Carbon Dioxide Removal:

Roles for Artificial Intelligence in Support of FECM RDD&D Priorities

August 2023

Artificial intelligence (AI) holds the potential to accelerate the transition to a carbon-neutral economy and help achieve the technology research, development, demonstration, and deployment (RDD&D) goals set forth by the DOE Office of Fossil Energy and Carbon Management (FECM) in its *Strategic Vision*. FECM and the National Energy Technology Laboratory (NETL) continuously expand, maintain, and curate extensive scientific data sets and AI tools essential to carbon management, and they are now standing up a robust AI Multi-Cloud Infrastructure to enable the DOE research community to share and leverage a collection of tailored resources to expedite progress toward equitable and sustainable solutions.

As one step toward prioritizing AI development activities, FECM is exploring specific roles for AI in meeting the top RDD&D needs identified in the *Vision*. This document summarizes a series of discussions in which a range of specialists from FECM, NETL, and the DOE Office of Science suggested potential roles for AI in Carbon Dioxide Removal (CDR). This document should be viewed as a representative sample of the types of AI applications that may be needed; it is by no means a comprehensive list.

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Potential AI Roles in Carbon Dioxide Removal

The United States is committed to achieving net-zero greenhouse gas (GHG) emissions to avoid the worst impacts of climate change. Strategies to cut GHG emissions are essential (energy efficiency, electrification, renewable energy, and point-source capture), but they do not address the emissions that are difficult to abate (e.g., steel, cement, and chemical manufacturing) or the trillions of tons of carbon dioxide (CO_2) that have already accumulated in our atmosphere. On a global scale, up to 10 gigatons of CO_2 ($GtCO_2$) will need to be removed from the atmosphere annually by 2050, and up to 20 $GtCO_2$ by 2100 (WRI 2023).

> **FECM Vision for CDR**
>
> Advance diverse CDR approaches in service of facilitating gigaton-scale removal by 2050, emphasizing robust analysis of life cycle impacts of various CDR approaches and a deep commitment to environmental justice, including rigorously evaluating CDR, defining conditions for success, and leveraging leadership and expertise.
>
> *FECM Strategic Vision*, p.22

In November 2021 Energy Secretary Jennifer Granholm announced the Carbon Negative Earthshot to remove gigatons of CO_2 directly from the atmosphere and durably store it for less than $100 per ton of net CO_2-equivalent. This target calls for an all-hands-on-deck effort to innovate and scale up technologies in the growing field of carbon dioxide removal (CDR). DOE defines CDR as a "wide array of approaches that capture CO_2 directly from the atmosphere [where CO_2 accounts for about 420 parts per million (ppm)] and durably store it in geological, biobased, and ocean reservoirs or in value-added products to create negative emissions." The vast majority of climate and energy models for achieving net-zero emissions by 2050 indicate the need to develop and deploy these CDR technologies in the near term (DOE 2021).

> "By slashing the costs and accelerating the deployment of carbon dioxide removal—a crucial clean energy technology—we can take massive amounts of carbon pollution directly from the air and combat the climate crisis."
>
> Secretary of Energy Jennifer M. Granholm

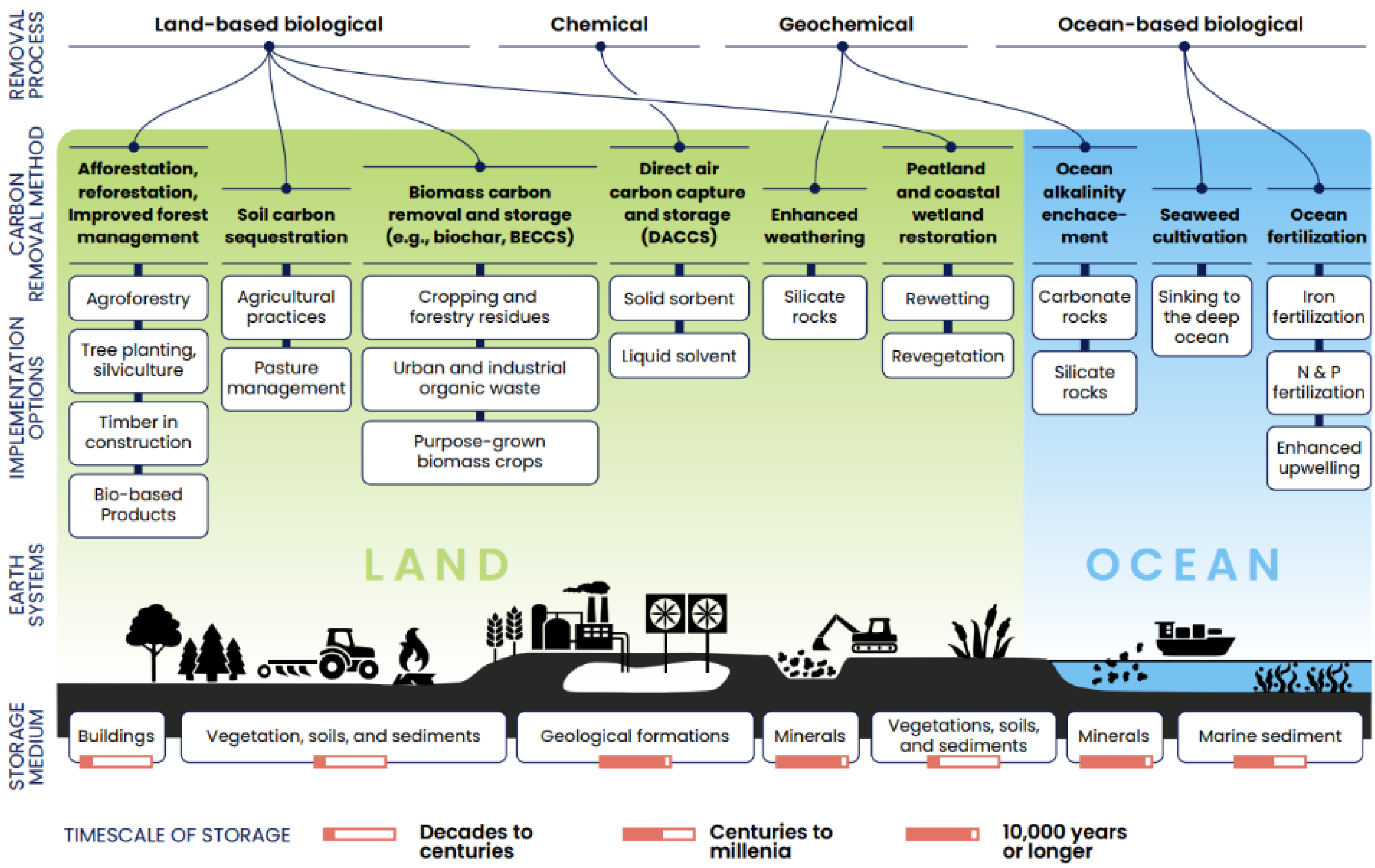
U.S. Department of Energy (DOE) research to support the Carbon Negative Earthshot explores diverse CDR approaches, including direct air capture (DAC), soil carbon sequestration, biomass carbon removal and storage (BiCRS), enhanced mineralization, ocean-based CDR, and afforestation/reforestation. Fully investigating and understanding these approaches will help decision makers select the appropriate pathways (see Figure 1) to effectively meet U.S. goals and a range of community needs while achieving equity, cost, and sustainability targets (DOE 2022).

The Bipartisan Infrastructure Law (BIL) and Inflation Reduction Act (IRA) provide significant funding for research into technologies that directly remove legacy CO_2 from the atmosphere responsibly, effectively, and affordably (WRI 2022). The CDR Program within the DOE Office of Fossil Energy and Carbon Management (FECM) pursues research, development, demonstration, and deployment (RDD&D) of the following CDR approaches:

- DAC
- Enhanced Mineralization
- BiCRS
- Enhanced Ocean Alkalinization
- Crosscutting Analyses.

Additional CDR approaches and supporting technologies are under development by other DOE programs, national laboratories, and members of the wider DOE research community. Each region of the country has a unique mix of climate conditions and resources, so a range of CDR approaches need to be explored and demonstrated to give all regions effective solutions and a full understanding of their impacts on ecosystems, economies, and communities (Wilcox 2022).

> **Carbon Negative Shot: Four Performance Elements**
>
> - **Reduced cost**: less than $100/net metric ton CO_2 equivalent for both capture and storage
> - **Robust accounting of full lifecycle emissions** (ensures accounting for emissions created when building and running removal technologies)
> - **High-quality storage for ≥100 years** with monitoring, reporting, and verification (MRV) costs demonstrated
> - **Gigaton-scale** removal.
>
> *CDR FAQs* (DOE 2022)



Notes: BECCS = bioenergy with carbon capture and storage; N&P = nitrogen and phosphorus..

Source: Boehm et al. 2022 via IPCC 2022

Figure 1. Range of CO_2 removal processes and their estimated time scales of carbon storage
[The FECM/CDR Program currently focuses on DAC, enhanced mineralization, BiCRS, and enhanced ocean alkalinity.]

CDR RDD&D seeks a deeper understanding of the many complex, natural, and human-assisted carbon capture processes; the ways novel technologies, materials, and conditions can influence those processes; and the potential lifecycle impacts of leveraged CDR approaches on interrelated systems now and in the future. As shown in Figure 2 (which reflects the structure of this document), artificial intelligence (AI) represents a uniquely powerful tool to potentially help FECM meet these key challenges on the pace required to achieve national CDR goals.

Summer 2023 Solicitation

FECM is planning a solicitation for research under the High-Performance Computing for Materials (HPC4Mtls) initiative for release this summer. The solicitation is expected to target materials for DAC, BiCRS, enhanced mineralization, and ocean CDR.

Direct Air Capture (DAC)

DAC technologies draw in ambient air, physically or chemically capture the CO_2, then regenerate the capture medium—releasing the CO_2 for long-term storage in value-added products or secure geologic formations. In addition to high costs, these technologies face a key challenge in achieving net-negative CO_2 emissions because of the energy required to efficiently separate the CO_2 from ambient air, in which the CO_2 is far more dilute than in the flue gases from power stations or industrial plants. For example, CO_2 in air is 100 times more dilute than in natural gas exhaust, 500-600 times more dilute than in cement or blast furnace exhaust, 1,000 times more dilute than in emissions from steam methane reforming, and 2,100 times more dilute than in bioethanol production (Wilcox, 2012). Most DAC technologies, many of which are currently at the prototype or demonstration stage, can be characterized as one of four main types (IEA 2022, NETL 2023): solid sorbents, liquid solvents, electro-swing adsorption, and membranes.

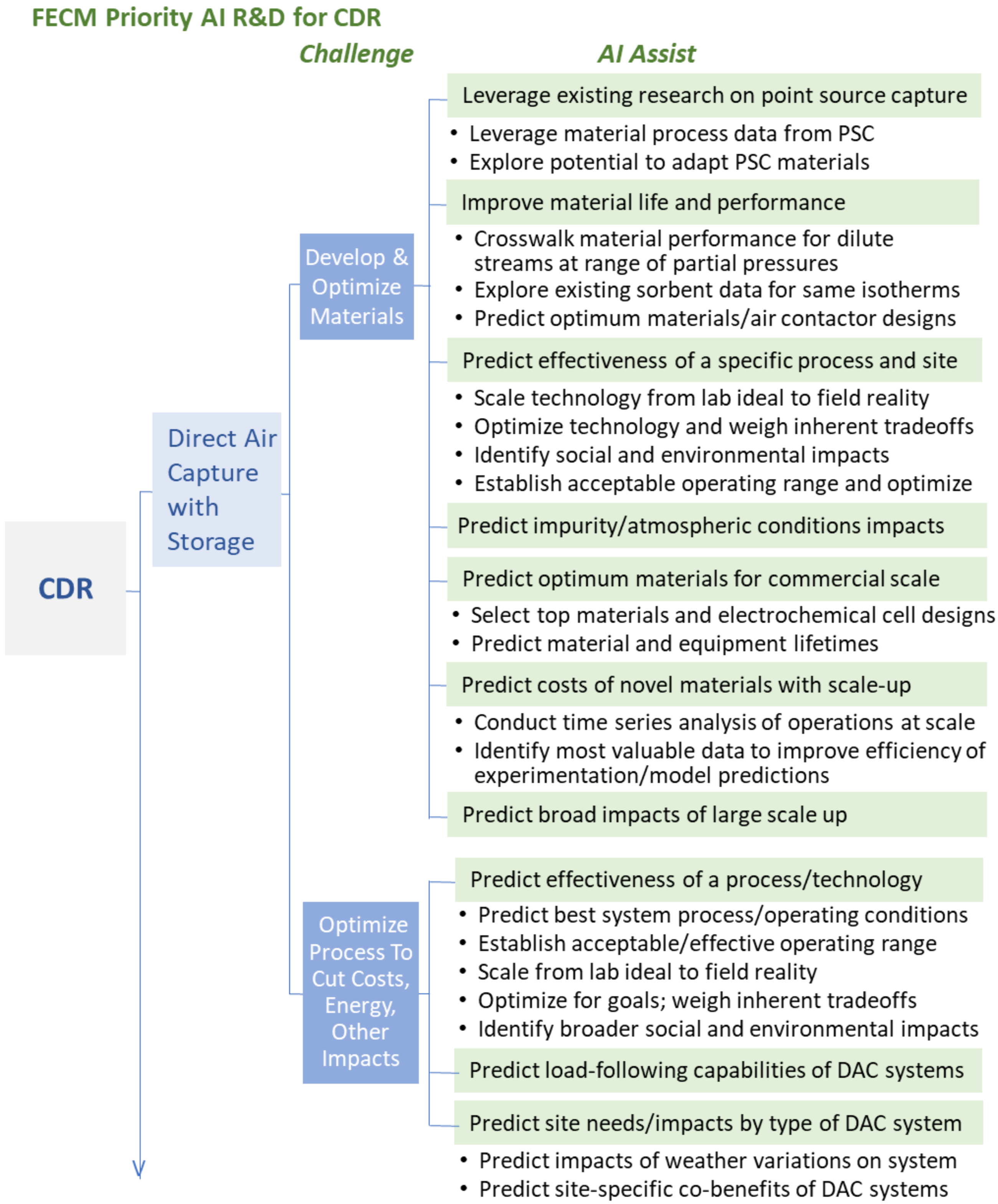


Figure 2. Summary of Potential AI Roles in Carbon Dioxide Removal

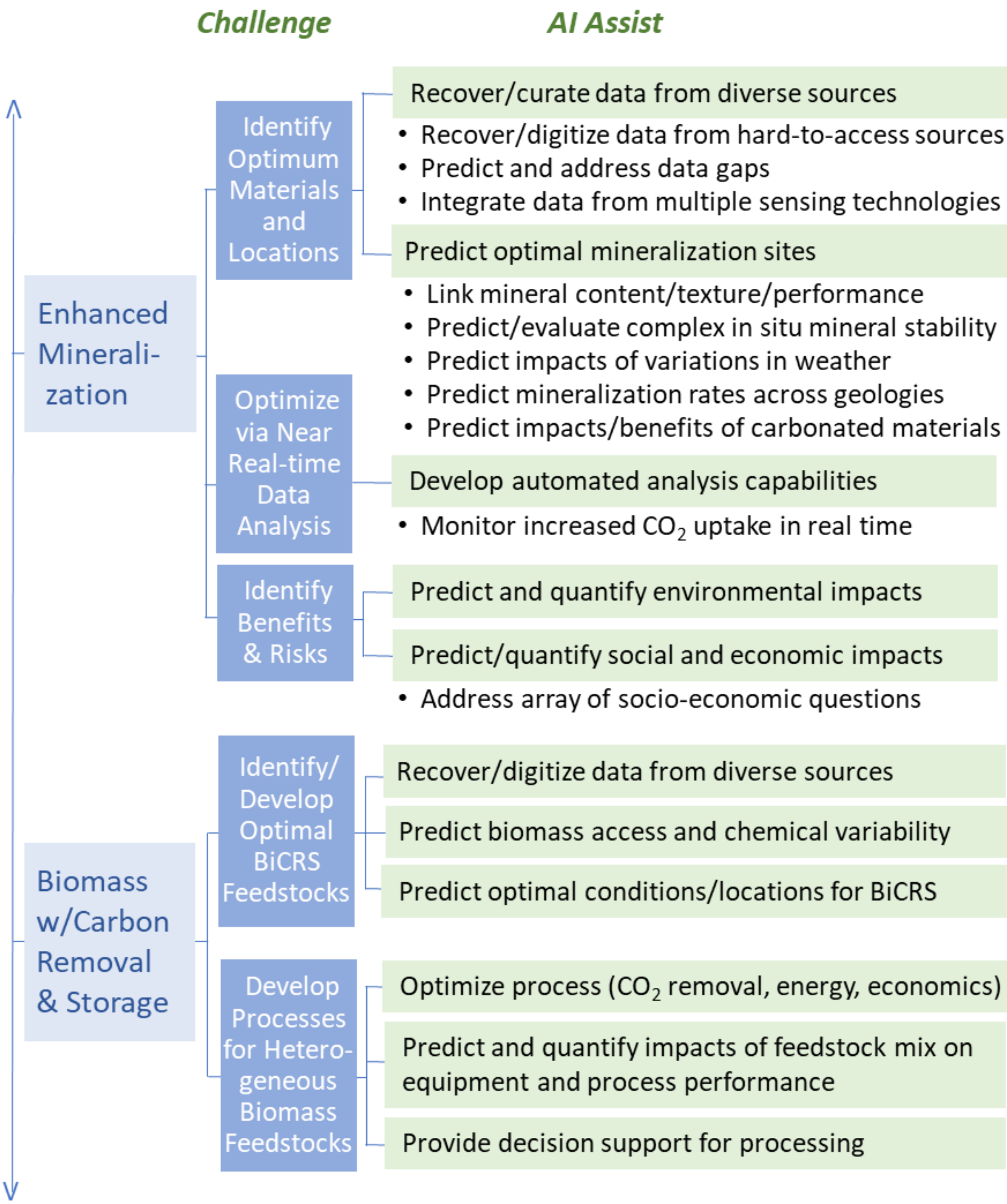


Figure 2. Summary of Potential AI Roles in Carbon Dioxide Removal (continued)

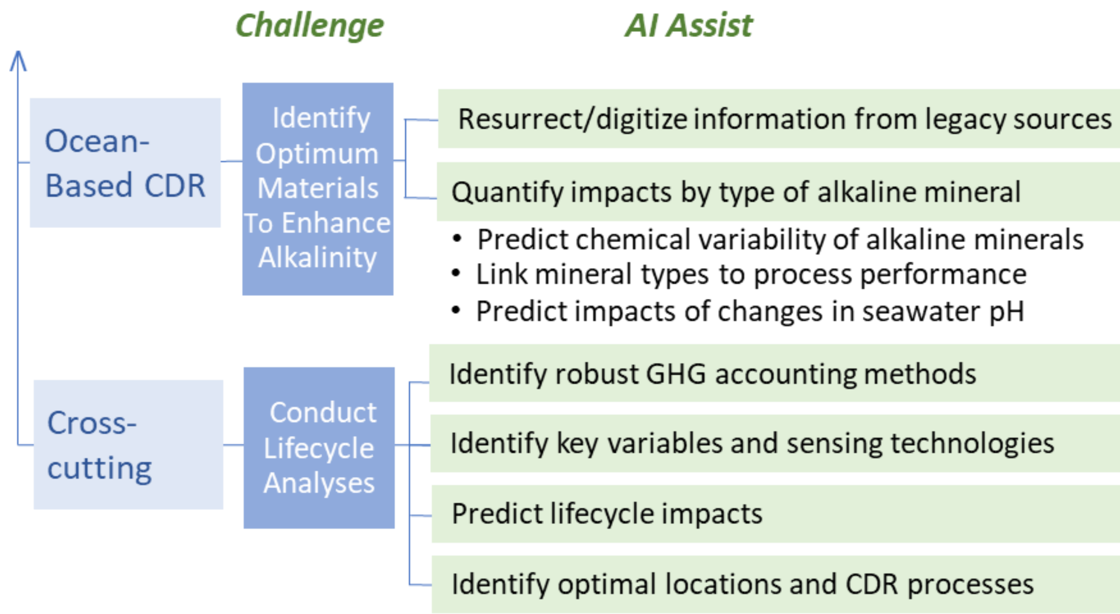


Figure 2. Summary of Potential AI Roles in Carbon Dioxide Removal (continued)

Solid sorbents: Sorbent-based DAC processes involve the chemical adsorption of CO_2, often using massive electric fans to move ambient air through the micro- or mesoporous channels of a solid sorbent framework coated with a base. The base on the sorbent's surface chemically reacts with and binds to the CO_2, which is released when the bonds are broken by various means. For example, sorbents release the CO_2 and regenerate with exposure to higher temperature, moisture or pressure swing, or other conditions, including hybrid approaches. These sorbent regeneration processes can require temperatures in the range of 80-120°C in fairly short thermal cycles (minutes to hours) using low-carbon energy sources like heat pumps, geothermal or solar-thermal energy, or waste heat. At present, the main issues with this technology are its high cost and the availability of materials (specialty chemicals and polymers).

> "We need to recognize that there are going to be some very, very hard-to-decarbonize sectors, like agriculture, aviation, shipping, long-haul trucks. And that carbon removal should be seen as the tool that helps to counterbalance those truly hard-to-decarbonize sectors, not as a tool to keep business as usual."
>
> Dr. Jennifer Wilcox, Assistant Secretary of FECM (Donnelly 2022)

Liquid solvents: Solvent-based DAC processes typically trickle a corrosive base solvent down a structured packing media to chemically absorb CO_2 from the air flowing through the column. The base is so corrosive that it is often diluted to make up about 30% of the solvent by weight, restricting its CO_2-capturing capacity (McQueen 2021). The captured CO_2 then gathers in an aqueous basic solution at the bottom of the column. The captured CO_2 is released as the liquid passes through a series of units operating at high temperature[1] (between 300°C and 900°C). Current processes could potentially operate using low-carbon fuels (e.g., biomethane or renewables-based electrolytic hydrogen) but would remove more carbon if clean energy sources were able to power the pumps and supply the high-temperature heat. This approach supports high-volume processing but requires a large-scale facility that uses a lot of water and energy.

[1] Solvents tend to require significant energy to heat the large amounts of liquid (water) and break the bonds to release the CO_2.

Electro-swing adsorption: This process uses an electrochemical cell in which a solid electrode adsorbs CO_2 when negatively charged and releases it when a positive charge is applied (i.e., swinging the charge rather than the temperature or pressure). Key challenges include the development of improved electrode materials and membrane contactors and the design of electrochemical cell and gas-liquid contactors for large-scale applications.

"The very low concentration of CO_2 in the air (0.042 vol%) makes DAC the most difficult carbon capture approach."

Mihrimah Ozkan and Radu Custelcean, *MRS Bulletin* (Ozkan 2022)

Membranes: Membrane-based processes use permeable or semi-permeable materials that enable selective transport and separation of CO_2 from air. This relatively simple approach offers a small footprint, but the partial pressure of CO_2 in ambient air is too low for the CO_2 to pass through membranes effectively (Keith 2010). The need to first compress a large amount of ambient air imposes a major cost and energy barrier, which has led researchers to explore multiple variations and applications. Recent work using process simulation suggests that nanomembranes could play a role at small-scale CO_2-capture sites like office buildings, schools, and malls, where average CO_2 concentrations can reach 1000 ppm or more (Fujikawa 2022). These small systems, if successfully developed, would also require on-site opportunities to convert or securely store the captured CO_2.

DAC systems are complex, and most existing systems use either a solid sorbent or liquid solvent. In both cases, the material/design should maximize the basicity of the sorbent, the amount of sorbent, and the surface area of sorbent exposed to the air (McQueen 2021). In 2022, DAC system costs ranged from \$225 to \$2,345 (average of \$1,113) to capture and store a single ton of CO_2 (CDR.fyi 2022), so significant work remains to reach the U.S. target of \$100/ton (Twidale 2023). Research focuses on materials and processes that increase the capture rate and capacity, extend material lifetimes, reduce energy needs, scale up and optimize component designs, and lower costs (NETL 2023). To advance the state of DAC technology, Congress and DOE have announced multiple initiatives (see inset on next page).

"Resources authorized by the Bipartisan Infrastructure Law will make it possible for us to prove these technologies out at scale and accelerate their deployment while providing good-paying jobs as our nation continues its transition to net-zero greenhouse gas emissions."

Assistant Secretary, FECM
Dr. Jennifer Wilcox

At present, all DAC processes require further work to lower costs, clarify potential modifications (e.g., reduced requirement for CO_2 purity), or identify alternative routes that would maximize benefits in specific applications and avoid unintended consequences. Although ambient air is ubiquitous, siting restrictions on DAC technologies may include temperature and humidity levels and access to clean energy resources as well as carbon transport and storage, utilization, or other supporting facilities.

The FECM CDR Program already uses machine learning (ML) and other AI tools to gain insights from existing data sets and better understand the critical data needed to simulate various DAC processes. In facilitated discussions, the Program team identified two main areas in which it expects AI to expedite progress:

- Optimizing processes to reduce costs, energy, and other impacts
- Developing and optimizing materials.

Develop and optimize DAC materials

Efforts to develop materials that can capture CO_2 from ambient air and later release it to create a more concentrated CO_2 stream focus primarily on reducing the associated energy penalty and cost. Associated aims are to maximize the capture capacity of materials, extend the lifetime of materials and equipment, reduce diffusion resistance, accelerate capture-and-release kinetics (across temperature and humidity levels), design for economical scale-up, and anticipate upstream and downstream impacts. With a few DAC prototypes now in operation, opportunities remain to improve performance and cut costs through RDD&D and learning from these early examples.

Critical research needs include more data on specific materials and systems, integrated processes, and performance under various environmental conditions. As of June 2023, FECM has awarded funding for more than 30 DAC research projects (mostly sorbents). Although data on any single technology may be limited, the Science-based Artificial Intelligence and Machine Learning Institute (SAMI) at the National Energy Technology Laboratory (NETL) may help locate and obtain additional relevant data sources, and physics-based models may generate other useful data. Once optimized at the lab or pilot scale, technology demonstrations should supply a better understanding of the feasibility of different DAC technologies under real-world conditions and how they affect environmental and socio-economic systems and communities throughout their life cycles and supply chains. To improve comparability across the data, it may be helpful to develop a list of standard measurement conditions (e.g., isotherms at defined temperatures) to guide future data collection efforts for DAC systems.

Initiatives To Accelerate DAC RDD&D

- **Five front-end engineering design (FEED) studies** to leverage existing zero- or low-carbon energy to supply DAC projects (with reliable CO_2 storage).
- **Two DAC prizes:**
  - Pre-Commercial Energy Program for Innovation Clusters (EPIC) Prize to plan incubators for DAC innovators (up to $3.7 M)
  - Technology Prize to help researchers scale and integrate DAC systems into the full carbon-management value chain and address energy or other resource and cost barriers (up to $3.2 M plus technical assistance)
- **Four regional DAC Hubs** to demonstrate a DAC technology or suite of technologies at commercial scale with the potential to capture at least one million metric tons of CO_2 annually and store it permanently in a geologic formation—or convert it into useful products.
- **45Q**: This section of the U.S. Inflation Reduction Act eases eligibility for the carbon capture tax credit, increases the credit amount, and offers more options for monetizing the credit. These changes will leverage private investment in DOE-supported projects and enable additional projects to move toward market with little or no federal funding.

Solid sorbents have generated considerable interest because of their large contact area (e.g., a gram of sorbent can provide a surface area the size of a football field [Wilcox 2022a]). Solid sorbents offer the further advantage of chemically binding the base to a solid framework, allowing the base to be applied at a much higher percent by weight (than liquid solvents)—increasing the number of interaction/binding points with CO_2 (McQueen 2021). The many contact points enable use of a weaker base to bind with the CO_2 and use of lower temperatures to later release it and regenerate the sorbent (Wilcox 2022a). Common types of DAC sorbents include amine-functionalized sorbents, metal-organic-frameworks (MOFs), and zeolites (among others); key challenges are to tune the sorbents to selectively bind to CO_2 over other gases and scale up production (McQueen 2021) in a sustainable manner. If the system uses fans to push air through the sorbent structure, a renewable power source would improve the carbon footprint, if space permits.

Leverage existing research on PSC materials: Technologies to capture far more concentrated CO_2 streams from power plants and industrial point sources have been in development for decades. Cost issues continue to limit wider use of point-source capture (PSC), but large volumes of data on a range of materials and equipment are now available (e.g., the National Carbon Capture Center has collected >80,000 hours of performance data and added DAC operations in 2020 [Wu 2022]). To the extent feasible, AI might **leverage material process data from PSC** to better understand and predict the conditions, limitations, and process requirements of materials for lower-partial-pressure DAC systems. Although DAC systems face greater constraints than PSC (more dilute CO_2, lower pressure, net negative emissions), AI might help **explore the potential to adapt PSC materials** (sorbents, solvents, etc.) for DAC applications.

Improve material life and performance: Rigorous exploration of promising DAC materials is likely to require extensive materials testing and data collection. Data is needed to identify and address the specific degradation mechanisms of sorbents/solvents under relevant environmental conditions. To effectively reduce process costs, DAC materials should be able to last for thousands of cycles, ensuring a service life of at least one year. In another approach, materials might be designed either for low-temperature adsorption or for more efficient regeneration—with heating applied only to the areas that have bonded to CO_2. A related challenge is to provide regeneration conditions that are correctly matched to the binding energy of a capture material—facilitating *combined* CO_2 capture and conversion (i.e., reactive capture) to a long-lived product (i.e., not a fuel or short-lived chemical).

AI might assist in designing or selecting the most promising materials for testing, and the resulting data can then be used to **construct a crosswalk on the performance of specific materials with dilute CO_2 concentrations** at a range of partial pressures. In the case of sorbents, if there is sufficient data on **sorbent performance at the same isotherm** (under a range of pressures), researchers might use AI to apply that data to processes under far lower partial pressures and detect patterns. This approach could work well if earlier data was collected at close to equilibrium at low pressure points for many different types of materials at that isotherm. With adequate data, AI might help to **predict the optimum sorbent, solvent, or other material and air contactor design** under various conditions (including the target purity of the output CO_2 stream).

P*redict effectiveness of a material and process for specific site/boundary conditions:* Lab-scale tests of materials are typically conducted in a controlled environment that may not reflect conditions in the field. Recognizing that humidity and temperature can affect material and process performance, AI might aid in **scaling DAC material technology that performs well in the lab to variable conditions in the real world**. In addition to weather considerations, AI may adjust the technology to variable boundary conditions such as the target purity of the output CO_2 stream. Currently, the final steps needed to attain 100% CO_2 purity tend to increase process costs considerably, and, depending upon the storage or conversion strategy, such high purity may be unnecessary.

A successful DAC material will likely minimize pressure drop, energy demand, and system cost while maximizing contact time with the CO_2 stream, productivity/capture efficiency, and life (resisting oxidation and water uptake) based on local conditions. In addition to meeting these priority parameters, the process of **optimizing a specific DAC material/ technology must necessarily weigh inherent tradeoffs** based on local environmental conditions, regional resources, and markets. Many parameters are interrelated, so optimization priorities are apt to be technology specific.

"A direct air capture plant can be up to a hundred times more efficient than a forest per given land area."

Dr. Jennifer Wilcox
Assistant Secretary of FECM
(Johnson 2022)

As part of FECM's commitment to planning for societal considerations and impacts (SCI), the development, demonstration, and deployment of DAC materials and technologies must also **consider socio-economic impacts in affected communities**—to make sure the deployed systems mitigate environmental impacts, distribute benefits fairly, remediate legacy harms, and deliver environmental justice (DOE/FECM 2023). AI may assist in identifying the predictable effects and setting the **acceptable range of operating parameters** to optimize overall operations and provide input to inform SCI. AI faces critical challenges in this area because social and environmental impacts are historically and contextually grounded. The selection of metrics for determining the full range of social impacts and optimum locations should be driven by best SCI assessment practices, based on the principles of energy and environmental justice, and developed in coordination with the affected communities (Spurlock 2022, Elmallah 2022, DOE/FECM/EJPA 2023). Related challenges are to accurately reflect community priorities in optimization models and to eliminate AI bias in the historical data.

Predict impacts of impurities and atmospheric conditions: In theory, DAC systems can be deployed any place that offers low-carbon energy and either secure carbon storage or a carbon utilization facility. The rapid pace and large scale of needed DAC system deployment dictate the need to carefully examine the diverse impacts of these systems in various environments. Researchers will need to accurately predict the impacts of atmospheric conditions and impurities (e.g., pollutants) on specific technologies/materials to be sure the systems achieve a net decrease in atmospheric carbon and avoid added costs or other unexpected impacts. For example, fans might draw insects, particulate matter, sulfur oxides, or nitrogen oxides into solvent- or sorbent-based systems, where impurities might accumulate to form undesirable products (NASEM 2019). AI can draw on existing forecast models to predict the potential impacts of precipitation, humidity, air pollutants, and extreme weather and assist in developing accurate predictions of system process improvements, efficiencies, and costs.

Predict optimum materials for commercial-scale operations: Achieving national CDR goals will require rapid deployment of commercial-scale DAC systems—despite the early stage of technology readiness today. AI might accelerate time to market by optimizing materials, predicting performance, defining supply chain requirements, predicting material life (and end-of-life strategies), forecasting costs, and anticipating impacts. By using detailed lab-scale data collected on various materials (e.g., thermogravimetric analysis [TGA], surface area, isotherms, solubility, permeability, etc.), AI might identify key factors to optimize critical properties at scale (e.g., maximize contact area, performance, CO_2 capture, service life, and productivity; minimize pressure drop, energy use, negative impacts, and cost) *for local conditions*. Local climate/weather (An 2022) and markets will factor into successful outcomes.

Given adequate lab-scale data, AI can potentially **predict and optimize materials and designs for electrochemical-based systems** when they are significantly scaled up for commercial deployment. In addition to the design of electrochemical cells, AI could support improved designs for gas-liquid contactors, electrode materials, and membrane contactors for large-scale applications. The ambitious scale of DAC deployment also underscores the need to accurately **predict material and equipment lifetimes** based on material structure, lab data, and a range of realistic operating conditions.

Predict costs of novel materials with scale up: Cost predictions for scaled-up novel materials will necessarily face data limitations, but just as ML can expedite material discovery and property prediction, ML can help minimize the cost and maximize the efficiency of material synthesis (Chan 2022). As production scales up, economies of scale tend to lower unit costs, but ML models can also help lower costs by forecasting material life and wear, optimizing materials use, and assisting with decision making and related issues (e.g., **conducting time series-based analysis of materials/operations at scale**). In addition, AI could potentially **identify the most valuable new types of data that should be tracked to improve the efficiency of experimentation and model predictions** to improve performance at scale using ML (e.g., Bayesian interference).

Predict broad impacts of large scale up: Environmental and economic equity are key values in every aspect of FECM RDD&D. Communities, particularly those that have traditionally suffered negative impacts from energy infrastructures, should be actively informed and engaged in decision making for any large DAC system. On the science side, this responsibility entails thorough assessment of the potential economic and environmental benefits and drawbacks of each DAC system (upstream, downstream, near term, and long term). Required reporting on predicted system impacts extends to system construction, materials sourcing and manufacturing, transportation of the captured CO_2 to storage, disposal of materials and equipment at the end of their service life, and potential CO_2 uses and markets. Specific equity guidelines are being developed by the DOE Office of Energy Justice Policy & Analysis.

> "Ongoing impacts of operating DAC plants will come from energy, land, and water use (for DAC plant and energy source) and chemical use for the sorbents and solvents that capture CO_2."
>
> Lebling, WRI, 2022

Optimize processes to cut costs and minimize energy, environmental, and social impacts

Technology developers typically seek to optimize the efficiency of a process to reduce capital and operating costs and boost productivity. Process optimization may be challenging for new technologies like DAC, which leverages novel materials and processes to achieve new objectives (i.e., capture CO_2 from ambient air). Experience and data on these systems are limited, but exploring and demonstrating many, diverse, early-stage DAC technologies should enable technological learning to support later cost reductions (i.e., learning by doing). A recent analysis notes that solid sorbent DAC may have a relatively high learning rate based on its modularity, whereas monolithic, site-built solvent DAC may have a somewhat lower learning rate but will benefit from economies of scale (McQueen 2021). Beyond costs, DAC system optimization targets include environmental and social impacts, which may require assessments on a project-by-project basis (Lebling 2022). AI tools could help expedite these assessments and help inform decisions.

As currently designed, most DAC systems require energy both to run the fans that draw in the ambient air and to heat and regenerate the sorbent. Such energy demands can lead to trade-offs with indirect emissions and other environmental impacts (Deutz and Bardow 2021). These energy requirements raise concerns that DAC energy costs may hinder deployment on the needed gigaton scale and delay anticipated technology cost reductions. One analysis found that DAC reliance on natural gas for process heat could potentially account for up to 25% of present-day global primary energy use before the end of the century (Fuhrman 2021). Leakage in the natural gas supply chain (U.S. national average is 2.3%) could reduce net CDR effectiveness and increase the cost of capture (McQueen 2021a). To cut costs and increase net removal, developers are working to reduce DAC energy requirements.

Predict effectiveness of a DAC process/technology: The diverse approaches to DAC systems now in development pose varying requirements for land, local temperature and humidity levels, water, supply of solvent or sorbent materials, and energy (see inset). Figuring out the most effective technology for a specific site will require the assessment of multiple, interrelated factors, including access to geological carbon storage or conversion technologies that securely store carbon for the long term. The destination of the captured CO_2 can also affect technology choice and reduce costs if the output CO_2 stream does not need to meet high purity standards.

To lower DAC system costs and potential negative impacts, researchers need **process simulation and optimization models of DAC processes.** ML might help build the needed algorithms and models of DAC operations to help reduce capital and operating costs and predict energy, land, water, environmental, and social impacts (jobs, health, co-benefits/disbenefits) for specified locations and boundary conditions (e.g., target purity of the CO_2). As an alternative to selecting the best DAC system for defined conditions, AI/ML may help **define for each DAC system/type the range of system process/operating conditions required** to minimize energy and costs and maximize the net CO_2 capture potential. For example, some

Energy Considerations of DAC Scale Up

"DAC scale up will require expanding the energy infrastructure and cost-benefit assessments of energy sources in diverse locations. DAC plants may connect to the grid or **use existing curtailed, stranded, or waste energy**; however, connecting to the grid would shift impacts elsewhere, and curtailed, stranded, and waste energy would be insufficient for large DAC facilities.

Energy carbon intensity is the main determinant of the net climate impact of DAC (Deutz and Bardow 2021; Terlouw et al. 2021). However, when energy sources have zero ongoing/on-site emissions, as with wind or solar photovoltaic (PV), other aspects of the system (like **construction and sorbent production**) play a larger role in determining climate impact (Deutz and Bardow 2021). These **renewable sources have other environmental and social impacts**.

Solar PV and wind turbines do not emit GHGs or other air pollutants, but they can fragment ecosystems and disrupt habitats (UCS 2013a, 2013b), depending on the location and method of construction. Integrating wind turbines and solar panels into grazing and farmland could reduce these impacts (Bergen 2020; McDonnell 2020), while offshore wind could also eliminate land use. Geothermal power would likely have similar ecosystem impacts, and, depending on the system, can produce some onsite emissions of sulfur dioxide (SO_2) and CO_2 (U.S. EIA 2020). **Geothermal power** has a relatively small surface footprint and can also share land use. Some projects have caused induced seismicity and land subsidence, but these can be avoided with appropriate siting, management, survey methods, and monitoring (U.S. DOE 2012; Sektiawan et al. 2016; Lowe 2012)."

Katie Lebling et al, "DAC: Assessing Impacts To Enable Responsible Scaling," WRI (Lebling 2022) technologies need wind, water, or a range of humidity levels to deliver optimal performance. AI might assist in setting the acceptable/effective operating range (minimum and maximum values) for each system and recommended adjustments when conditions approach one end of the range. Many parameters affect each other, so social/ environmental impacts may be hard to predict, and the “optimum” outcome may be subject to debate.

Removing gigatons of CO_2 from the atmosphere by 2050 will require the rapid scaleup and deployment of diverse DAC technologies (see inset) from ideal conditions in the lab to a wide range of real-world conditions in the field. AI may help **scale DAC technologies for successful deployment** by predicting the likely cost reductions of scale up and any constraints imposed by regional or global supply chains, including steel and concrete (McQueen 2021). Additional factors affecting deployment include (at a minimum) system modularity, the energy required for sorbent/solvent regeneration, and material manufacturing requirements.

Technology developers must **optimize across a range of goals** for a DAC process/design (i.e., maximizing system efficiency/ productivity, contact area, and CO_2 capture rate/capacity while minimizing pressure drop, energy demand, and cost). Unfortunately, impacts of the diverse goals often interact, conflict, overlap, and/or reinforce each other so that deployment decisions are invariably complex and must inevitably weigh inherent tradeoffs (regional resources, environmental conditions, markets for mineralized products). It may be possible for AI models to accelerate wholistic simulations for different priority rankings, summarize the outcomes, and assist in weighing the impacts. A recent study shows that the environmental impacts of DAC with carbon storage could follow different trajectories depending on the background energy system (Qiu 2022), and another analysis highlights the impact of DAC costs on future energy and climate outcomes (Williams 2022).

In addition to supporting CO_2 removal goals, FECM conducts DAC RDD&D to align with the social, economic, and environmental equity goals in the Bipartisan Infrastructure Law. To the extent that relevant, unbiased data is available to feed the models, AI might help to **identify broader socio-economic and environmental impacts** to facilitate DAC deployment decisions that promote environmental justice, community health, equity, workforce development, domestic supply chains, and manufacturing opportunities.

More DAC Concepts

Use existing structures (Noya): Transform the >2 million operating cooling towers across the nation into DAC plants using a CO_2 capture mixture (proprietary). https://fiftyyears.substack.com/p/direct-air-carbon-capture-is-crazy

HDVAC: Couple HVAC and DAC in recirculation mode to lower energy demand in commercial buildings, improve indoor air quality, and store/deliver CO_2 to nearby industry. (Soletair Power, CarbonQuest, and others)

Synthetic Resin: A team from Lehigh Univ. and Georgia Tech designed a sorbent made of synthetic resin dipped in copper-chloride solution that forces CO_2 in the air to bind to the resin. This reaction runs faster and uses less energy than other designs in the lab, and the sorbent can regenerate using seawater—producing carbonic acid rather than carbon (Chen 2023). https://techxplore.com/news/2023-03-air-capture-device-efficient-current.html

Ionic Liquids: Ionic liquids offer low vapor pressure, high thermal stability, and great tunability for carbon capture applications via physisorption or chemisorption. Composite materials might combine the ionicity and reactivity of ionic liquids with the porosity of support materials, leading to enhanced CO_2 transport and selectivity (Fu 2022)

Other Novel Approaches Summarized:

- Mission Innovation 2022 (pp. 12-13, 20)
- Ozkan and Custelcean in the MRS Bulletin, Vol. 47, April 2022. (Ozkan 2022)

Predict load-following capabilities of DAC systems: While research continues to reduce DAC energy requirements, this potentially paradigm-shifting technology must be deployed rapidly to achieve success. DAC systems will take advantage of renewable energy sources when readily available and feasible but, initially, many DAC systems may need to rely on power from natural gas with carbon capture and storage until the grid can be decarbonized. An in-depth analysis explores the ramifications of this reliance and confirmed the validity of this approach:

> Even if the region is no longer building new high-carbon plants but is still running its old ones, shutting down these old plants in favor of low-carbon energy sources is likely to be a better use of these low-carbon

sources than powering DAC. Only when the region's electricity system is nearly completely decarbonized, do the opportunity costs of dedicating a low-carbon electricity source to DAC disappear (McQueen 2021a).

In addition to potentially maximizing DAC service life, system performance, capital costs, and environmental and social impacts, AI might also assist in optimizing the use of excess grid power to lower operating costs—while also helping balance grid loads. The AI would train on big data to create a detailed model, then generate streamlined models for rapid edge processing to predict/optimize DAC load following at the local level. Based on modularity, solid sorbent-based systems may be more amenable to load following than liquid solvent-based systems.

Predict site needs/impacts by type of DAC system: The rapid deployment of various DAC systems is expected to generate needed data and knowledge to accelerate further system development and maturation. Deployment may prove the theoretical flexibility of DAC siting, but the early demonstration projects should be deployed at locations that meet the basic needs of each technology and avoid unduly challenging emerging systems with limited data on integration. AI could help to predict system needs and the sites likely to meet them. Similarly, AI might assist in identifying system vulnerabilities/impacts that can be avoided by informed siting *or* system benefits that could be amplified in certain settings.

Some passive DAC systems may require wind, and others may need water or a minimum temperature or relative humidity level to run efficiently. Another location may be too hot, humid, or polluted for a specific technology option. To address these issues, AI might **predict the impacts of weather variations on DAC systems** based on existing daily, seasonal, and annual data, trends, and projections.

As the nation invests in DAC and other clean energy demonstration facilities, the Department seeks to minimize negative impacts and maximize benefits to host communities. Data remains limited on the potential local impacts of DAC systems, but AI may be able to help **predict site-specific co-benefits** at potential deployment locations. Depending upon the specific technology, state and local policies, site conditions, and community needs, co-benefits may include water production, cleaner air, jobs creation, and other positive social and environmental impacts.

DAC Water Use and Production

"The solid sorbent DAC systems in development and production today vary widely in terms of water usage, depending on the sorbent regeneration method. A system that uses steam condensation to regenerate the sorbent may result in water losses to the environment — a typical plant may use 1.6 tonnes of water per tonne of CO_2 captured. Other systems regenerate the sorbent using indirect heating, meaning minimal water losses. And these indirect heating systems, such as Climeworks' solid sorbent systems, are actually net water producers, yielding an estimated 0.8-2 tonnes of water per tonne of CO_2 captured."

Katie Lebling et al, *6 Things To Know About DAC, WRI* (Lebling 2022)

Enhanced Mineralization

As igneous or metamorphic rocks rich in calcium and magnesium weather, they naturally react with CO_2 to form solid carbonate minerals such as calcite or magnesite. Scientists are exploring technologies and modified land-use practices to accelerate this natural mineralization process as a way to *permanently* remove CO_2 from the atmosphere with relatively low energy and logistical needs.

Enhanced mineralization harnesses the chemical energy made available when rocks from deep underground are exposed at the surface, where they are far from being at equilibrium with the ambient air and water (NASEM 2019).

These volcanic rocks (rich in calcium and magnesium but low in aluminum) may reach the surface by natural processes, such as uplift or erosion, or through mining or industrial activities (e.g., steelmaking). [See inset on types of carbon mineralization.]

Some proposed projects would use energy to gather, grind, and transport basalt, then expose the powdered rock to streams of concentrated CO_2. To enhance reactivity, reactors can create engineered pressure and temperature conditions. The mineralized carbon may then be used in various building materials to help offset process costs. Depending upon where boundaries are drawn, the energy needed for the synthetic sorbents or solvents and the subsequent compression of CO_2 could prevent this approach from achieving net carbon removal (Dipple 2021).

Types of Carbon Mineralization

- ***Ex situ:*** Minerals rich in calcium and magnesium are extracted from the subsurface, transported, crushed, and reacted with fluid or gas rich in CO_2. The process can be accelerated by heat and elevated pressures, which require energy.
- **Surficial:** Ambient or concentrated CO_2 is reacted with crushed alkaline rock (e.g., mined rocks, tailings), alkaline industrial wastes, or sedimentary formations rich in reactive rock fragments at the surface.
- ***In situ:*** CO_2-bearing fluid or gas is injected and circulated deep underground, where it reacts with minerals within the rock.

(NASEM 2019)

At FECM, the CDR Program is interested in ex situ and surficial mineralization. The program is initially exploring enhanced weathering as a pathway that avoids energy-intensive heating and pressurizing steps and relies on alkaline materials to passively react with atmospheric CO_2 under ambient conditions. The focus is on maximizing mineralization using accessible basalt or olivine, existing mine tailings, and suitable industrial waste byproducts (e.g., cement kiln dust, fly ash, steel slag), potentially dispersing the crushed minerals along coastal beaches and across agricultural land. Elsewhere in FECM, the Carbon Transport and Storage Program addresses *in-situ* mineralization pathways via carbon injection deep in the subsurface, and the Carbon Conversion Program leverages mineralization, along with other processes, to create value-added products.

Mineralization overlaps and complements other negative emissions technologies (such as carbon conversion and storage, DAC, and direct ocean capture) because of its ability to securely trap CO_2 for up to hundreds of thousands of years. It can also produce diverse co-benefits. For example, ground-up olivine mixed with sand and spread on ocean beaches, where the waves accelerate the mineralization process, can also help restore eroded coasts and temper storm surges. Similarly, pulverized basalt rock can be applied to farmland to simultaneously remove carbon and improve soil quality (see Figure 3). In addition, researchers are working on processes to co-optimize carbon mineralization and the extraction of critical minerals, which are important to a range of clean energy technologies (Riedl and Lebling 2023).

> "Mineralization occurs naturally during weathering of Mg- and/or Ca-rich, Aluminum-poor materials (e.g., "ultramafic rocks" composed mainly of the minerals olivine, serpentine, brucite, and/or wollastonite).
>
> Columbia University Climate School
> (Columbia University 2023)

CO_2 mineralization processes may also generate negative impacts, which need to be better understood. For example, rock dust may contain toxic trace metals (e.g., chromium and nickel), and heavy metals could leach from powdered rock into soil or groundwater. Scaling up mining operations to obtain enough of the right types of rock for mineralization could create jobs but could also adversely impact local communities and ecosystems (Riedl and Lebling 2023).

Unlocking the benefits of mineralization while avoiding negative effects could accelerate CDR and potentially lower the cost. FECM/DOE and its partners (universities, research institutions, other federal agencies, state and local

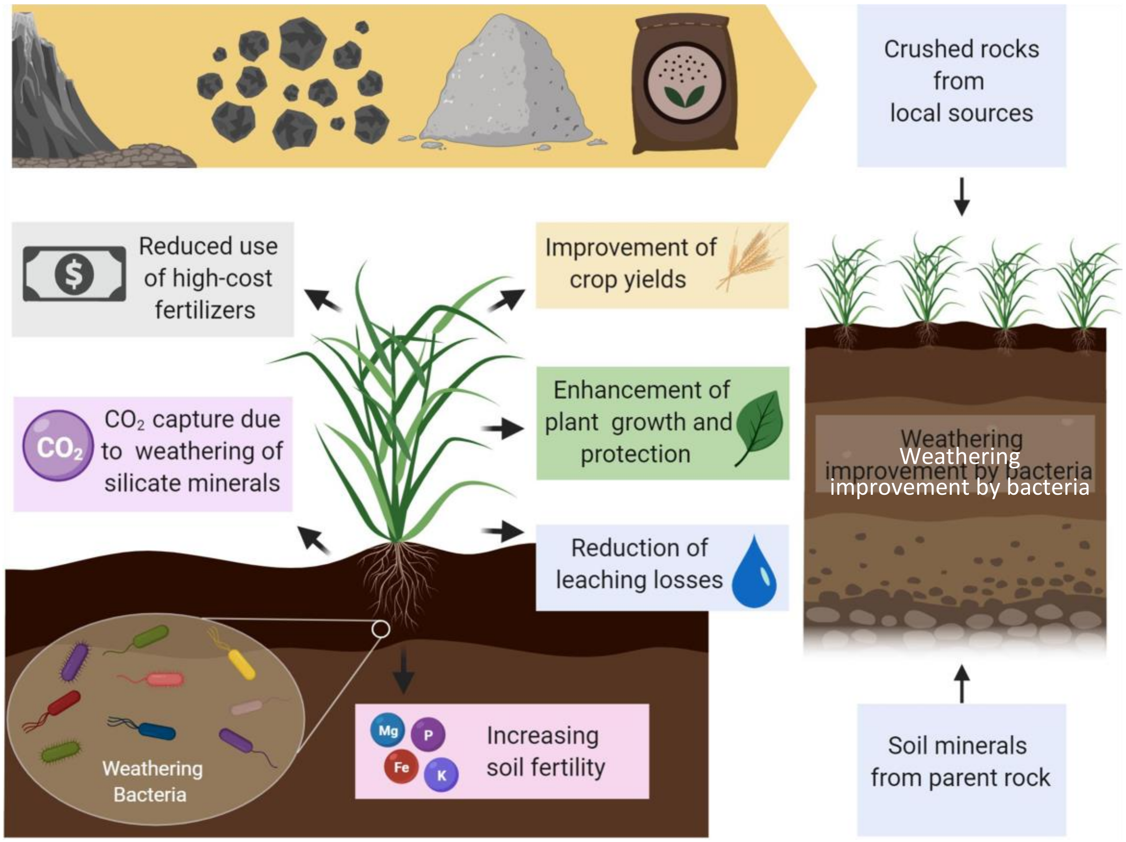


Figure 3. Beneficial effects on crops from the use of rock powder associated with weathering bacteria.
Source: Ribeiro, Volpiano, Vargas, Granada, Lisboa, and Passaglia (created with BioRender.com), 2020.

governments, tribes, and the private sector) recognize the need to gain a much better understanding of process kinetics and impacts. For example, Mission Innovation[2] identifies its priorities for enhanced mineralization as:

- *Mineralization Kinetics:* Characterize mineralization rates and kinetics across different mineral types, reaction fronts, and environmental conditions.
- *Energy Use, Land Use, and Environmental Impacts:* Understand the benefits and risks associated with introducing particulate matter to environments.

Critical steps to facilitate the needed research into enhanced mineralization include collecting and curating a wide range of reliable data and developing accurate tools and methods to measure, report, and verify diverse impacts. AI can help develop, apply, and rapidly improve the tools needed to expedite progress. Three key areas in which AI might play a significant role are to identify best materials and locations, optimize processes using automated analysis, and identify the specific benefits and risks.

Identify optimum materials and locations for mineralization

The United States has suitable geologic resources across the country to enable mineralization. In particular, Idaho, Oregon, and Washington have large areas of basalt at the surface, and all of Hawaii is made of volcanic basalt. In addition, widespread regions near the east and west coasts and in the upper Midwest contain significant amounts of ultramafic rocks and mine tailings (USGS 2019). Ultramafic mine tailings and alkaline industrial wastes spontaneously react with CO_2 in the air to form carbonate minerals during surficial weathering (Kelemen 2019). Enhanced

[2] Mission Innovation is a global public-private partnership working to pioneer clean energy solutions (Mission Innovation 2022).

weatherization utilizes existing waste and is compatible with other land uses. Figure 4 provides a useful overview of the relative storage capacities and costs of various enhanced mineralization approaches.

The FECM CDR Program seeks to better understand the diverse combinations of factors that influence mineralization processes, including the selection and preparation of rocks and minerals (e.g., mineralogy, particle size, reactive surface area, mineral pre-treatment steps) and the influence of the environment (e.g., temperature, humidity, etc.). All of the needed research will require robust datasets, including process kinetics, rock mechanics, and numerical simulation (NASEM 2019) as well as extensive measurement, reporting, and verification (MRV) activities.

Recover and Curate Data from Diverse Sources: Optimizing materials and locations for enhanced carbon mineralization will require extensive, high-quality data on the location, quantity, and mineralogical/geochemical makeup of commercial, industrial, and mining wastes. The USGS has developed a geodatabase of geologic formations and mine locations explicitly for exploring potential CO_2 mineralization, and NETL's Energy Data Exchange (EDX) has compiled large datasets and tools that could assist in identifying promising sites for enhanced mineralization; however, additional detail will likely be needed at a finer scale. Much of this needed data may exist in outdated, nondigital formats (e.g., old ledgers, paper files, logs, etc.) or is held by companies that consider the information proprietary. In the case of abandoned mine sites, it may be difficult to track down the owners. If states have assumed site ownership, no records may be available to determine resource suitability for carbon mineralization.

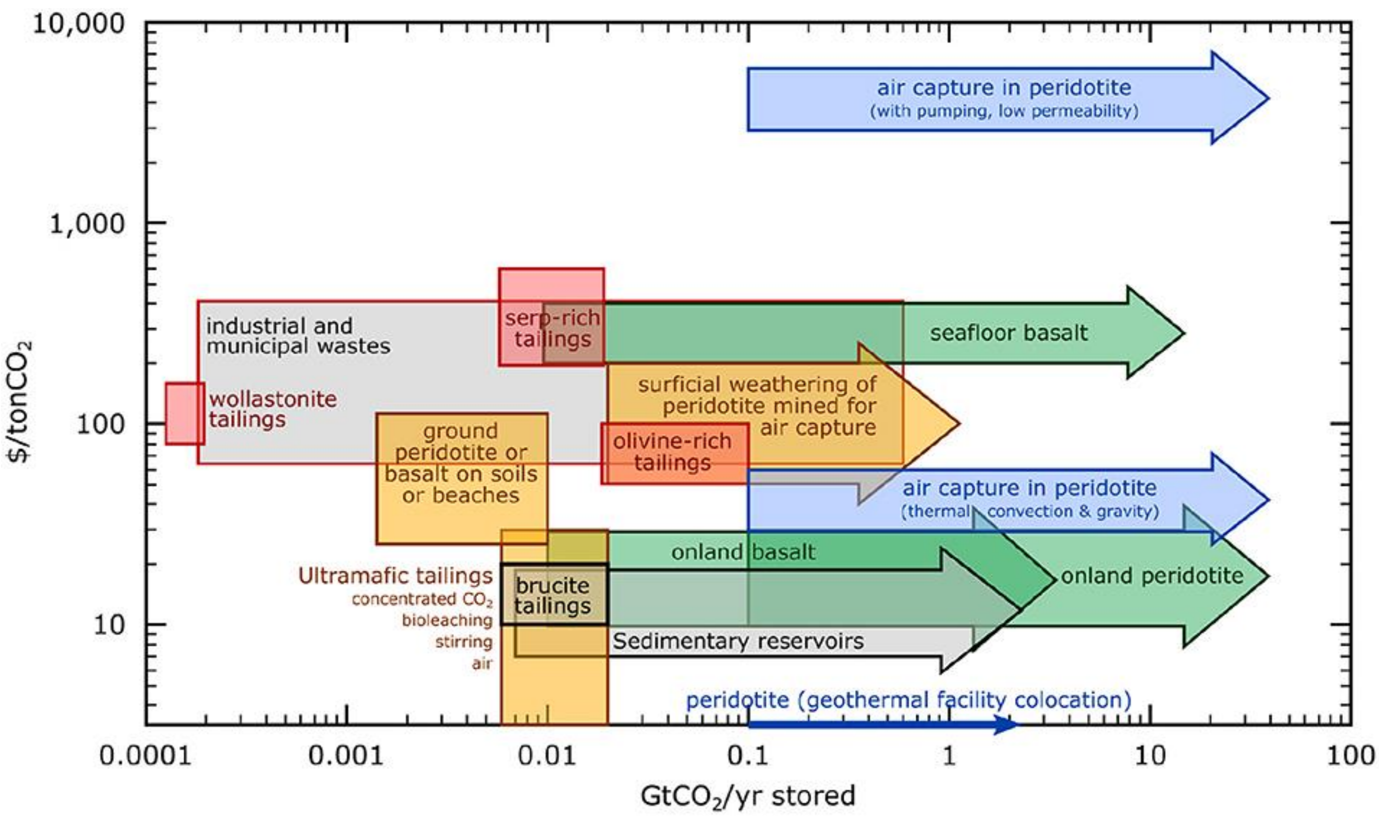


Figure 4. Summary of the cost of CO_2 stored (US\$/tCO_2) vs. annual storage potential of CO_2 (GtCO_2/yr)

This is a modified version of a chart originally developed by the National Academies of Sciences (NASEM 2019)

Key: Red boxes: Costs and rates for ex-situ CO_2 mineralization using heat and concentrated CO_2.

Yellow boxes: Surficial CO_2 mineralization of mine tailings, of ground peridotite added to soils or beaches, and of peridotite mined and ground for the purpose of CO_2 removal from air with solid storage.

Green, blue, and gray arrows: Various types of in-situ carbon storage.

Source: Kellemen 2019 (Kellemen, Benson, Piloge, Psarras, and Wilcox), modified from NASEM 2019.

AI can assist in **digitizing and characterizing legacy data** using natural language processing (NLP), optical character recognition (OCR), or other tools. Industrial site owners may be persuaded to share their characterization data on rock waste and mine tailings if they understand the benefits of mineralization. For example, mineralization can be used to help shrink a site's carbon footprint or reduce some environmental or health hazards, such as asbestos (Kelemen 2019). With access to plant records, AI could also help locate minerals of interest. Both mine waste and industrial rock waste may have been moved about over time, piled on or mixed with other rock types, and subjected to varying weather conditions.

Research will attempt to determine the optimal reaction pathways and thermophysical properties of various rocks/minerals and environments for CO_2 removal. AI can assist in **filling and predicting critical data gaps**, but extensive, high-quality data is needed at the outset to enable AI to generate useful models and algorithms (with data reserved for verification). With adequate data characterizing the available commercial, industrial, and mining wastes, AI might pair or prioritize resources and preparation methods based on reaction rates and CO_2 uptake potential. In the case of enhanced weathering, sufficient environmental data might enable AI to clarify the impacts of temperature, rainfall, humidity, plant-mineral interactions, and soil properties (pH, clay content, organic matter, carbonate content) on the rates at which specific rocks and minerals weather.

AI models rely on data feedback to continuously learn, adapt, and improve their predictions. If data is scarce, validated models may be used to generate synthetic data (using interpolation or extrapolation within appropriate boundaries). At some point, robust models may be able to predict the types of additional data required to greatly refine their outputs or improve their utility. If connected to an extensive virtual data library, AI may even interrogate datasets to identify and request access or flag emerging data gaps.

In the absence of adequate data, AI might be used for analyzing and **integrating data from multiple sensing technologies** to provide new insights on mineralogical/geochemical resources, such as rock/mineral concentrations, volumes, and estimated carbon capacity (see "Critical Minerals: Roles for AI" in this series). ML algorithms might process hyperspectral imaging and drone photography to generate maps of geological materials and sites suitable for mineralization.

> "It's the problem of our generation. We need big solutions. We need to return the carbon back to where it came from, which is the Earth."
>
> Kári Helgason
> Head of Research and Innovation, Carbfix

Predict optimal mineralization sites: AI could assist in evaluating a broad range of factors to identify the most promising sites for implementing enhanced mineralization. The initial focus of this effort would be to **link the mineral content and texture of the rocks to their performance in capturing CO_2**—which will require detailed data on the mineral makeup of rocks, diverse particle sizes, and the demonstrated rates and amounts of resulting carbon reduction. Quantifying the link between mineral content, mineral texture, and process performance may necessitate time-stamped measurements at multiple, strategically decisive points in the mineralization process.

With the capability to predict basic mineralization outcomes, the scope would then broaden to better understand additional factors affecting capture rates and CO_2 capacities (e.g., pollution levels, water action, climate, and other environmental conditions). Ultimately, AI models might be enriched to help decision makers select sites that minimize costs and help attain important social, environmental, and economic benefits. Detailed data would be needed on locations, quantities, and properties of the minerals and wastes since deployment sites may need to be co-located with a resource to minimize the cost and energy penalties of transportation.

AI could also be used to **evaluate and predict complex *in situ* mineral stability** in the presence of groundwater, formation water, and natural geochemical processes. This AI may use a mix of physics-based or physics-informed models and deep learning. Knowing the mineral stability might pave the way for AI to then **predict the impacts of weather variations** on the effectiveness of carbon reduction over diverse time periods (e.g., day, season, year). Silicate minerals are known to weather more readily in warm, humid regions, where soil temperatures exceed 20 °C and annual rainfall is above 1500 mm. One study of olivine particles with a diameter of 50 µm found that half would dissolve in under 10 years at 19 °C but would take about 50 years to weather as much in identical soils at 4°C (Pogge von Strandmann 2022, Renforth 2015). AI models might use ongoing data feedback to adjust for shifts in climate in the decades ahead.

AI development is expected to continue and contribute to a stronger understanding of mineralization under diverse conditions. Once AI has demonstrated the ability to predict mineralization performance at specific sites, AI models may be scaled up to **predict mineralization rates across geologies**—forecasting mineralization effectiveness across larger areas (mapped by USGS and others). AI might even suggest strategies to increase the rate/capacity of carbon uptake by the mineral types present. Finally, for ex situ processes, AI might then learn to **predict the properties of the resulting carbonate minerals, including their impacts** or value. For example, AI might assess impacts on the land, water, and air (e.g., potential to leach beneficial or toxic minerals/elements), economic benefits (e.g., potential use of carbonated minerals in value-added products).

Optimize mineralization with near real-time data analysis

To accelerate critically important reductions in atmospheric CO_2, continuous monitoring and evaluation will help ensure that enhanced mineralization projects perform effectively. Key challenges include the cost and energy intensity of monitoring carbon uptake and storage over long periods of time. AI can potentially evaluate sensor data in near-real time to rapidly characterize and optimize the mineralization process and any associated systems.

Develop automated analysis capabilities: Measuring the extent to which a natural process has been enhanced requires an accurate baseline. In the case of enhanced mineralization (via grinding, mixing, etc.), researchers need to know how much CO_2 is absorbed by volcanic rocks and minerals naturally—before any enhancement. This task is particularly challenging in an open natural system (against a spatially and temporally variable background). Setting baselines will require extensive data collection on CO_2 removal by natural processes under diverse conditions (i.e., high-quality mineralogical, process, and performance data).

In open systems, it may be economically infeasible or physically impractical to sample all of an area in which minerals have been applied. AI tools can assist in several ways. For example, AI might develop algorithms to identify the best project-specific sampling locations (based on soil properties, topography, etc.) and sampling frequency to minimize cost, energy use, and uncertainty about carbon removal rates and quantities. AI may also assist in selecting the best types of sensors (e.g., gas flux, solid carbonate precipitates, aqueous bicarbonates and carbonates in soil pore waters) to measure mineralization at specific sites. Depending on site properties, some combination of sensors may offer greater certainty at reduced cost and energy use.

AI can assist in developing advanced detection tools to collect the needed data, define baselines, and develop automated analysis capabilities to **monitor real-time CO_2 uptake rates and quantities** achieved through mineralization enhancement. These AI analyses could also provide decision support to help operators optimize performance and CDR. AI models could play a valuable role in tracking and verifying carbon reductions in open systems over time, potentially resolving the current discrepancies between models and experiments. Integrated modeling-experimental approaches should improve estimates of field weathering rates and CDR efficacy when silicate materials are spread across diverse soil types or over a variety of crops or other vegetation in different climates (Calabrese 2022).

Identify benefits and risks of mineralization

DOE/FECM is committed to informing and actively engaging local communities in the decision making for CDR projects, underscoring the need to clearly define the environmental, social, and economic benefits and risks of each project. Key benefits of enhanced weatherization are that it is a natural process with tremendous storage capacity and in use by parts of the agricultural and mining sectors. As noted above, AI might assist in data collection (depending upon access and format) and assessment. With adequate data, ML tools may use lifecycle analysis to examine the long-term impacts of enhanced mineralization in various settings.

Predict and quantify environmental impacts: The impacts of enhanced mineralization may vary widely by location based on the variability of approaches, materials, and processes. Benefits may include revenues from carbon credits, soil pH amendment, improved crop yield and/or quality, stimulated biogenic CO_2 uptake, reduced fertilizer usage, and lowered N_2O and ammonia emissions. Some impacts could be positive or negative (e.g., enhanced or reduced leaching of minerals or elements, waste site remediation/disturbance, air and water impacts, etc.). Other approaches may offer tradeoffs that local communities will need to weigh according to their priorities. For example, spreading powdered rock over agricultural and forest soil can release nutrients like potassium and phosphorous, stabilize organic matter, increase water retention, and buffer soil acidity (Sandalow 2021). If enhanced by microbial processes, this approach may rival DAC in terms of CO_2 reduction, but ultramafic and mafic rocks contain heavy metals that, once oxidized, could accumulate in soils and pose a health risk (Kelemen 2019), and farm workers could inhale particulates. The extent to which dust from enhanced weathering practices poses a hazard to farmworkers will depend on grain size and application method (Almaraz 2022).

Predict and quantify social and economic impacts: Some analysts point out that alkaline powdered rocks are relatively abundant on Earth and inexpensive to quarry and grind without special engineering or technologies (Sandalow 2021). In addition, many industrial wastes (e.g., steel slag, cement kiln dust, and waste concrete) react with CO_2 and could be used in place of natural rock (Renforth 2019). Use of these wastes would avoid mining and grinding—and all of the associated energy use and costs. Additional research is needed to assess the potential of different waste streams and ensure that local communities receive real benefits, e.g., water and air quality, jobs. Although the basic science of the process is well understood, some uncertainty remains about potential unintended consequences. AI may help to **address an array of socio-economic and spatio-temporal questions** using time series analyses, cluster analysis (unsupervised ML), classification methods (supervised ML), and ensemble modeling.

Biomass with Carbon Removal and Storage (BiCRS)

The *Biomass Carbon Removal and Storage (BiCRS) Roadmap* of 2021 (Sandalow 2021b) introduced the term "BiCRS" and defined it as "a process that (a) uses biomass to remove CO_2 from the atmosphere, (b) stores that CO_2 underground or in long-lived products, and (c) does no damage to—and ideally promotes—food security, rural livelihoods, biodiversity conservation, and other important values." BiCRS is a hybrid of natural and engineered approaches to achieve a net removal of CO_2 from the atmosphere (including indirect land use impacts)—while protecting ecosystems and, ideally, generating economic benefits and supporting social values (Sandalow 2021b). Significant research is needed to fill existing knowledge gaps about the interactions across complex ecosystems over various time spans. This knowledge is needed to inform standards, guide policy, and achieve global consensus and cooperation to achieve effective carbon removal.

Aines Principle

Named for Roger Aines, Chief Scientist, LLNL

"In the context of climate change, the value of biomass for removing carbon from the atmosphere may exceed the value of using biomass for energy generation."

Sandalow 2021b

Potential feedstocks for BiCRS should be sustainably produced and not interfere with food crops, other land uses, or water resources. The best feedstocks include a wide range of plant wastes such as agricultural and forest waste, black liquor, and municipal solid wastes (which are all affordable and available with limited impact on land use and the environment); carbon-removal crops; dedicated energy crops like sugar cane, rapeseed, corn, and woody biomass; and cultivated microalgae (Sandalow 2021b).

Many energy-generating BiCRS processes are fairly well developed (e.g., biomass to fuels, hydrogen, and chemicals with CO_2 capture and storage). Newer, non-energy-yielding approaches require additional study. Bioliquid injection into geologic storage offers great potential for permanent CO_2 removal, whereas biomass conversion to engineered products (e.g., biofiber entombment and engineered wood) could generate economic benefits (see inset). In addition, research is required to develop crops that are specifically optimized for life-cycle carbon removal — potentially paving the way for far higher carbon removal rates. Challenges for BiCRS include potential water and land use competition; cultivating, transporting, and processing microalgae at large scale; and measuring, monitoring, and crediting carbon removal (Sandalow 2021b).

Certain subareas of BiCRS are the shared purview of other FECM or DOE programs, necessitating collaboration on research. For example, conversion of biomass to long-lasting products is also a focus of FECM's program on Carbon Dioxide Conversion; the use of biomass to produce energy, liquid fuels, or heat (e.g., bioenergy carbon capture and storage [BECCS]) is also a focus of FECM's Point Source Capture and Hydrogen with Carbon Management programs; and biofuels are a focus of the Bioenergy Technologies Office in the DOE/EERE Office of Sustainable Transportation. The FECM CDR Program has awarded some front-end engineering design (FEED) studies in the BiCRS area. The goal is to support novel types of biomass CO_2 disposal to show the potential for negative emissions through methods like biomass burial, the intersection of biomass and ocean CDR, and integration of biomass into industrial CCS projects. The Program identified two main areas in which AI might assist in future BiCRS research: (a) identifying or developing optimal BiCRS feedstocks and (b) developing processes to handle heterogeneous biomass.

Diverse Options in BiCRS

BiCRS expands the use of plants and algae to remove CO_2 from air beyond energy pathways.

BECCS (bioenergy with carbon capture and storage): An energy pathway during which CO_2 is captured from a biogenic source and permanently stored. Concerns over net carbon impacts have limited widespread deployment.

Bioliquid injection: Biomass is converted (e.g., direct liquefaction) to bioliquids for injection into deep geological storage reservoirs. Industries that formerly avoided bioliquid byproducts (e.g., black liquor) could facilitate carbon removal.

Biofiber entombment: Micro-biofibers could be used as composites to store carbon and improve the strength or durability of cement and concrete. Research is needed to optimize feedstocks, treatments, economics, and performance.

Engineered wood products: Carbon can be stored in long-lived engineered wood products in buildings (e.g., oriented strand board and mass timber) often displacing cement production and its hard-to-abate CO_2 generation.

Biochar: Biochar is a recalcitrant charcoal created by pyrolyzing biomass at high temperatures and often used to enrich soil fertility. Research may clarify the impacts of feedstocks and environment on the duration/security of carbon sequestration.

Microalgae: Microalgae strains cultivated in ponds, reactors, or land offer an extremely efficient way to convert sunlight into biomass and capture CO_2.

(Sandalow 2021b)

Identify or develop optimal feedstocks for BiCRS

AI could assist FECM in better understanding the types of biomass that are best suited to capture large amounts of CO_2 and match them to the BiCRS processes most likely to provide long-term CO_2 storage or removal from the atmosphere. This research may identify existing plants or algae or suggest modifications to increase their effectiveness in specific BiCRS strategies.

As a first step, researchers will need access to large datasets describing the available amounts and locations of candidate plants and their chemistries. AI can help to **collect relevant plant data from diverse sources and resurrect data from legacy formats** (outdated or nondigital) using OCR, NLP, and similar tools. The next step may involve using AI to **predict and quantify the chemical variability and amount of biomass feedstocks available** based on location, daily and seasonal weather, time of harvest, and other factors. Finally, AI might help **predict optimum locations for deploying BiCRS** to maximize use of waste materials and the environmental, social, and economic benefits while minimizing costs as well as adverse land, water, energy, environmental,[3] and social impacts (see bottom of page 8).

[3] Stanford researchers recently found that "when elevated CO_2 levels drive increased plant growth, it takes a surprisingly steep toll on another big carbon sink: the soil." These "results contradict a widely accepted assumption in climate models that biomass and soil carbon will increase in tandem in the coming decades and highlight the importance of grasslands in helping to draw down carbon" (Garthwaite 2021).

Challenges to the use of AI in these roles are the limited availability, quantity, and quality of data on diverse BiCRS approaches and the difficulties in measuring, monitoring, and crediting carbon removal by plants and algae. Past biomass inventories tended to focus on the energy content of plants rather than their CO_2 capturing and storage capacity. In addition, social and environmental impacts and benefits may not be easily known, distinguished, or understood, and they depend on a variety of factors and perspectives.

Optimize BiCRS processes to accommodate heterogeneous biomass feedstocks

Traditional biomass conversion processes optimized for energy extraction, whereas BiCRS processes must optimize CO_2 removal. AI may help researchers adjust or **control biomass conversion processes to maximize carbon removal** based on real-time energy availability and economics (e.g., grid load following). BiCRS conversion facilities might lower overall costs and CO_2 emissions (e.g., transport) by using a range of biomass grown near the facility. AI might assist in developing a tool for determining the processing impacts of using heterogenous biomass feedstocks. Specifically, AI might **predict and quantify the impacts of various feedstock mixes/biomass types on equipment and process performance** (e.g., measuring real-time chemical variability of the biomass to control downstream operating parameters to minimize costs and impacts and maximize environmental, social, and economic benefits). As part of this effort, AI might **predict the impacts of various feedstock mixes/biomass types on pollution control equipment.** Validated predictions could lead to AI tools that **provide decision support for operators** on adjusting either the incoming mix of feedstocks or the system operating parameters to optimize processing objectives.

> "Our analysis suggests that BiCRS processes could capture and store 2.5-5.0 gigatons of CO_2 annually ($GtCO_2$/y) by mid-century. Although this figure is more modest than those used in some integrated assessment models for BECCS (which range as high as 20 $GtCO_2$/y), BiCRS could be an important part of global efforts to achieve net-zero emissions in the decades ahead."
>
> Sandalow 2021b

Ocean-Based CDR

The Earth's oceans capture an estimated 25–30% of human-generated CO_2 emissions, and ocean-based CDR (also known as marine CDR) has the potential to significantly increase this CO_2 uptake and provide long-term storage. Key concerns about ocean CDR include accurately measuring the amount and duration of CO_2 extraction and storage in an immense natural system (monitoring, reporting, and verification); the potential for changes in seawater chemistry to adversely affect ecosystems (NETL 2023); and the sheer magnitude and complex interactions among evolving open ocean systems (Figure 5), which underscore data gaps and resist scientific certainty (Climate Tech VC 2023). Diverse approaches can potentially increase the uptake of CO_2 and its long-term storage in the ocean depths.

Researchers need a better understanding of the overlapping physical, geochemical, and biological processes that influence the near- and long-term CO_2 exchange between air and ocean—and of the near- and long-term impacts (as well as the potential for unintended consequences) on marine food webs, biodiversity, societies, and economies. For this reason, the National Academies of Sciences, Engineering, and Medicine (NASEM 2022) prepared the *Research Strategy for Ocean-Based Carbon Dioxide Reduction,* which calls for developing a robust code of conduct and an enabling governance system for ocean CDR research. In addition, a range of international working groups (e.g., GESAMP 2019, IMO 2023) have produced important bodies of work as well as relevant international treaties and conventions.

> "The nascent nature of most approaches and the many open questions call for a coordinated effort to test effectiveness, evaluate potential environmental risks, and work closely with coastal communities."
>
> Antonius Gagern, CEA Consulting (Our Shared Seas 2021)

Foundational research is needed to better understand the feasibility and consequences of a variety of proposed approaches. The NASEM Strategy recommends that CDR research should be open, interdisciplinary, and collaborative—and conducted in coordination with indigenous communities and international partners in accordance with existing laws and regulations (Doney 2021). With many companies eager to begin field demonstrations, the Strategy promotes fundamental research to maximize learning from early pilot tests and support informed decision making.

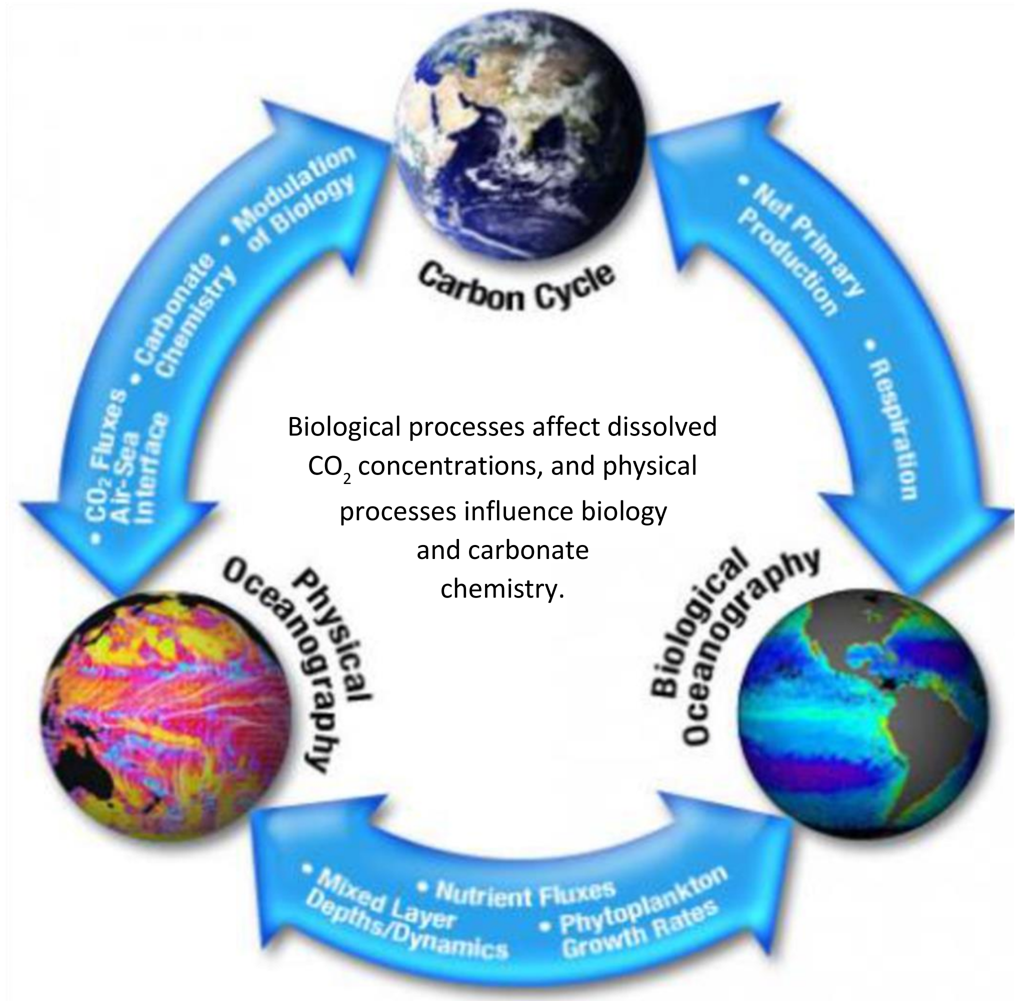


Figure 5. Earth's carbon cycle interacts with biological and physical ocean systems.
Source: NASA 2023 (Center text added.)

AI and ML could assist in scanning data sources and identifying patterns to explore the complex relationships among systems relevant to ocean CDR (Sonnewald 2021). The FECM CDR Program focuses its ocean-based CDR efforts on developing and improving models to better understand the challenges and feasibility of enhancing alkalinity. Due to the inherently interactive nature of natural ocean systems, the program will continue to exchange information on research progress and findings with other U.S. agencies and national and international research organizations engaged in related RDD&D. As the knowledge base grows, the CDR Program might, in the future, expand its ocean-based CDR focus to include seaweed cultivation and/or electrochemical processes.

Identify optimum materials to enhance alkalinity

Ocean alkalinity enhancement involves various methods to make seawater more alkaline so that it will absorb significantly more CO_2 than it does naturally. Enhanced alkalinity should also counteract ocean acidification (see inset on next page) and help protect marine ecosystems. A proposed mechanism is to spread large quantities of finely ground silicate or carbonate rock (from mine tailings or purpose-mined) on the surface of the ocean or along coasts to react with the CO_2 dissolved in seawater (NETL 2023). These reactions would produce carbonate and bicarbonate ions (dissolved inorganic carbon), which would eventually sink and become carbonate sediments on the ocean floor.

Recent lab experiments suggest this process may be more complex than anticipated and subject to local ocean chemistry. For example, after dissolving fine-grained sand (mostly olivine) in artificial seawater, researchers at the GEOMAR Helmholtz Centre for Ocean Research in Germany (see inset on next page) found that water alkalinity decreased over the following 134 days (Temple 2022). Other research efforts have noted variable results based on starting local pH levels, the minerals used, pattern or rate of application, specific locations, proximity to gyres, and time period—with more research needed on the ecological and biogeochemical impacts (Butenschön 2021, Bach 2019, Burt 2021). Additional concerns include the CO_2 emissions and potential local environmental, social, and sustainability impacts of the increased mining and other industrial and transportation activities to supply the needed minerals. AI might help researchers better understand the critical mechanisms and complex impacts of ocean alkalinization.

Resurrect/digitize data from legacy sources: Access to large volumes of accurate data can help build, validate, and continuously improve models that will inform efforts to increase ocean uptake and long-term storage of CO_2 while protecting marine ecosystems and biodiversity. The National Oceanic and Atmospheric Administration (NOAA) offers a range of carbon data for the ocean surface and near subsurface along with relevant publications and tools. Many research organizations currently pursuing experiments in enhanced ocean alkalinity recognize the value of data sharing to enable an adequate global response to climate change, and the experiments noted above appear to point to the need for more data on a wider range of variables within localized areas (e.g., chemical data on alkaline minerals, optimal powder size and mineral types under specific ocean conditions, and other relevant ocean data). To the extent that the needed data exists, AI can assist in digitizing it from legacy (nondigital) formats (e.g., optical character recognition, natural language processing, ML).

Quantify impacts based on the type of alkaline mineral: Research is needed to better understand how to select and prepare alkaline minerals to optimize their performance in capturing and storing CO_2 in the oceans. The amount and duration of CO_2 capture is sensitive to a wide range of factors (Middleburg 2020). With adequate data, AI/ML can rapidly examine massive data sets and potentially identify patterns to help researchers **predict and quantify the chemical variability of alkaline minerals** and potential impacts on the extent of carbon uptake and on marine life. Alkaline minerals can release byproducts (e.g., silica, magnesium, and trace metals),

Ocean Acidification

- Excess CO_2 in the atmosphere reacts with the surface water of oceans to form carbonic acid, which decreases ocean pH (i.e., makes seawater less basic) and lowers carbonate ion concentrations (NOAA 2023).
- Organisms like clams, oysters, corals, and some plankton use carbonate ions (aragonite) to build shells and skeletons. When the aragonite saturation state falls below 3, these organisms become stressed—and when it falls below 1, shells and other aragonite structures begin to dissolve. Ocean acidification may dramatically change ecosystem diversity (NOAA 2023).
- The largest decreases in aragonite saturation have occurred in tropical waters; however, decreases in cold areas may be of greater concern because colder waters typically have lower aragonite saturation levels to begin with (EPA 2023).
- Surface ocean waters can absorb CO_2 from the atmosphere in a few months, but it can take decades or centuries for changes in pH and mineral saturation to spread to deeper waters, where aragonite saturation levels are naturally lower. This suggests that the full effect of increased atmospheric CO_2 on ocean acidity may not be known for a long time (NOAA 2023).

Investigating Ocean Alkalinization in the Marine Environment

Scientists from seven nations led by GEOMAR Helmholtz Centre for Ocean Research Kiel are using *mesocosms, sealed structures that serve as oversized test tubes* (20 meters deep and two meters in diameter), to safely explore the influence of ocean alkalinization on marine communities. The experiment off the coast of Norway uses slaked lime (representing calcium-based minerals) and magnesium silicate (representing siliceous minerals) for the alkalinization because they dissolve easily and are free of the impurities often contained in minerals. The researchers hope to clarify how effectively this approach sequesters additional CO_2, which of the two substances produces better results, and how the change in chemistry affects marine life.

OceanNET, IAEA, Ocean Acidification International Coordination Centre, May 2022 (OA-ICC 2022) which can be good or bad for the phytoplankton and marine ecosystem. The aim is to better understand and eventually optimize the chemical makeup and particle size of crushed alkaline minerals to safely enhance carbon removal. Additional objectives are to control operating parameters to minimize costs and impacts while maximizing environmental, social, and economic benefits—though perceived impacts vary based on local factors, community priorities, and perspectives.

> "Carbon sequestered in organic forms like ocean sediments can be re-released by natural or human-made disturbances, while carbon stored geologically is chemically altered into solid minerals or stored so deeply in the earth that it would take thousands of years to naturally cycle back into the atmosphere."
>
> Danielle Riedl and Katie Lebling, WRI
> (Riedl and Lebling 2023)

Researchers might similarly use AI tools to **identify the critical linkages between alkaline minerals, ocean conditions, and CO_2 storage capacity and duration**. CO_2 capture rates and storage duration may vary with ocean conditions such as temperatures, the presence of biota/phytoplankton, currents, depth of the air-ocean boundary layer (mixing), and the current acidity or alkalinity. Researchers will also need to understand and **predict the subsequent impacts of changes in seawater pH** on ocean biochemical reactions, equilibrium conditions, and biological activity (locally and on a larger scale). More and better data from lab and field experiments and novel sensors will lead to a better understanding of sensitivities to alkalinity enhancement. Once alkalinity enhancement measures stop, for example, there is a risk of rebound to acidic conditions harmful to marine life (suggesting the need for careful long-term planning for the phase out of any large-scale alkalinization projects (Riedl and Lebling 2023).

Challenges for the development of AI tools to enable ocean alkalinity enhancement include the need for more up-to-date data on diverse factors affecting relevant ocean conditions, particularly in deep ocean regions. Another difficulty will be accurately measuring, monitoring, and crediting carbon removal in such an enormous and complex natural system as the open ocean.

> "Fortunately, ocean CDR research is at an early enough stage that the community can still gather evidence, utilize inclusive methodologies, understand different points of view, and explore alternatives. Solving the climate crisis is too important to double down on solutions that don't work the way we hope or that wreak havoc on the people and ecosystems we're trying to protect. Investing in a solid research agenda for this solution set is our best bet to get it right."
>
> Cooley and Laura 2022

Crosscutting Issues

Multiple CDR approaches must be deployed at scale in the near term to achieve net-zero emissions in the United States by 2050. Approaches to CDR that employ well-understood reactions under controlled conditions and/or end in secure geologic carbon storage present fewer uncertainties than those that seek to artificially scale up natural processes in complex open systems or store the carbon in ocean reservoirs, other bio-based forms, or value-added products (Riedl and Lebling 2023, NETL 2023). The urgency to deploy a wide range of large-scale CDR projects around the world underscores the importance of rapidly learning their efficiency, unintended impacts, and sustainability.

Conduct lifecycle analyses

Research is needed to explore, optimize, and verify the effectiveness and durability of various CDR approaches and their diverse impacts on ecosystems, economies, and communities across time scales. With adequate high-quality data, AI might assist researchers in predicting the longer-term and possibly unintended impacts of specific CDR methods or combinations of methods during and after implementation. At a minimum, researchers will need to predict how a CDR activity will impact natural systems, biodiversity, water consumption, land use, food security, and diverse ecosystems. These predictions may leverage new data provided by innovative sensor systems; ensemble, multi-dimensional, and variate modeling; and time series-based methods.

Identify robust GHG accounting methods: Robust life cycle GHG accounting is a crucial framework for determining the net CO_2 (or net CO_2 equivalent) removal of a CDR approach and its environmental implications across the life cycle phases. As codified in the ISO 14040/14044 standards, LCA can also help assess potential tradeoffs with other environmental impacts. To complement the ISO standards as applied to CDR (specifically DAC), FECM published *DAC LCA Best Practices* in 2022 (see inset). The publication highlights additional factors to consider when applying LCA or technoeconomic analysis (TEA) to technologies that are not yet commercially mature (Cooney 2022).

Life Cycle Assessment (LCA)

LCA is an analytical approach that can help inform decision making by accounting for the potential impacts of a technology from cradle to grave.

Key considerations for applying LCA to CDR:

- Clarity and consistency in functional units
- System boundary definition
- Negative emissions accounting
- Life cycle data consistency/representativeness
- Temporal dynamics for removal & emissions
- Early TRL scaling uncertainty.

Greg Cooney, FECM (Cooney 2022)

LCA can support all phases of the multi-step measuring, reporting, and verification (MRV) process. MRV goes beyond LCA and TEA to prove that a CDR activity has, in fact, removed a specified amount of GHG emissions (usually in tons of CO_2-e) over a specified period for a minimum duration so that actions can be converted into credits with monetary value. MRV entails careful tracking and measurement of the captured emissions according to the applicable standards—and subsequent reporting of the results, which are subject to third-party verification by an accredited entity. Once verified, emissions reductions are certified and can be sold for credit. These carbon credits are important to stimulate further investment and build a sustainable cycle of climate action.

The World Bank recognizes this pivotal role of MRV and plays a key role in setting the standards, certifying results, and fostering capacity development. To facilitate MRV in the future, the World Bank is promoting the development of digital MRV systems to expedite the process and cut the cost of creating carbon credits while increasing transparency and security (World Bank 2022). Other organizations are also actively developing methodologies (at various levels of detail) for measuring and reporting carbon removal through diverse pathways (see inset).

AI can assist LCA and MRV processes for tracking CDR impacts from cradle to grave. Potential applications include image-based ML for advanced quantification and detection (neural networks, etc.), ensemble ML modeling for multi-dimensional and scale predictions, and big data-based supervised ML from sensor and point source data.

Evolving MRV To Support Carbon Credits

Public and private entities are developing MRV tools, methodology, and infrastructure to enable the sale of carbon credits and accelerate CDR technology deployment. Examples include the following:

- In May 2023, FECM awarded $15 million to four selected projects led by National Laboratories to advance MRV practices and capabilities for CDR.
- CarbonDirect/Microsoft: Advisory services
- CarbonCure : Technologies for concrete industry
- ClimeWorks: Third-party-verified DAC CDR services
- Gold Standard: Project certification
- Puro.earth: Crediting platform
- Verra: Verified Carbon Standard (VCS) Program

Identify key variables and sensing technologies: Some CDR approaches have been tested only in the laboratory, limiting knowledge of interactions with open systems, dynamic real-world conditions, and potential feedback loops. Researchers will need to be inclusive and interdisciplinary in identifying variables that would indicate positive or negative impacts on carbon removal over time. In some cases, as in the deep ocean, CDR methods may require new types of sensors to determine the baseline of natural systems, measure the best indicators of the quantity and duration of CDR, and assess associated impacts on the process and environment.

A range of federal agencies, national laboratories, universities, international partnerships, private companies, and other entities are developing novel sensors and other tools to expand scientific data and understanding of natural and accelerated CDR processes and track the quantity and duration of carbon removal (see inset). Tracking the fate of captured CO_2 in the deep ocean—the only resource with the potential to rapidly take up and store carbon at the required scale—remains elusive, and novel sensors for this region may be costly, but better data is essential to establish the effectiveness of ocean-based CDR and the ground rules for its use (de Monocal 2023).

Novel Sensors for Ocean-Based CDR

ARPA-E: DOE's Advanced Research Projects Agency–Energy's new Sensing Exports of Anthropogenic Carbon Through Ocean Observation (SEA-CO2) program will provide:

- Sensor technologies that quantify and validate ocean carbon capture
- Ocean carbon transport and storage models that integrate and estimate the combined major carbon cycles likely to be impacted.

(DOE/ARPA-E 2023)

NIST: The National Institute of Standards and Technology is working on a global *ocean carbon reference material* distribution network and helping an international team to develop a *carbon system and metal speciation model for seawater.* (NIST 2022)

Woods Hole Oceanographic Institution: The organization is leading an initiative to build an Ocean Vital Signs Network—a hub to support a large network of autonomous vehicles with smart sensors to continuously monitor and communicate data on carbon cycling processes and ocean health (de Monocal 2023).

Private Companies:

- Running Tide has deployed open-ocean monitoring systems that collect geo-chemical and oceanographic data to track the impacts of ocean CDR interventions.

Predict lifecycle impacts: More and better sensors will produce more and better data to guide life cycle assessments of proposed CDR approaches—potentially improving predictions and speed of deployment. The FECM CDR Program uses LCA, life cycle cost analysis, and other methods to evaluate the environmental, economic, and social impacts of CDR technologies (Cooney 2022).

In some cases, the potentially adverse impacts of one CDR approach can be offset by combining it with another CDR or net-neutral project. For example, a DAC system might co-locate with a facility that recycles concrete into aggregate to mineralize the CO_2 and prevent its premature return to the atmosphere (Riedl and Lebling 2023). Seaweed farming could supply biomass for BECCS—where the anaerobic digestion releases methane, which would be used to produce energy, and the carbon would be captured during digestion and combustion for subsequent geologic storage (Gagern and Kapsenberg 2021). Similarly, ocean alkalinization activities might use mine waste to avoid ramping up new mining activities with all of the associated environmental impacts.

Combining activities will necessarily expand the LCA scope to include the diverse impacts of all activities and their potential interactions. In the case of substituting mine waste for purpose-mined rock, for example, some types of mine tailings can be used not just for mineralizing the carbon but also for neutralizing hazardous materials like asbestos or for reclaiming useful chemicals from mining wastes. On the negative side, rock dust may contain trace metals (e.g., nickel or chromium) that are toxic to ecosystems and people. In some cases, co-location can pit new jobs and economic opportunities against environmental impacts, which is another reason that local tribes and communities should be engaged early in the decision-making process.

AI can potentially support LCA by predicting chemical, biological, and geological system impacts and interactions over time (e.g., ensemble, multi-dimensional, and variate modeling of water consumption, land use, biodiversity, and ecosystems), but social and environmental impacts and benefits may not be easily known, distinguished, or understood, and may rely on a variety of factors and perspectives.

Identify optimal locations and CDR processes: Ample, detailed data and AI models of interactive natural and engineered CDR processes are likely to improve scientific understanding of the critical factors in selecting the site for a particular CDR activity or combined CDR activities. As suggested by the examples above, it will require a clear understanding of the tradeoffs associated with each approach, and each project must be assessed on its own merits, accounting for the impacts and local context in which it would be applied (Riedl and Lebling 2023).

Accelerating Progress Through Partnerships

AI is a data-driven technology, so reliable, high-quality data is essential. Based on the relatively early technology readiness level (TRL) of many CDR approaches, data on integrated processes is particularly scarce. A related data gap exists for technology performance under a range of environmental conditions. Better data resources should become available as models are developed and continuously refined and as technologies are demonstrated at pilot and commercial scales (learning by doing). As noted earlier, physics models, hybrid models, and transfer learning may provide alternative routes, as long as sufficient data is reserved for model validation. Until data needs are met, researchers will need to exercise caution in trying to extend a successful model to a similar yet distinct process. To assess applicability, the DOE research community might improve comparability across data sets by defining the specific data points or some common conditions under which data should be measured and collected. Collaborative partnerships across programs, agencies, corporations, governments, and non-profit organizations can expedite progress in obtaining the required data and help accelerate AI-driven solutions to the existential threat of climate change.

FECM coordinates its RDD&D with a range of partners in other FECM programs; DOE program offices; other federal agencies; national laboratories; state, tribal, and local governments; organizations in the public and private sectors; and other nations and global organizations. These partnerships are essential to fast-track critical RDD&D that will save lives and economies in America and around the globe in coming decades. While many partners are named in this document, hundreds more (too numerous to mention) deserve our thanks for their dedicated contributions and collaborative approach to protecting our shared planet.

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