and facilities increase their removal capacity. For DAC, for example, adsorbent production would need to be expanded to the scale of today's commodity polymers, indicating the need for a detailed analysis of future adsorbent supply chains (DOE 2022, Deutz 2021). The current small-scale production of amines for the adsorbent would need to be scaled up by more than an order of magnitude to reach roughly 0.5 Gt removal capacity (Deutz 2021). Additionally, background data used to model other areas of the supply chain may change as the energy system continues to decarbonize. For scale-up of BiCRS pathways, it is important to keep in mind the increased competition for resources (e.g., land, water, food).

Few comparable reference projects. A thorough LCA study provides a comparison of newly proposed processes to existing references, but since very few and diverse CDR technologies are deployed today, it is often difficult to develop baselines for comparability. LCA methodologies should be supported by comprehensive and consistent baselines and clear assumptions about future conditions, and measures of removal should be based on atmospheric drawdown rather than estimates of offsets relative to a nonstationary baseline. Comparison with other LCAs can also be a challenge when there is inconsistency in methodological choices such as system boundary and functional unit. Harmonization of studies is only possible when sufficient technical performance data is also provided in addition to the LCA results. A comparable functional unit (e.g., mass of CO_2 removed from the atmosphere and stored in a manner intended to be permanent) could be developed to easily compare LCA results. In the case of storing CO_2 in long-lived products, the system is multi-functional and system expansion should be used to avoid double-counting. This requires a functional unit that reflects all the functions delivered by the system (Müller et al. 2020, Raadal and Modah 2022).

Monitoring land use and cover change and water consumption. Monitoring land use and cover change is an important input for comprehensive LCA where data is limited. This is relevant directly for BiCRS and surficial mineralization approaches but also important for

[57] ghgprotocol.org

[58] Useful guidelines have been published by Müller et al. (2020).

DAC since high energy use requirements may necessitate extensive land use. One approach to monitoring land use and cover change is to use satellite-based remote sensing, which allows global coverage and relatively high precision. In addition, monitoring water use is important, particularly for BiCRS and DAC, which could have large water footprints in water scare areas depending on the technologies and pathways implemented.

Techno-economic Analysis

An important consideration for CDR approaches is the cost of the technology, which includes both capital expenditure and the operating costs. Capital costs include any one-time purchases, including the initial investment in major equipment/infrastructure and any associated engineering fees. Operating costs include any recurring costs required for the continuous operation of a system (e.g., energy purchases, minerals/feedstock gathering, chemicals, water, labor, maintenance). The main challenges of CDR techno-economic analyses (TEAs) are similar to LCA challenges (summarized in **Table 6**):

- High uncertainty associated with data for new or low-TRL approaches.
- Geographic limitations since the results of TEAs are usually specific to a particular geography due to the dependency of feedstocks, materials, and energy on specific locations.
- Lack of consistent definition of system boundaries such that all upstream and downstream operations, in addition to the CO_2 removal process itself, are within the boundaries.
- The timing aspects, e.g., projected prices of energy and other commodities.
- Inconsistency in capital cost scope, especially indirect costs, such as engineering, procurement and construction management, owners costs, and contingency.

Table 6. Key Technical Challenges and Innovation Gaps for LCA and TEA of CDR Approaches

Technology Challenge Area	Innovation Gap
System Boundaries	• Robust data to inform development of protocols for consistent system boundaries that consider upstream (e.g., feedstocks, supply chain) and downstream processes (e.g., CO_2 fate, waste management), temporal boundaries consistent with durable removal, inclusion of displaced product/commodity supply chains (e.g., biochar production displacing use of sawmill residues for furniture, or biochar use displacing synthetic fertilizer use)
Data Availability	• Development of data sharing platforms especially for low TRL approaches
Standard Methodologies	• Harmonization of variables (e.g., land, process, time frame)
	• Harmonization of capital cost estimation methodology for a given technology readiness level
	• Emissions accounting when supply (e.g., biomass feedstock or mineral extraction) is not co-located with consumption (e.g., different jurisdictions)
	• Separate methodologies for emissions avoidance, reduction, and removals
	• Standard methods for consistently factoring financial incentives and taxation implications in TEAs across multiple jurisdictions
	• Standardized methodology for treatment of residues
	• Framework for quantification and verification of net CO_2 emissions along the entire chain and reporting net negative emissions
Scale up	• Analysis of future supply chains to meet materials needs (e.g., biomass, solvents/sorbents, minerals)
Comparable References	• Development of comparable key functional units (e.g., mass of CO_2 removed from the atmosphere and stored in a manner intended to be permanent) to easily compare LCA results
Monitoring Land Use and Cover Change	• Development of algorithms to interpret remote sensing data
	• Forest and farm monitoring and accounting (a combination of sensors, artificial intelligence, and remote sensing)

3 Landscape Analysis

3.1 Current domestic focus

CDR Mission member governments are investing significant resources in RD&D and deployments for the next generation of CDR technologies. Among the list of recent and current CDR projects in CDR Mission member countries, DAC and BiCRS projects vary in their focus, ranging from early R&D to pilot-scale/demo projects to deployment, whereas enhanced mineralization projects tend to focus on earlier TRLs.

Members also have a keen interest in advancing methodologies for LCAs and TEAs and better understanding the environmental and socio-economic implications (challenges and opportunities) of various CDR approaches.

Select research areas and seminal pilot-scale/demo projects are highlighted below.

Select research areas

DAC – Fundamental research (U.S.)

TRL <4

In fiscal years 2020 and 2021, over $27.5 million was awarded for basic research pertaining to DAC. The projects span a range of fundamental materials and chemical science efforts, aimed at discovering novel materials, chemistries, and processes for removal of carbon dioxide from air and other dilute sources such as surface waters.

BiCRS – Biocarbon Sequestration (Canada, CanmetENERGY Ottawa)

TRL 3

This project will focus on a new approach to carbon sequestration wherein harvest residues are converted directly to biocarbon that is then applied to the soil (e.g., buried). This is a local solution that is not dependent on transport or aggregation (i.e., conventional approaches such as carbon dioxide sequestration or subsequent energy intensive conversion to inert compounds).

Enhanced Mineralization – Assessing the Domestic Potential of Mineralization (Saudi Arabia)

TRL 2

Saudi Arabia will explore the potential capacity to employ mineralization in Saudi Arabia. These efforts will develop a techno-economic framework for feasibility and scale-up and identify paths toward deployment.

DAC – Moonshot Research and Development Program - Moonshot #4 (Japan)

TRL 1-3

METI is implementing multiple early stage projects for advancing DAC under NEDO's management.
Examples include advancing bio-electrical processes, membrane-based capture, and solid absorbents. The program is expanding its focus to include additional negative emissions technologies, including BiCRS and Enhanced Mineralization.

A stage-gate review will be applied to the adopted projects, and promising projects will be advanced to the demonstration phase with the aim of deploying commercial scale technology globally by 2050.

BiCRS – Bio-energy CCS (Canada)

TRL 5

This project will focus on advancing energy systems that are suitable for biomass feedstocks and optimal for carbon capture. Namely, the focus is on oxy-fired fluidized bed combustion and steam-oxygen blown fluidized bed gasification. CanmetENERGY Ottawa will leverage existing expertise, pilot-scale equipment, bench-scale equipment, and models. The project will assess and compare promising BECCS pathways and integrate these pathways into a National CCUS Modelling Framework so that CDR technologies can be assessed at a high level by policymakers and industry players.

Enhanced Mineralization – Synthetic Calcium Carbonate Production by CO_2 Mineralization of Industrial Waste Brines (U.S.)

This project aims to develop and evaluate methods for the production of precipitated calcium carbonate while utilizing CO_2 and industrial solid and liquid wastes. University partners will investigate the physical and chemical processes involved in the two carbonation pathways and optimize process parameters for the production of high purity calcite through each of the mineralization routes. A laboratory-scale system will also be constructed to demonstrate the process.

Seminal pilot-scale and demo projects

DAC – Regional DAC Hubs (U.S.)

For fiscal years 2022-2026, U.S. DOE is investing $3.5 billion to lead the development of four regional DAC hubs. Each hub will have the capacity to capture and store and/or utilize one million metric tons of CO_2 per year. The hubs will be networks of DAC projects, potential CO_2 off-takers, transportation, and storage infrastructure, enhancing DOE's efforts to demonstrate durable CO_2 removal in support of America's goal of net-zero emissions by 2050.

BiCRS – Fortum Oslo Varme (Norway)

FOV is a waste-to-energy (WtE) plant in Oslo and forms part of Norway's Longship Project. 50% of the waste is biological. The objective of FOV is to demonstrate that a full CCS chain from WtE is doable and to gain regulatory and technological learnings from the project. Start-up is planned for 2026.

(The Longship Project is a full-scale carbon capture and storage (CCS) project that will demonstrate the capture of CO_2 from industrial sources, as well as transport and safe storage of CO_2).

DAC – Airthena (Australia)

This project aims to provide a viable technology for removing carbon dioxide from the air. The primary objective is to reduce the greenhouse gas levels in our atmosphere to counterbalance emissions. The secondary aim is to provide a feedstock for industries that can utilize carbon dioxide to maintain a closed loop carbon cycle.

This work was funded through the Science and Industry Endowment Fund at a total of $750K with the remaining funded through CSIRO.

Priorities of Member Governments

Common interests and priorities among CDR Mission member governments include:

Technical Track	Top Innovation Priorities
Direct Air Capture with Storage	Energy use
	Material performance
	CO_2 capture and desorption kinetics
	Environmental impacts and siting
Enhanced Mineralization	Mineralization kinetics
	Energy use, land use, and environmental impacts
Biomass with Carbon Removal and Storage	Biomass feedstocks (e.g., optimizing or advancing our understanding of opportunities with various feedstocks)
	System logistics (e.g., evaluating biomass availability, value chains, and ensuring that processing occurs close to biomass sources)
	Utilization
Cross-cutting	Life cycle analysis
	Techno-economic analysis
	Measurement, monitoring, and verification

3.2 Existing CDR initiatives

In recent years, there has been increased attention to CDR among governments, media, industry, and the public. With that has come a proliferation of CDR initiatives and projects. The CDR Mission endeavors to identify key stakeholders in the CDR space and opportunities for collaboration in order to find synergies, avoid duplication of efforts, and maximize impact.

The table below summarizes the types of stakeholders and the potential value-add of collaboration between the CDR Mission and these organizations.

Stakeholder	Possible Value-add for Stakeholders	Possible Value-add for CDR Mission
CDR Innovators	• Connections with other international initiatives • Connections with public and private investors • Cross-promotion of objectives and activities • Govt funding for RD&D projects • Access to govt lab testing facilities	• Knowledge exchange on innovation gaps and RD&D needs • Lessons learned from innovators on LCAs/TEAs • Lessons learned from innovators from first-generation CDR projects • Cross-promotion of objectives and activities
CDR Purchasers and Investors	• Government partners for de-risking investments in CDR projects (e.g., via govt funding and/or technical expertise) • Cross-promotion of objectives and activities	• Private-sector funding and/or expertise to scale up CDR technologies • Insights around purchaser needs • Connections to innovators, other investors • Cross-promotion of objectives and activities
Academia, Research Institutes, Think Tanks, and NGOs	• Co-development and testing of methodologies for LCAs and TEAs • Knowledge exchange on innovation gaps and RD&D needs • Insights on tech to market strategies • Cross-promotion of objectives and activities	
Other International Initiatives	• Knowledge exchange on RDD&D, policy, business models, regulation, and governance • Access to existing networks and collaborative mechanisms • Cross-promotion of objectives and activities	
Other Governments	• Knowledge exchange on RDD&D, policy, business models, regulation, and governance • Cross-promotion of objectives and activities	

4 Next Steps

CDR Mission members will use this Roadmap as a key resource for identifying mutual areas of interest among member countries. It is also a starting point for members to build an Action Plan and uncover specific opportunities for collaboration that will accelerate progress toward enabling CDR technologies to achieve a net reduction of 100 $MtCO_2$ per year globally by 2030. Members recognize the importance of collaborative RD&D efforts in achieving this ambitious goal.

CDR Mission members will develop an Action Plan based on the following:

- Information contained in this Roadmap
- Additional insights gained through CDR Mission workshops and from input provided by partners and other stakeholders
- Feedback from surveys and other solicitation mechanisms for conveying member interest, considering each member's unique circumstances

The Action Plan will articulate practical activities to be led by mission members that address priority needs in the near-, mid-, and long-term.

Recognizing that the CDR space is rapidly evolving, mission members will continue to monitor the progress of CDR technology development and adjust priorities commensurate with changing needs. This includes periodically updating the Roadmap and Action Plan.

Glossary

anthropogenic emissions	Emissions of greenhouse gases (GHGs), precursors of GHGs and aerosols caused by human activities. These activities include the burning of fossil fuels, deforestation, land use and land-use changes (LULUC), livestock production, fertilisation, waste management and industrial processes.
BECCS	A type of BiCRS called bioenergy with carbon capture and storage (BECCS), which pairs plants' ability to capture CO_2 from the atmosphere with energy-producing technologies like power generation. BECCS works by generating electricity via burning biomass, creating a high concentration of CO_2 in the exhaust gas which may be separated, captured and stored. BECCS is distinct from fossil-based CCS because the original source of CO_2 has been recently captured from the atmosphere (through biomass). BECCS pathways do not include CO_2 captured and stored from the combustion of human-made waste, such as plastics commonly found in municipal solid waste streams, as those waste streams do not result in removal of carbon from the atmosphere.
BioCCS	Approaches that capture and permanently remove biogenic CO_2 by combustion or conversion of biomass (e.g., into heat, electricity, hydrogen, or liquid fuels), where the resulting CO2 emissions are captured and stored. BioCCS is a type of BiCRS.
BiCRS	Biomass Carbon Removal and Storage (BiCRS) describes a range of processes that use plants or algae to remove CO2 from the atmosphere and store it underground or in long-lived products. CO2 is produced from the combustion, gasification, or other conversion of low- or zero-carbon biomass, for example to generate electricity or produce hydrogen, and the resulting CO2 emissions are captured and then stored in a manner intended to be permanent.
biogenic CO2 emissions	CO_2 emissions related to the natural carbon cycle, as well as those resulting from the combustion, harvest, combustion, digestion, fermentation, decomposition, or processing of biologically based materials. Examples of biogenic CO2 emissions include: - CO_2 from the combustion of biogas collected from biological decomposition of waste in landfills, wastewater treatment, or manure management processes - CO_2 from combustion of the biological fraction of municipal solid waste or biosolids - CO_2 derived from combustion of biological material, including forest-derived and agriculture-derived feedstocks
CDR	Carbon dioxide removal refers to anthropogenic activities that deliberately remove CO2 from the atmosphere and durably store it in geological, terrestrial or ocean reservoirs, or in products. (Source: IPCC)
CO_2 capture	The process of separating CO2 from a concentrated flue gas stream or from the air. Note that capture does not imply storage or utilization in long-lived products, so it is not the same as CO2 removal.

CO_2 equivalent	Describes the impact of a given GHG (CO_2, CO, CH_4, N_2O, etc.) by converting its mass to the equivalent mass of CO2 that would have the same global warming effect. The mass of a GHG is converted to the mass of CO2e based on the GHG molecule's potential to affect global warming, or its global warming potential (GWP). The GWP takes into account both the radiative forcing effect of the GHG and the gas's lifetime in the atmosphere, and is dependent on the time horizon, which is most commonly 20 years (GWP20) or 100 years (GWP100). These values are different because the GWP is time-integrated and the GWP of CO2 is always 1, regardless of the time horizon. (Source: CDR Primer)
DAC	Direct air capture refers to technologies that use a chemical approach to capture CO2 from ambient air and then securely store it. To be a CDR approach, a direct air capture facility must be paired with secure storage, such as geologic sequestration or utilized in long-lived products in a manner intended to be permanent.
durable	Ability to withstand environmental factors such as weather or pressure changes that could damage the medium or otherwise cause accidental release of its contents (e.g., CO_2). See also Permanence.
enhanced mineralization	Acceleration of the natural reaction of CO_2 with alkaline minerals to form stable carbonates. The CO2 is stored permanently in mineral form (rocks) or separated and stored in geologic reservoirs or incorporated into long-lived products in a manner intended to be permanent.
equity	The principle of fairness in access to opportunities, power-sharing, and burden-sharing. Equity is crucial to determining how to deploy strategies to address climate change, including CDR, that minimize harm to marginalized people and frontline communities. (CDR Primer)
feedstocks	Any renewable, biological material that can be used directly as a fuel, or converted to another form of fuel or energy product.
geologic storage	Geologic storage involves injecting CO_2 into rock formations deep underground, where it remains stored for thousands of years or more. Geologic storage (also referred to as geologic sequestration) can be paired with a variety of removal pathways as part of CDR, including DAC and BECCS to permanently store CO_2.
gigatonne of CO2	Refers to a billion metric tonnes (metric tons) of CO_2, which is equivalent to 1015 g. One $GtCO_2$ is equivalent to 0.273 gigatonnes of carbon (GtC). This unit of measurement is used most frequently when discussing the scale of CDR required to prevent the worst impacts of climate change. (Source: CDR Primer)
hard-to-avoid emissions / hardest-to-decarbonize / hard-to-abate	Emissions that are either physically extremely difficult to eliminate within a certain timeframe (e.g., because of dependence on a particular infrastructure with a long lead time for carbon-free substitution, or because avoidance would require a technology that relies on a scarce resource) or which would be unacceptable to avoid from a social justice perspective (e.g., if mitigation would deprive people of the means to satisfy their basic needs, like food security). (Source: CDR Primer)

LCA	Life cycle analysis of the balance of positive and negative emissions and other impacts associated with a certain process or system, which includes all of the flows of CO_2 and other greenhouse gases along with impacts on other environmental or social impacts of concern. LCA also includes greenhouse gas emissions that result from the materials used to construct a given process (commonly referred to as embodied emissions), as well as from the energy resources used to meet the energy demands of the process. (Source: CDR Primer)
long-lived products	Products in which carbon is securely stored in a manner intended to be permanent..
megatonne	Equal to one million tonnes. (1 million metric tons)
Mission Innovation	Global initiative to catalyze action and investment in research, development and demonstration to make clean energy affordable, attractive and accessible to all this decade. This will accelerate progress towards the Paris Agreement goals and pathways to net zero. mission-innovation.net
negative emissions	Physical removal of greenhouse gases (GHGs) from the atmosphere by deliberate human activities (i.e., in addition to the removal that would occur via natural carbon cycle processes) and storage in a manner intended to be permanent.
net CO2 removed	Amount of CO_2 removed on a life cycle basis. See LCA.
net-negative emissions	A situation of net negative greenhouse gas emissions is achieved when metric weighted anthropogenic greenhouse gas (GHG) removals exceed metric-weighted anthropogenic GHG emissions. Where multiple GHG are involved, the quantification of net emissions depends on the metric chosen to compare emissions of different gases (such as global warming potential, global temperature change potential, and others, as well as the chosen time horizon). (Source: IPCC)
net-zero emissions	Achieved when the total emissions entering the atmosphere are counterbalanced by the total removal of emissions from the atmosphere. It is sometimes used interchangeably with the term carbon-neutral. (Source: CDR Primer)
Paris Agreement	A 2016 agreement formed by Parties to the UNFCCC to combat climate change and to accelerate and intensify the actions and investments needed for a sustainable low-carbon future.
permanence	The duration for which CO_2 can be stored in a stable and safe manner. Storage duration can differ significantly, depending on the type of storage unit. For example, concentrated CO2 stored in geologic formations deep underground is effectively permanent (thousands of years), whereas forest carbon stocks can release carbon back into the atmosphere due to wildfire or tree harvesting. (Source: CDR Primer)
Sustainably	Meeting the needs of the present without compromising the ability of future generations to meet their own needs. (Source: UN Sustainable Development Goals)
tonne (t)	A metric unit of mass equal to 1,000 kg

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