Frontiers of CDR



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Rock Solid

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About Energy Futures Initiative

The Energy Futures Initiative advances technically-grounded solutions to climate change through evidence-based analysis, thought leadership, and coalition-building. Under the leadership of Ernest J. Moniz, the 13th U.S. Secretary of Energy, EFI conducts rigorous research to accelerate the transition to a low-carbon economy through innovation in technology, policy, and business models. EFI maintains editorial independence from its public and private sponsors.

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About this Series

In September 2019, EFI published Clearing the Air: A Federal RD&D Initiative and Management Plan for Carbon Dioxide Removal Technologies, a major report that outlined a 10-year, \$11-billion research, development, and demonstration (RD&D) program to bring more CDR approaches to deployment readiness. Several of these approaches, such as bioenergy with carbon capture and storage (BECCS) and direct air capture (DAC) are garnering increased funding support in Congress, but other pathways have received much less attention. Building on the work of the Clearing the Air report, EFI identified three CDR "frontiers" deserving of deeper evaluation: **(1) technologically enhanced terrestrial and biological CDR; (2) marine CDR; and (3) carbon mineralization.** The need for a broad portfolio of CDR options at Gt scale, compatible with the geography and geology of different regions of the U.S. and the world, underscores the need for increased investment in these relatively underexplored CDR "frontiers."

EFI organized six virtual workshops, involving over 100 scientific and technical experts, to address these pathways. The workshops identified the range of CDR approaches, their respective stages of development, and high-priority RD&D needs and opportunities ("big ideas").

This series of reports combines the findings of those workshops with analysis from EFI to provide policymakers with new insight into the potential benefits of these frontier CDR pathways and detail key priority research areas to promote their development. The report in this series are:

- → From the Ground Up: Cutting-Edge Approaches for Land-Based Carbon Dioxide Removal
- → Uncharted Waters: Expanding the Options for Carbon Dioxide Removal in Coastal and Ocean Environments
- → Rock Solid: Enhancing Mineralization for Large-Scale Carbon Management

Series Sponsors

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The content of this report is not attributable to any of the workshop participants, and the view expressed here are EFI's and do not reflect the views of the participants or their employers.

Table of Contents

Key Findings and Recommendations for Policymakers	06
The Need for Carbon Mineralization The Role of Carbon Mineralization in the Global Carbon Cycle Opportunity for Technologically Enhanced Carbon Mineralization EFI Mineralization CDR Workshops	08 08 08 10
RD&D Priorities for Specific Mineralization Pathways Ex Situ (Surface) Mineralization In Situ (Subsurface) Mineralization	12 12 20
Synergies and Co-benefits of Carbon Mineralization	27
Cross-cutting Carbon Mineralization RD&D Challenges	29
Cross-cutting Fundamental Research Opportunities and Pilot-scale RD&D Regional Level Evaluation Techno-economic and Lifecycle Assessments Developing Monitoring, Reporting, and Verification Standards Creating an Enabling Policy Environment for Large-Scale Deployment Implementation: Funding, Organization, and Management Regional Collaboration Hubs Incorporating Mineralization Into Existing RD&D Programs International RD&D Collaboration	
Appendix A: Clearing the Air Funding Levels for Mineralization RD&D	38
Appendix B: Examples of Federally Funded Mineralization RD&D	40
Abbreviations	41
References	42
Figure References	44

Key Findings and Recommendations for Policymakers

Key Findings

- → Carbon mineralization provides a pathway to near permanent isolation of carbon dioxide (CO_2) from the environment. Mineralization is a naturally occurring process that reacts atmospheric CO_2 with certain types of rocks to form relatively inert carbonate minerals. The reaction can take place either at the surface of the Earth (*ex situ* mineralization) or through the capture of CO_2 and injection into underground rock formations (*in situ* mineralization).
- → Technological enhancements can expand and accelerate natural carbon mineralization, making it feasible to achieve gigaton (Gt) scale CO₂ removal (CDR). Natural rock weathering currently removes about 1 Gt of CO₂ per year globally, a significant level of offset to pre-industrial CO₂ emissions but well short of offsetting current anthropogenic emissions. Technologically enhanced ex situ and in situ mineralization options could increase the rate of natural mineralization by a factor of five to ten.
- → Carbon mineralization has several co-benefits that enhance its attractiveness. These benefits include the addition of carbon-absorbing minerals as an agricultural soil amendment, potential beneficial use of certain mining and industrial process wastes as carbon-absorbing material, and synergies between in situ carbon mineralization with point-source carbon capture and direct air capture CDR pathways.

Recommendations

- → Increased federal investment in carbon mineralization research development and demonstration (RD&D) should include a portfolio of carbon mineralization methods that encompass both ex situ and in situ pathways. Ex situ mineralization involves the application of finely ground, reactive minerals in soil, rivers, and oceans, or within industrial landscapes such as mines, to capture CO₂ directly from the atmosphere. In situ mineralization involves the injection of captured CO₂ into reactive underground mineral deposits and requires a concentrated source of CO₂. Each has relative strengths, and there are shared RD&D objectives between them. A carbon mineralization RD&D portfolio should address the following four major pathways:
 - Surface (i.e., ex situ) carbonation of mineral wastes from mining and materials processing
 - Enhanced rock weathering and carbonation in soils on agricultural fields, forests, riverbanks, and coastal areas
 - Surface capture of CO₂ via calcium and magnesium oxide carbonation and subsequent looping or recycling of capture materials
 - Subsurface (i.e., in situ) injection into mineral formations (basalt and ultramalfic rocks) of CO₂-bearing water or CO₂ captured via various means (e.g., post combustion carbon capture or DAC)

Each of the pathways requires further RD&D to determine technical and economic feasibility, but if successful, each has the scaling potential to achieve Gt-scale CDR within a cost range of less than \$100 per ton of CO_2 . The September 2019 EFI report *Clearing the Air* recommended a focused 10-year investment of \$1.4 billion in carbon mineralization RD&D. The Report also recommended a \$2 billion CDR demonstration project fund that could support large scale carbon mineralization projects selected on a competitive basis.

- → Determining technical and economic feasibility of carbon mineralization RD&D for potential deployment at gigaton scale requires scale up to larger field-scale pilot projects. Due to funding and other constraints, R&D on carbon mineralization has been largely conducted at relatively small (i.e., 10-m²) scale, with a few exceptions. Experiments at larger scale—along with better geologic surveys of potential mineralization sites and inventories of potential feedstock materials—are crucial to answer questions of Gt-scale application, such as the rate of CO₂-mineral reactions, ultimate conversion efficiency, and stability of carbonate formation.
- → Location-specific climate, geological and land use considerations requires a regional approach to carbon mineralization RD&D. The effectiveness of carbon mineralization is sensitive to site-specific variations in climate, geology, and agricultural activity. Realistic assessment of carbon mineralization must take these site-specific considerations into account. Regional carbon mineralization RD&D collaboration hubs, modeled after the Department of Energy Regional Carbon Sequestration Partnerships (RCSP) and the Carbon Storage Assurance Facility Enterprise (CarbonSAFE) programs, would provide an effective programmatic structure for advancing carbon mineralization methods and practices. Differences in mineralization suitability on a global level will require international collaboration in planning and implementing RD&D projects.
- → Fundamental research supporting carbon mineralization, including further validation of cobenefits, should be incorporated into existing federal research and development programs. These could include the Department of Energy (DOE) Fossil Energy R&D and Advanced Manufacturing programs; the Department of Agriculture (USDA) Agricultural Research Service (ARS) and other programs; and the Department of Interior Geologic Survey (USGS) and Office of Surface Mining Reclamation and Enforcement (OSMRE). Carbon mineralization also should be included as a key component of a revitalized DOE Subsurface Science, Technology and Engineering Research and Development (SubTER) crosscut.
- → Deployment of carbon mineralization at gigaton scale also will require development of new methodologies for techno-economic analysis (TEA), lifecycle analysis (LCA) and monitoring, reporting, and verification (MRV) standards. Current methods and practices for geologic sequestration of CO₂ in saline aquifers do not adequately account for some of the unique technical aspects of in situ carbon mineralization. There also will need to be public education to address perception concerns regarding land and water use needed for mineralization, as well as the potential for expanding domestic mining activity for mineralization materials.
- → Large-scale deployment of carbon mineralization also will require parallel policy analysis and development. The application of environmental regulatory requirements under the Clean Air Act, the Clean Water Act, and the Resource Recovery and Conservation Act will need to be clarified. Modifications to financial incentive polices such as the Section 45Q tax credit and state-level incentives also will need to be addressed.

Harnessing Mineralization for Large-Scale Carbon Management

The Need for Carbon Mineralization

The Role of Mineralization in the Global Carbon Cycle

 CO_2 mineralization is the transformation of atmospheric CO_2 into carbonate minerals by a

multi-step process that starts with rocks and minerals at the Earth's surface slowly dissolving into weakly acidic rainwater and groundwater. This dissolution process is also referred to as "rock weathering." Dissolved rock material is transported to the oceans by rivers, adding calcium, magnesium, and other minerals to ocean water, and eventually

FIGURE 1

Enhancements to CDR Can Significantly Leverage the Global Carbon Cycle



The global carbon cycle involves the exchange of CO_2 among the atmosphere, land, water, and subsurface. Green arrows denote estimated natural fluxes prior to the Industrial Era (circa 1750). Orange arrows denote anthropogenic fluxes averaged over the time period 2000-2009. Frontier CDR options can increase the existing negative fluxes—including terrestrial photosynthesis, rock weathering, and ocean fluxes—to combat climate change Source: EFI, 2020. Compiled using data from Intergovernmental Panel on Climate Change, 2013.

BOX 1 -

About Carbon Dioxide Removal

Carbon dioxide removal (CDR) refers to methods to remove carbon dioxide (CO_2) from the atmosphere and upper levels of the oceans and sequester or convert the CO_2 into an inert form. CDR is an essential complement to CO_2 emissions reductions to achieve net-zero emissions goals and subsequently net-negative emissions, thereby providing the opportunity to reverse some of the effects of historical greenhouse gas (GHG) emissions and "restore" the climate.

The 2018 Intergovernmental Panel on Climate Change (IPCC) *Special Report on Global Warming of 1.5°C (SR1.5)* outlined the importance of reaching net-zero emissions by 2050 in order to limit warming to 1.5 degrees.² SR1.5 estimated that 3 to 7 billion metric tons (gigatons, or Gt) of CDR per year would be required globally by 2050 and up to 15 Gt per year by the end of the century.³

There are a variety of well-established **natural CDR pathways** to increase the size of natural carbon sinks, such as planting more trees; adopting sustainable agricultural soil management; expanding coastal ecosystems; and increasing natural geochemical CO₂ removal. Expanding natural CDR pathways, while necessary, will not be sufficient to meet the SR1.5 goals, and certainly not to move towards climate restoration. The carbon removal capacity of natural systems can be **technologically enhanced**through the application of modern technology—including use of biotechnology to enhance CDR in soils, plants and trees; enhancing the reactivity of CO₂-absorbing rocks; increasing ocean biomass through cultivation or artificial fertilization; and reversing the trend toward increased acidity in the oceans. **Direct technological capture** pathways involve engineering extraction such as direct air capture (i.e., atmospheric scrubbing) and direct ocean capture through electrochemical conversion, both of which produce a concentrated stream of gaseous CO₂. The captured CO₂ can then be injected into subsurface saline aquifers or mineralizing rock formations. Alternatively, it can be converted into long-lived carbon-based materials.

causing carbonate minerals to form and accumulate on the ocean floor as limestone.

Carbon mineralization is a continually occurring foundational process in the global carbon cycle that has contributed to the historical stability of atmospheric CO_2 , climate and the biosphere. Geologic evidence indicates that the Earth has maintained a livable surface temperature for hundreds of millions of years—prior to the advent of fossil fuel use and other anthropogenic sources of GHGs—because there are natural pathways that remove CO_2 from the atmosphere at about the same rate that it is added slowly by volcanoes.^a

Carbon mineralization was an essential component of the carbon cycle in the preindustrial era. The rate of addition of

a. Other natural emissions from the terrestrial and ocean biospheres were similarly offset by carbon-removing processes in those systems. See the other reports in the *Frontiers of CDR* series.

anthropogenic CO₂ emissions to the atmosphere now well outstrips the rate of uptake by natural rock weathering (Figure 1). Because the rate of rock weathering is relatively slow, the excess anthropogenic CO₂ instead accumulates in the atmosphere, the oceans, and in plants and soils.

Opportunity for Technologically Enhanced Carbon Mineralization

The limitation of the natural carbon mineralization process is that it removes CO_2 from the atmosphere at a rate of just over 1 Gt per year, which is about the same rate that natural processes such as volcanism add CO₂ to the atmosphere. A wide variety of methods have been proposed for technologically enhancing the rate and scale of carbon mineralization as a means to complement efforts to mitigate anthropogenic CO₂ and help stabilize and ultimately reverse adverse climate change. To do so, new approaches to technologically enhancing carbon mineralization on a gigaton scale, multiple times the natural rate, will be needed in order to have a material impact in combating climate change.

Technologically enhanced carbon mineralization methods include both surface and subsurface processes (Figure 2). Surface, or ex situ mineralization, involves the application of finely ground, guickly reacting minerals that can result in direct formation of carbonate minerals in the soil, rivers, and oceans. Subsurface, or in situ mineralization, involves the injection of captured CO₂ into subsurface reactive mineral deposits that can result in conversion to a solid phase material. In situ mineralization is gualitatively different from ex situ mineralization because in most cases it requires a separate CO₂ capture process-either another CDR method or pointsource carbon capture.

A key attribute of carbon mineralization is its

ability to convert atmospheric CO₂ to a solid form where it can be retained indefinitely. Mineralization is attractive because it effectively reverses the key characteristic of fossil fuel and industrial emissions, which is that they represent the release, by combustion and calcining, of carbon that would otherwise remain permanently stored in the Earth (as coal, oil, gas, and limestone). Mineralization CDR returns carbon permanently to the Earth.

Technologically enhancing the effectiveness of carbon mineralization, in addition to helping to mitigate climate change by removing CO₂ from the atmosphere, can provide co-benefits and also help avoid some of the challenges facing other CDR methods. For example, if mineralization can reduce the amount of CO₂ currently being absorbed by the oceans, it can avoid some ocean acidification, and in some cases even contribute to reversing acidification by adding alkalinity. Mineralization also avoids adverse impacts on ecosystems, which is a concern with some land- and ocean-based CDR pathways. Some mineralization pathways can be co-located with existing agriculture, mining, etc., avoiding some concerns about land use change. Carbon mineralization thus can assist in environmental remediation, enhance agricultural productivity and achieve synergies with other greenhouse gas mitigation efforts.

EFI Mineralization CDR Workshops

Following the publication of the September 2019 report *Clearing the Air*, EFI initiated a follow-on dialogue with leading scientific experts to explore in greater detail the opportunities for technologically enhanced carbon mineralization. The expert panel convened for this report identified key areas for action that are needed to expand carbon mineralization on a Gt scale. They advised on both the principal RD&D needs and opportunities, as well as the implementation strategies and policy framework, needed to

FIGURE 2

Overview of CDR and Non-CDR Pathways for Mineralization



This figure shows pathways for ex situ and in situ mineralization, including those that do and do not contribute to CDR. Purple arrows show movement of carbon; white arrows show where transportation of mineralization feedstocks is necessary. This figure does not include in situ CDR approaches that remove carbon without the need for DAC or another source of CO_2 . Source: EFI, 2020.

facilitate deployment. RD&D and policy priorities include:

- 1. RD&D on specific in situ and ex situ mineralization pathways
- 2. Solving cross-cutting basic research questions via pilot-scale projects
- 3. Conducting evaluations and RD&D at

the regional level to account for heterogeneity within the U.S.

- 4. Techno-economic and lifecycle analysis
- 5. Creating monitoring, reporting, and verification (MRV) standards
- 6. Creating an enabling policy

FIGURE 3

RD&D, Policy, and Implementation Opportunities for Carbon Mineralization



This figure shows the major priorities identified in this report for pathway-specific RD&D, cross-cutting RD&D, large-scale deployment, and implementation. Source: EFI, 2020.

environment for large-scale deployment, including regulatory change and financial incentives

Implementation priorities include:

- 1. Regional collaboration hubs
- 2. Incorporating mineralization into existing federal programs
- 3. International collaboration

RD&D Priorities for Specific Mineralization Pathways

Ex Situ (Surface) Mineralization

The application of carbon mineralization for

CO₂ removal requires finding ways of improving the conversion effectiveness and the rate of the natural rock weathering process.

Conceptually technologically enhanced ex situ carbon mineralization involves the following steps: quarrying certain types of rocks that can dissolve relatively quickly when exposed to atmospheric CO₂, grinding the rock to fine sand to increase the surface area per unit mass, and spreading it out in agricultural and other areas where it will be naturally exposed to air, rainwater, and groundwater. This application of finely crushed rock could result in direct formation of carbonate minerals or enhancement of the alkalinity of rivers, ultimately resulting in an increase of ocean pH and enhanced carbonate mineral formation in the oceans. Adding alkalinity to the oceans would act to partially counteract acidification

TABLE 1 Summary of Characteristics of Selected Mineralization CDR Methods

CDR Method	Possible CDR Capacity (GtCO ₂ /yr.) and Land Use (km²/Gt/yr.)	Estimated Cost (per tCO ₂)	Possible Co-Benefits	Issues, Risks, Limitations, Uncertainties	Technology Readiness
Carbonation of Mineral Wastes	2-9 Gt/yr. >2,000 km²/Gt/yr. using existing mines	Tailings management practices: \$10s CO ₂ injection: <\$50 Accelerated leaching: >\$50	Mitigating heavy metal/dust mobility; slope stabilization via cementation; potential integration with point-source capture	Reactivity of mineral wastes; carbon accounting frameworks	Medium
Enhanced Rock weathering and Carbonation in Soils	<1-2 Gt/yr. (cropland only) >10,000 km²/Gt/yr.	\$8-\$100, depending on feedstock	Enhancing carbonate alkalinity in the oceans; delivery of essential trace nutrients to plants and soil microbes	Soil contamination; efficiency/rate of mineralization in soil environment; opening new mines to quarry fresh rock	Medium
Calcium and/or Magnesium Oxide Looping	~4 Gt/yr. (global magnesite reserves) >400 Gt/yr. (including limestone) >2,000 km²/Gt/yr.	\$50-\$150		Efficiency and timeframe; minimizing carbon from heating; identifying practical feedstock	Low to Medium
Subsurface Mineralization In Basalt	Dependent on capture technology ≥6,000 km²/Gt/yr.	~\$20-50 for storage, plus costs of capture		Uncertainty on rates of CO ₂ conversion to minerals; some possibility of biomass C uptake; use of seawater instead of fresh water	Medium
Subsurface Mineralization in Ultramafic (UM) Rocks	(based on Carbfix experience, with open space between wells) Dependent on capture technology	~\$20-50, plus costs of capture if UM rocks used only for storage	Potential integration with point-source carbon capture, DAC and BECCS, renewable energy	Similar to basalt, but faster, lower permeability; feedbacks: "clogging vs cracking; risk of induced seismicity	Low
Sub-Seafloor Mineralization		Substantially greater than on land		Cost of working in deep water; technology has not been tested	Low
In situ mineralization for CDR and DAC hybrids	Dependent on capture technology; up to 10 Gt/yr.	~\$20-50 for storage, plus costs of CDR		Similar to basalt	Low

Ex situ pathways are in white; in situ in purple. Note: These designations represent best estimates as of 2020 based on expert discussions. It is important to remember that most of these ranges are preliminary and tentative because most of these CDR pathways are still in early stages of development or demonstration. More RD&D is needed to further test and refine these approaches which in turn will provide more precise capacity and cost estimates. These can then better inform ocean CDR policy and RD&D decisions. Source: EFI CDR Workshops, 2020. of the oceans due to direct dissolution of atmospheric CO_2 into the oceans.

It is also possible to use industrial solid wastes such as slag from steel manufacturing or tailings from mining operations that are already exposed to air and rainwater. Such wastes are commonly contained in large (multiple km²) storage facilities where waste management processes might be tailored to enhance their carbonation in a controlled, industrial setting.

The challenge to achieving carbon mineralization at Gt scale requires that this process be accelerated to several times the normal global rate. The "normal" rate represents weathering of about 80% of the rocks and soils exposed on the surface of the continents, about 120 million km.^{2,4}

The basic technical questions affecting the rate of ex situ mineralization are:

- → Will the pulverized rock/minerals dissolve as fast as predicted? Are there methods to accurately predict dissolution rates under applicable conditions?
- → What fraction of the weathering of the pulverized rock will result in (a) formation of carbonate minerals composed of carbon from the atmosphere, (b) increased production of soil carbon and biomass, or (c) the predicted increase in global riverine alkalinity?
- → What are the best ways to apply pulverized rock to enhance CDR?
- → How much land area needs to be involved per ton of CO₂ removed?
- → What are the best ways to monitor the process and measure the amount of CO₂ removed?

These technical questions are just the first step in assessing feasibility, because the effort needs to be international, verifiable, and environmentally benign.

("Ex Situ" Carbonation of Mineral Wastes)

By one estimate, as much as 7 Gt per year of alkaline waste materials are generated annually, and with increasing demand for resources they may have the potential to remove 2.9 to 8.5 GtCO₂ per year by 2100.⁵ However, these estimates should be considered an upper limit, as they do not incorporate real-world reaction rates and efficiencies, which vary with mineralogical composition. Some calcium- and magnesiumbased components of waste materials undergo rapid CO₂ uptake in the weathering environment, others (e.g., calcium-aluminum silicates in steel slag) react more slowly. The main sources explored have been ultramafic (UM) and mafic mine tailings (see Box 2) and slag from iron- and steelmaking; other proposed sources include red mud from bauxite mining and aluminum production, cement kiln waste, coal fly ash, municipal solid waste incinerator ash, and saline brines produced during hydraulic fracturing for shale gas (Figure 4).

Pulverization of rocks and granularization of industrial wastes increases their surface area and thus their ability to react with atmospheric CO₂. Carbonation of mine tailings from UM-hosted ore deposits provides a parallel to the concept of in situ carbonation of UM rock. Much of the fast reactivity of UM mine tailings for CDR comes from carbonation of highly reactive materials such as brucite, which comprises 0 to 10 percent of serpentinite tailings.⁶ Currently produced UM tailings (about 400 Mt per year) could potentially mineralize approximately 20 MtCO₂ per year if relying solely upon passive reaction of tailings with atmospheric CO₂.⁷ Similar considerations apply to industrial sources of

BOX 2

Mafic and Ultramafic Rocks (Adapted from Clearing the Air⁸)

The Earth consists of three major types of rocks, classified according to their chemical and mineral composition and the conditions under which they form. Igneous rocks (formed when hot molten rock solidifies)⁹ and metamorphic rocks (formed when pre-existing rocks react and recrystallize at high temperatures and pressures) are especially suitable candidates for the purposes of carbon mineralization due in part to their relative abundance of divalent metal cations.^{10,11} Sedimentary rocks also have some capacity for carbon mineralization; carbon sequestration via injection in saline formations or oil wells is generally in sedimentary rock.

Igneous and metamorphic rocks include mafic (e.g., basalt) and ultramafic (e.g., peridotite, serpentinite) rock that have strong potential as a source material for mineralization given their high level of availability and relatively fast carbonation kinetics.¹² "Mafic" describes igneous rocks with high concentrations of magnesium and iron; "ultramafic" refers to rocks with very low silica content that are composed of a high percentage of mafic minerals. Rocks are aggregates of one or more minerals, which are elements or compounds with consistent chemical compositions and properties. Minerals found in ultramafic rocks include olivine, serpentinite, and brucite. Mineralization pathways may also harness other naturally occurring minerals, such as calcium-based wollastonite, which occurs in some metamorphic rocks. They may also use calcite (calcium carbonate) or magnesite (magnesium carbonate) from sedimentary rocks for Ca and Mg looping.

Basalt (especially basaltic glass) is reactive due in part to the large composition of calcium, magnesium, and iron that can constitute up to one-fourth of its weight, but reaction times are slow. Basalt rocks are commonly found in nature (within Earth's crust), covering most of the ocean floor and 10 percent of the continental surface.¹³ Peridotite and serpentinite, ultramafic rocks that are particularly rich in magnesium, are also highly reactive but are less common compared to basalt.^{14,15}

alkalinity. Further acid/base treatments, injection of high purity CO₂ gases, and the use of biological amendments have been shown to lead to mineralization of other portions of UM rocks and tailings, albeit at increased cost to the mine operator.^{16,17,18} As such, demonstration of acceleration strategies that access the reactivity of silicate minerals, which make up the bulk of UM rocks, is the ongoing focus of RD&D in this field.

Research protocols exist to measure the rate of CDR in waste storage facilities, and several studies have documented current rates and found easy ways to accelerate them (Figure 5). For instance, the Mount Keith Nickel Mine in Western Australia has the potential to increase its rate of CDR (currently estimated at about 40 kt of CO_2 mineralization per year) six-fold simply by changing tailings management practices to increase exposure to atmospheric CO_2 . Small-scale experiments have been done to monitor passive CDR in mine tailings and to demonstrate components of this pathway for accelerated CDR.¹⁹ Increasing the capacity of this technology is the main focus of ongoing field experiments (e.g., De Beers Project CarbonVault).

CDR mineralization in industrial wastes, such

FIGURE 4

Theoretical Contributions of Mineralization Sources to 1 Gigaton of Mineralization CDR



This figure shows one conception of how different mineralization sources could contribute to one gigaton of removal. Industrial wastes that are already extracted and abundant can provide a significant fraction, but use of natural sources will likely be required to reach gigaton scale. Source: EFI, 2020. Adapted from Power et al., 2013.

FIGURE 5

Technology Ladder for Mineralization at Mine Sites



Increasing cost

This figure shows how different options for mineralization of mine tailings could contribute different amounts to CDR, based on data from the Mount Keith nickel mine. Enhanced passive carbonation through tailings management and injection of CO₂ could carbonate more than 10 percent of tailings and offset a mine's entire emissions, at a price point under \$50 per ton. This provides a major incentive for mining companies to invest in mineralization RD&D. Source: EFI, 2020. Adapted from Power et al., 2014

as mine tailings, benefits from implementation at industrial sites that operate under existing environmental regulations and that have a skilled workforce. It also provides environmental and operational co-benefits, discussed further on Page 28. There also has been some discussion of the concept of dedicated mining solely for the purpose of CDR, though that also could raise questions of public acceptance and environmental impact.

Key RD&D needs and questions:

- To what extent can the reactivity of alkaline industrial wastes be enhanced within industrial storage compounds (via heating, increased CO₂ pressure, acid or base dissolution, biologically enhanced dissolution, and other treatments) at a reasonable cost?
- 2. How can CDR mineralization using industrial wastes be measured within existing carbon accounting frameworks so there is incentive to adopt this technology?
- 3. How can CDR be embedded in mining methods and heavy industry to optimize co-benefits?
- 4. How will public perception and acceptance of mining affect implementation of this technology? Could implementation improve public perceptions of mining?

Enhanced Rock Weathering and Carbonation in Soils

Enhanced rock weathering and carbonation (ERWC) involves the application of quarried

and finely pulverized rock to agricultural fields, forest soils, rivers and riverbanks, and coastal environments.^b The original conception of ERWC was to quarry the UM rock called dunite, which contains the minerals olivine, serpentine, and sometimes brucite. More recent studies typically use more common materials, such as mafic basalt, or locally abundant mineral resources, such as wollastonite.²⁰ Given the ready availability of mineral wastes (see above), there may be potential to use some of these for ERWC,^{21,22,23} following successful trials and pending approval for use in agriculture. This approach to using mineral wastes may yield a faster carbonation rate than mineralization in waste storage facilities. Figure 6 shows the availability of both natural and industrial sources in the United States.

A recent estimate suggests that 0.5 to 2.0 Gt CO_2 per year could be removed from the atmosphere if ERWC were deployed in 10 to 50 percent of cropland globally.²⁴ It is important to note that the same uncertainties about mineralogical composition, reactivity and carbonation efficiency of rocks and mineral wastes raised previously applies to ERWC and indeed most mineralization CDR technologies. Many current estimates of potential reflect upper estimates. Nations with relatively warm climates and productive agriculture industries, such as the USA, Brazil, China and India, have the greatest potential to capitalize on ERWC in agricultural soils.²⁵ This pathway does not just store carbon as carbonate minerals: some is taken up by plants (a much shorter-term carbon storage mechanism); some is dissolved in soil porewater, groundwater, rivers, and oceans; and some could eventually be converted to biogenic carbonate in the oceans. As such, robust approaches to quantifying the scale

b. A similar approach, ocean alkalinity modification, involves applying rock or alkaline wastes directly to the ocean. It is discussed in depth in another report in this series, *Uncharted Waters: Expanding the Options for Carbon Dioxide Removal in the Oceans.*

FIGURE 6

Natural and Industrial Sources of Alkalinity in the Contiguous United States



This map shows both natural and industrial sites that may be conducive to mineralization, as well as sedimentary geologic sequestration. The variety of both geologies and industrial clusters in different regions of the country underscores the need for regionally tailored efforts and collaborations. This map does not show Alaska, which has locations with surface mafic and ultramafic rocks as well as sedimentary formations conducive to sequestration, or Hawaii, which is replete with surface basalts due to its volcanic origin. Source: Kolosz and Pilorgé, 2020 (in forthcoming CDR Primer)

and longevity of CDR using ERWC are needed.

There are important regional considerations that must be accounted for with ERWC. Freshly mined rock or waste rock needs to be sourced locally for CDR via ERWC to be most effective from a cost and a GHG perspective.^{26,27} The co-location of agriculture, forestry, mining and heavy industries that produce alkaline wastes is the ideal condition for EWRC implementation. There are outstanding questions regarding whether waste materials can be safely utilized for EWRC, the efficiency and kinetics of carbonation in the soil environment, and whether to open new mines to quarry for EWRC. Key RD&D needs and questions:

- 1. Can alkaline waste materials be used as soil amendments for ERWC or must new mines be opened to quarry fresh rock?
- 2. What are the limits placed by mineral dissolution kinetics, mineral surface passivation, and CO₂ availability in soils on the potential of ERWC?
- 3. How would ERWC impact the health of plants and soil microbes, and how might that limit or promote ERWC deployment?
- 4. How can ERWC be monitored and verified within the carbon cycle of a

farm, a watershed, and globally?

- 5. How does ERWC impact harmful metal accumulation in soils and plants?
- 6. How does the efficiency of carbonation in soils vary with rock type, mineralogy, soil type, crop type, and climate?

Calcium and Magnesium Oxide Looping

Oxide looping is a CDR method that leverages the high reactivity of calcium (Ca) or magnesium (Mg) oxides and hydroxides to remove CO₂ from air (Figure 7).^{28,29,30} The starting materials are pure calcium or magnesium carbonate minerals. Heating them to temperatures of approximately 900°C and 600°C, respectively, produces solid calcium oxide or magnesium oxide and CO_2 . The CO₂ released during heating would then be captured and sequestered or used. The other byproducts, calcium or magnesium oxide, can be converted to calcium hydroxide (portlandite) or magnesium hydroxide (brucite), which react rapidly with atmospheric CO₂ to produce various solid carbonate minerals. The produced oxide/hydroxide sediment could be distributed in fields, tilled periodically to expose unreacted sediment. and recovered after a period of months to years to begin the process again.

If the total known global reserve of magnesite $(MgCO_3)$ were to be mined and employed in this process, and if it were 100 percent efficient, it could remove approximately 4 Gt CO_2 per year from the atmosphere. Conversely, Ca looping, which is already used as a carbon capture technology for power generation, starts with pure limestone, a regionally widespread commodity of vast abundance. Limestone is quarried in vast quantities for cement and concrete production, used as a soil amendment in agriculture, and as a building stone. Thus, CaO might be preferable to MgO in many regions, despite the higher calcining temperature.

Calcium and magnesium oxide looping has not yet been demonstrated beyond laboratory and limited-scale outdoor experiments. Models suggest that 2,000 to 7,000 km² of land would be required per Gt of CDR per year, covered with oxide or hydroxide sediment about 5 cm deep. This amount of land is on the scale of the 100 to 200 largest mines in the world, but this technology has the potential to be a more efficient and long-lived CDR pathway than mineralization at industrial sites if the required land use can be justified.

Key RD&D needs and questions:

- What is the rate of carbonation for calcium and magnesium oxide/ hydroxide sediments in ambient weathering conditions?
- 2. What are the benefits and costs of amendments that speed carbonation at ambient weathering conditions, such as stirring, misting, and use of passive contactors?
- 3. How can the GHG intensity of heating the resulting calcium and magnesium carbonate sediment be decarbonized?
- 4. What is the most practical feedstock mineral/material for this process?
- 5. What will be the public perception of mining and land use for CDR?

As with other mineralization pathways, this technology requires larger-scale demonstration; more questions will likely arise as it moves up the technology readiness ladder.

FIGURE 7 Process Design for Magnesium (or Calcium) Oxide Looping



This figure shows one possible process design for looping starting with magnesite. This process design would also work with calcium-based minerals, such as calcite, which are more abundant. Recent research has indicated that most of the oxide material could be carbonated in two months or less then calcined again Source: EFI, 2020. Adapted from McQueen et al., 2020

In Situ (Subsurface) Mineralization

An attractive aspect of ex situ mineralization is that it is a CO_2 capture and storage mechanism in one. In situ mineralization, by contrast, is a form of subsurface carbon sequestration that requires a separate process to first capture the CO_2 and then use mineralization as storage, by injecting CO_2 underground into rocks that will react quickly and potentially mineralize it before it can return to the surface. In situ mineralization requires a concentrated stream of CO_2 , which could come from another CDR method—such as DAC, BECCS, Mg-oxide looping—or from carbon capture on point sources—such as power plants and industrial facilities. In situ mineralization thus is an alternative to geologic sequestration of CO_2 in saline aquifers that is location specific depending upon the nature of the subsurface geology.

In situ mineralization, however, is similar to ex situ mineralization in that the final form of storage is a solid rock material. The subsurface process that accomplishes this conversion is exactly analogous to natural rock weathering, with the difference being that the water involved is in the pore space of the subsurface rocks, rather than in soils, rivers and the ocean. The EFI workshop participants considered in situ mineralization as important to any discussion of CDR because, as with ex situ mineralization, the CO_2 can be considered to be permanently removed from the atmosphere-ocean system.

In situ mineralization requires the CO_2 to be in a fluid, which can be done in one of two ways. The traditional route is to compress it into supercritical (liquid-like) CO_2 (s CO_2) for injection deep underground (as in geologic sequestration without mineralization), where it can dissolve into pore space water. An alternative approach is to dissolve CO_2 into water at a small concentration (typically less than 1 percent) and inject it into the subsurface. This is known as CO_2 -saturated water (CW).

A key attraction of subsurface mineralization is the potential for relatively fast conversion of CO_2 to minerals. This results in permanent storage of the CO_2 . The precise rate of the mineralization process and its relationship to the rate of injection represents a key area for further research.

Subsurface Mineralization in Basalt

Subsurface mineralization in basalt, a form of volcanic rock, is one of the most mature mineralization pathways, with several field-scale experiments to date:

→ Carbfix in Iceland reported that in their first phase in 2012, 280 tons of CW were injected into a basalt formation at 30°C and completely mineralized within two years. In a later phase of the project starting in 2014, the injection rate has been increased to 10 to 15 kilotons per year, with injection into rocks at greater depth and higher temperature. Some of the CO₂ in the second phase was captured from a co-located DAC plant. The high temperature of the basalt produces a faster reaction, and studies to date indicate that a large fraction of the CO₂ injected is being converted to minerals on a timescale of months. In 2021, Carbfix will start two additional injection projects; A pilot injection of about 1 kt per year from a second geothermal plant owned and operated by Reykjavik Energy, and a scale-up of the DAC operations, injecting up to 4 kt per year into a separate, shallower reservoir. (Figure 8)

Carbfix began as a collaboration between the publicly owned utility Reykjavik Energy and several universities and has been funded by several grants from the European Union, Columbia University's Earth Institute, and the government of Iceland. It enjoys several built-in advantages, including favorable geology, abundant fresh water, and existing infrastructure at the site of a geothermal power plant.

- → An experiment at Nagaoka, Japan, injected about 10 kt of sCO₂ into a volcanic sedimentary formation. Postinjection fluid sampling and analysis indicates that appropriate mineral-fluid chemical reactions were proceeding in the subsurface, but no definitive estimates for mineralization rate were made.
- → An injection of 1 kt sCO₂ into basalt was done as part of the Wallula project in Washington State, supported through the DOE Regional Carbon Sequestration Partnership Initiative (RCSP). Post-injection sampling and analysis confirm that mineralization reactions occurred, although the fraction of injected CO₂ that was mineralized is uncertain.

Both sCO₂ and CW have been used for mineralization in basalts. One of the technical

FIGURE 8 The Carbfix Process



This figure shows the flow of water and gas through the Carbfix site. Carbfix started off only using captured CO_2 , but it has transitioned to also including CO_2 captured by DAC (from the Swiss company Climeworks). Carbfix has plans to scale up their injection of CO_2 from DAC. Carbfix is one of the largest-scale demonstrations of mineralization today, and illustrates the benefits of co-location of mineralization with emissions sources, other CDR, and other subsurface economic activities such as geothermal power. Source: EFI, 2020. Adapted from NASEM, 2019.

challenges with the use of sCO₂ as the injectant is that it is less dense than water so it tends to rise toward the surface, making it essential to ensure secure sealing of the storage reservoir during and after the injection of the sCO_2 phase. This is especially challenging during onshore injection into volcanic rocks since these formations are often highly fractured. Achieving effective mineralization requires that the injected sCO_2 be retained long enough for it to become mineralized. The retention time is a key research challenge, and there are suggestions that achieving effective sCO₂ mineralization could take hundreds of years at large scale. The results from Wallula, however, suggest that mineralization with sCO₂ can succeed under the right conditions, such as when the rock

formations physically trap sCO_2 (Figure 9 offers a comparison between trapping in sedimentary sequestration with sCO_2 and mineralization with CW).

The use of CW, as at Carbfix, offers both advantages and challenges. The risk of leaks is mitigated by the dissolution of the CO_2 in water, resulting in greater density and almost immediate solubility storage. There is little risk of CO_2 returning to the surface, but a major drawback of this approach is that a large quantity of water may be required. This water, however, could be sourced from the target reservoir, as at Carbfix, providing benefits for monitoring and preventing pressure build-up in the reservoir due to injection. The applicability of this technology to more arid

FIGURE 9



CO₂ Trapping in Sedimentary Injection and In Situ Mineralization

This figure shows the change in contribution of different carbon-trapping mechanisms from injection of CW in peridotite and carbon sequestration in sedimentary rock. Mineralization generally provides a more secure storage mechanism. More structural trapping may be needed for mineralization operations that use supercritical CO_2 . Source: EFI 2020. Adapted from NASEM, 2019 and Benson et al., 2005

regions or regions that rely on groundwater as a source of potable water is limited. Seawater may provide an adequate alternative. Carbfix is currently exploring the use of seawater as an alternative carrier. The large quantity of water required for CW also requires more wells, but since they are not required to withstand the pressures and the risk of corrosion associated with injection of sCO₂, their cost can be much lower.

An unforeseen consequence of injecting CW into basalt during the Carbfix project was that it supplied carbon to subsurface microorganisms living within the rock, leading to the growth of a biomass of unknown volume. There is some uncertainty regarding what proportion of the injected carbon is stored in minerals versus biomass, which is a shorter-term carbon storage medium. Carbon isotope measurements at Carbfix demonstrated that this biota increase contributed negligibly to the subsurface carbon fixation, but biomass growth could be a concern for future experiments.

Key RD&D needs and questions:

- 1. What is the carbonation rate of this pathway, both for sCO₂ and CW, and how does it depend on temperature, pore structure, alteration stage, and mineralogy of the rock formations?
- 2. At what rates can CO₂ be injected with the expectation of near-complete mineralization? Will those rates change over time?
- 3. What characteristics of individual

basalt formations are most indicative of capacity, ease of injection, and mineralization efficiency?

- 4. What are the relative advantages and disadvantages of using sCO₂ or CW and how are they dependent upon sitespecific geology?
- 5. What other forms of CO₂ trapping occur in basalt formations (e.g., biomass, solubility) and do they contribute to storage security if mineralization is not 100 percent efficient? More specifically, where are practically accessible, porous, reactive basalts overlain by impermeable cap rocks?
- 6. What are the costs and benefits of using seawater rather than freshwater to inject dissolved CO₂ into basalt?

Subsurface Mineralization in Ultramafic (UM) Rocks

Another proposed approach to subsurface mineralization is to use ultramafic rocks as the storage medium.^{35,36} UM rocks are not as porous, and hence cannot accept significant volumes of CW or sCO₂ unless there is a network of fractures present. The mineral content in UM rocks reacts particularly rapidly with CW, and the resultant reaction expands the volume of the resulting rock material. Based on numerous geologic examples of sustained carbonate vein formation in UM rocks over tens to hundreds of thousands of years, it is hypothesized that this volume increase can induce further fracturing so that porosity can be increased as CO_2 is injected. The rates in natural systems, however, are poorly constrained, and this technology has not been tested in an engineered system. Recent work by Tutolo et al. suggests that fluid is able to percolate through some types

of UM rocks in the subsurface via interconnected networks of nanometer-scale pores, though the role of this small-scale porosity for carbon mineralization is not well understood.³⁷

The CO_2 injection rates for CW (at about 100) parts per million of CO_2) injected into UM rocks are likely at or lower than the 10 kt per year rate currently achieved at Carbfix. Moreover, the low CO₂ concentrations in CW fluids magnify pumping costs. At Carbfix, water descends to injection depths with little or no pumping, but such favorable hydrology may not be widely available. Alternatively, it is proposed that thermal convection may be used to achieve useful flow and CDR rates. Using sCO₂ rather than CW would enhance injection rates significantly. Based on laboratory results, there appears to be the potential for 100 percent of carbon from injected sCO_2 or CO_2 -rich, high-pressure aqueous fluids to be fully mineralized via reaction in fractured UM formations.³⁸

Key RD&D needs and questions:

- Do injection and reaction lead to increased or decreased permeability ("cracking versus clogging") during long-term addition of CO₂ to UM rocks?
- Can thermal convection in UM rocks (or basalt) be used to facilitate injection of CO₂ at useful rates?
- 3. What scale and type of experiment can be done to test this concept?
- 4. Are fracture spacing, reactive surface area, and natural reaction rates in fractured UM rocks sufficient to make the concept viable?
- 5. How does the process vary with different UM rock types?

FIGURE 10

Locations of Feasible Geological Formations for In Situ Mineral Carbonation



Basalts are relatively common throughout the world, including in the Northwestern U.S. and Hawaii; subocean basalts may provide an even larger potential resource for mineralization. Oceanic ridges younger than 30 million years old are shown in orange, and oceanic igneous plateaus and continental flood basalts are shown in purple. Source: Snaebjornsdottir et al., 2020

Offshore Basalts

In addition to basalt and UM formations available on land, most of the ocean floor is made of basalt (underneath a small layer of sediment) (Figure 10). Because of the size of the oceans, rocks beneath the ocean floor presents an extremely large potential resource for subsurface mineralization. It is, however, much more challenging due to the cost of working in deep water, and transporting CO_2 , but nevertheless it should be evaluated for its large potential to contribute to CO_2 disposal.

RD&D into subseafloor mineralization is in a very early stage. The Cascadia Basin project was proposed to evaluate a particular subseafloor disposal strategy offshore the U.S. Northwest, but it did not advance to a stage where feasibility could be adequately tested.

There are a number of characteristics of the subseafloor strategy, beyond mineralization potential, that are unique and could be worth further assessment. For example, the high density of CO₂ at the lower temperatures in the deep oceans would avoid challenges of managing sCO₂, providing some advantages over mineralization in onshore basalts. An offsetting factor is that because the basalt formations themselves are usually fairly cold, mineralization will be relatively slow. While slower reaction rates can be planned for in experimental or operational design, the temperature issue has led to attention being focused on ocean floor basalts that are close to mid-ocean ridges where rocks are warmer at equivalent depths, similar to subsurface conditions in Iceland. These formations might also be favorable because they are fresh and reactive, so their pores and fractures may not

FIGURE 11

Process Design for Integrating Offshore In Situ Mineralization with Other Decarbonization Technologies



This figure shows a potential integration of different clean energy technologies with offshore or coastal in situ mineralization, based on research focused on the Kerguelen Plateau in the Indian Ocean. Mineralization could be co-located with DAC, low-carbon energy such as offshore wind, and power-to-gas, to achieve both CDR and zero-emissions fuels. Source: EFI, 2020. Adapted from Goldberg et al., 2013

be filled with secondary minerals.

There are few mid-ocean ridges that are relatively close to populated areas, but one is the Juan de Fuca ridge off the coast of Oregon, Washington, and British Columbia. Hawaii presents a somewhat different but potentially significant target. Key RD&D needs and questions for offshore mineralization are generally similar to mineralization in onshore basalts. Offshore mineralization also presents opportunities for novel configurations, such as a proposal to combine it with DAC powered by offshore wind (Figure 11).³⁹

In Situ Mineralization for CDR

In situ mineralization, in addition to being a storage mechanism that can be paired with other CDR (or point-source capture) methods, can also serve as a capture pathway in its own right.

Because laboratory rates for subsurface carbon mineralization in UM rocks and "glassy" basalts at temperatures above 50°C are relatively fast, compared to other abundant geological formations, a possible method for in situ CDR involves subsurface circulation of CO₂-bearing surface water in these rocks. This idea is inspired by observation of alkaline springs where waters from aquifers in UM rocks absorb CO_2 from the air to produce enormous calcium carbonate travertine deposits, both on land and on the seafloor.^{40,41,42,43} Many aspects of such a process would be similar to in situ mineralization for CO_2 storage.

As noted above, because the cost of pumping is generally prohibitive for aqueous solutions with smaller quantities of CO_2 (less than 1,000 parts per million), the overall concept is to use thermal convection to circulate surface water through reactive rocks, and then return calcium-rich, CO₂-depleted water to the surface where it will absorb more CO₂ from the air. In order to minimize water use, it would be necessary to reuse the produced water, once it has returned to equilibrium with atmospheric CO₂. In addition, one could use seawater at coastal sites, such as the giant outcrops of UM rocks along the shores of the United Arab Emirates, Oman, and New Caledonia. Such methods have potential synergy with geothermal power generation. Sites where UM formations are present in the subsurface in areas with high temperatures at shallow depth-such as The Geysers area and Mount Shasta in northern California-and sites of glassy basaltic lavas-such as near Medicine Lake, CA and in central Oregon-are particularly suitable for exploring such synergy.

Also worthy of consideration are methods involving hybrids of DAC and in situ mineralization. DAC could be used to create air with greater concentrations of CO₂ (e.g., 5 percent). This CO₂-enriched air could then be equilibrated with water to form a solution, and then injected for mineralization. Thermodynamic considerations suggest that this "partial DAC" may be cheaper than producing a stream of 90 percent or more CO₂ with DAC.⁴⁴ As such, hybrid combinations could be less expensive than either DAC (plus storage) or in situ carbon mineralization alone. This approach is a relatively new one and is ripe for optimization. Currently, however, engineered DAC systems are designed to produce nearly pure CO_2 , so lower-cost systems for partial CO_2 enrichment would have to be designed from scratch.

Key RD&D needs and questions (in addition to those outlined above for in situ CO₂ storage):

- What are the sizes of natural carbondepleted, UM- and basalt-hosted aquifers? What are their hydrologic characteristics? Are there sites where this water can be produced, to remove CO₂ from air at low cost?
- 2. Can thermal convection of water through UM or glassy basalt formations be rapid enough for practical application of this method to CDR? In addition to permeability, what are the rates of reaction, and thus recharge, in appropriate aquifers?
- 3. What scale and type of experiment can be done to test these concepts?
- 4. Can low-cost, engineered systems for partial enrichment of CO₂ in air be designed?
- 5. What are the theoretically optimal combinations of partial DAC and in situ carbon mineralization?

Synergies and Co-benefits of Carbon Mineralization

Carbon mineralization has significant potential co-benefits in several areas (Figure 12), including the co-benefits of ex situ mineralization with soil enhancement and more environmentally responsible management of mining and industrial wastes as part of an ex situ carbon mineralization

FIGURE 12

Co-benefits of Carbon Mineralization



In addition to its emissions benefits, mineralization has several co-benefits, which vary by pathway. For example, use of existing mine and industrial wastes can provide benefits for the management of those wastes; ERWC in soils can improve crop health and productivity. Co-benefits can act as an RD&D "pull" on technologies, helping generate opportunities for them to scale up. Source: EFI, 2020.

program.

Application of crushed silicate rock to agricultural lands can also improve soil conditions. Uptake of EWRC has been shown to be more effective if there are co-benefits to farmers, such as delivery of essential nutrients to plants and soil microbes, pH regulation of soils, and improvements in the health and yield of crops.

Carbon mineralization with industrial wastes has several co-benefits, including improving water quality by trapping heavy metals within carbonate products of CDR, destroying asbestos, dust mitigation, and stabilization of mine tailings. In addition, it also has a potential to produce new products such as building materials, and to recover useful products through re-processing historical tailings. This could bring about significant environmental, financial, and reputational benefits to mining and other industries that perform mineralization, including helping corporations meet their own GHG targets.

The use of mining and industrial wastes for carbon mineralization should also take into account potential concerns about public perception and acceptance. Mineralization with industrial alkaline wastes may face opposition from stakeholders who have larger concerns with the operation of extractive industries such as mining or heavy industry such as steel. Some may consider CDR to be a strategy for these industries to engage in "greenwashing" or obtain license to expand their activities. Other mineralization pathways may require new mining, substantial land use change, or water use, all of which have potential environmental and economic consequences that must be carefully considered in public processes. It is imperative for any RD&D efforts in mineralization to have transparency in addressing these concerns, and to prevent harm and minimize impact where possible. It is likewise important to ensure than any localized co-benefits accrue, at least in part, to the communities where CDR is taking place.

Other benefits of mineralization stem from the many synergies with other GHG mitigation strategies, which can help accelerate RD&D. In situ mineralization presents opportunities to co-deploy with point-source carbon capture, DAC, and BECCS; ex situ mineralization can be combined with efforts to increase biological CDR in forests, agricultural lands, coasts, and oceans (see the other two reports in the Frontiers of CDR series). There is also the possibility of RD&D cross-pollination with carbon utilization options that use similar chemical reactions to produce useful products such as cement and other building materials (see Chapter 7 of *Clearing the Air*).⁴⁵

Cross-Cutting Carbon Mineralization RD&D Challenges

Cross-Cutting Fundamental Research Opportunities and Pilot-Scale RD&D Projects

Predicting Mineral-Fluid Reactions

The essential characteristic of mineralization is that it requires chemical reaction between fluids and solids at the microscopic level. Predicting the rate at which mineral-fluid reactions occur in nature is difficult, and rates vary substantially in different environments. The type of material (granular materials like soils versus lava flows versus fractured crystalline rock), its hydrological properties, fluid flow rates, temperature, and other factors need to be included in useful predictions. The ultimate issue, however, is that rocks and soils tend to be heterogeneous at the meter-tokilometer scale that is required for large-scale mineralization. There are limited options for characterizing them at this scale in a manner that is useful for modeling mineral-fluid reactions. While small-scale laboratory experiments and modeling can provide some useful information, these dynamics need to be investigated at larger scales. For example, the permeability of fractured porous reservoirs is difficult to investigate at lab scale, since the largest fractures are commonly far apart.

In general, there are two approaches to improving reaction rate predictions. One is to measure the reaction rates in microscopic and sub-microscopic samples at laboratory scale and then attempt to extrapolate or "scale up" these measurements to larger systems. The other is to take measurements from large-scale systems, use them to develop simple predictive models that can be broadly applicable. A combination of the two is generally the best approach.

A major conclusion from the workshop is that mineralization technologies cannot advance without demonstration experiments at relatively large scale (Figure 13). Research on many mineralization pathways has been limited to small scale (e.g. the 10-m² scale), and reaching a larger scale is crucial to answering the fundamental research questions. However, such field-scale demonstrations require parallel efforts to refine knowledge at laboratory scale of how the mineral-fluid reactions work. The two approaches are self-reinforcing: field-based validation of small-scale processes will need to be done during deployment of CDR at scale (Figure 13).

FIGURE 13 RD&D Opportunities from Field-Scale Pilot Studies



Field-scale pilot studies have the ability to answer key questions about mineralization. and have cross-cutting benefits that cannot be adequately addressed by modeling. They can also help develop frameworks for monitoring and verification, techno-economic analysis, and lifecycle analysis. Source: EFI, 2020. Adapted from presentation by workshop participants

System Evolution Over Time

Another major issue in deploying mineralization CDR at scale is understanding how the rock or soil systems may change over time as they are being used for mineralization for periods on the scale of decades. As minerals dissolve and form other minerals, many aspects of mineral-fluid reactions can change. Some of these changes could enhance mineralization, but performance could also degrade with time. This is another aspect of the process that needs to be investigated not only in the laboratory, but also validated in long-term field-scale demonstrations.

Maximizing Carbonate Formation

Developing better models to predict how fast primary minerals dissolve is necessary, but it is not sufficient. The objective of mineralization is to produce carbonate minerals, either directly or through intermediate reactions. Some of the weathering-type reactions that underlie mineralization also result in the formation of other minerals, typically clay and clay-like minerals that do not store significant amounts of CO₂. Mineral dissolution also releases Ca, Mg, and iron that can be incorporated into carbonate or non-carbonate substances. The efficiency of carbonation reactions is thus dependent on the chemical compositions and atomic structures of feedstock minerals; the availability of CO₂, oxygen and water; and the available temperature and pressure conditions. Research directed at determining how to maximize the formation of carbonates could be helpful. One aspect of this effort might be to better characterize the mineralogy of basalts, ultramafic rocks, and mineral wastes in the United States. Not all minerals contained in these rocks are easily carbonated and the proportion of reactive minerals can vary greatly. A nationwide survey would help ascertain the maximum capacity of these rocks and mineral wastes for mineralization CDR.

Additional Cross-Cutting

The EFI workshop participants identified a number of additional fundamental research needs that would enable all methods of carbon mineralization. Specific cross-cutting fundamental research opportunities that would enable advances in ex situ mineralization methods include:

- → Monitoring mineralization and estimating CO₂ fixation at large scale;
- → Incorporating reactive transport, kinetics, and biologically mediated reactions in models; and
- → Understanding heterogeneity in mineral and rock composition and its effects on mineralization.

Additional cross-cutting fundamental research opportunities to enable advances for in situ mineralization include:

- → Reducing fluid requirements by increasing the solubility of CO₂ in the carrier fluid;
- → Maintaining or enhancing subsurface

permeability during mineralization;

- → Better monitoring of mineralization and estimation of CO₂ fixation; and
- → Minimizing dissolution and ensuring reprecipitation of pre-existing carbonate minerals, which are common in basalt and UM rocks.

Regional-Level Evaluation

The applicability and ultimate feasibility of carbon mineralization will be location specific; feasibility will vary across the U.S. (and globally) with climate, geology, and agricultural activity. Different regions of the country have different advantages and limitations, and these are different for each technology. Rock weathering processes are much different in the desert Southwest, the humid Southeast and Hawaii, and the relatively colder Northeast. The total area of land dedicated to agriculture varies, crops vary, and some regions have basalt and UM rock formations while others do not. There may be other conditions-political, social, infrastructure, CO₂ sources—that also vary regionally.

While the various mineralization technologies share some cross-cutting technical issues, a realistic assessment of their feasibility can only be evaluated regionally, where the specific implementation issues can be appropriately assessed.

Techno-economic & Lifecycle Assessments

Methodologies for techno-economic analysis (TEA) and lifecycle analysis (LCA) of mineralization pathways are needed to enable comparison among mineralization pathways

FIGURE 14 Key Considerations for Lifecycle Analysis of Carbon Mineralization



Many steps of the carbon mineralization process will have land, water, energy, and emissions considerations that need to be considered for LCA and TEA; these will vary from pathway to pathway. This figure shows components of a potential LCA for ex situ mineralization. LCAs will also need to consider factors outside of the "gate-to-gate" analysis, such as indirect impacts on land use. Source: EFI ,2020. Adapted from Kirchofer et al., 2012

and comparison with other forms of CDR.

TEA for carbon mineralization is challenging because of the heterogeneity of mineralization pathways. Mineralization TEA must consider process conditions, material reactivity, scale, material availability, and end product utilization, as well as the costs of land, equipment, energy, raw materials, and transportation. A TEA framework for mineralization must incorporate the complexity and variety of these technologies. Having a consistent framework will be crucial to comparing these pathways to each other and to other CDR methods, and for their inclusion in policy and carbon markets.

LCA helps understand the risks, costs, and cobenefits of mineralization pathways (Figure 14). Formal LCA of carbon mineralization pathways have been very limited. Those that have been done focus mostly on ex situ pathways, and only on energy and carbon impacts. "Lifecycle thinking" is required to determine whether a mineralization process is truly net-negative. The upstream and downstream impacts of mineralization including land use change, infrastructure construction, raw material mining and transport, mineral crushing, CO₂ transportation, calcination emissions, energy use, mineral distribution and recovery, and downstream product use—can greatly change the emissions calculus of a pathway. It is also necessary to consider in LCA the potential for offsetting emissions effects (e.g., conversion of cropland or forest land for purposes of ex situ mineralization resulting in changes in crop or vegetation patterns). In addition, while the focus in CDR is mostly on CO₂, it is important to consider other GHGs as well as non-climate impacts (e.g., conventional pollutants, water consumption, ecosystem disruption, etc.).

Improving LCA and TEA will require improved baseline information and shared methodologies, allowing comparison across other pathways. RD&D funding also needs to support TEA and LCA in early stages of research and throughout the innovation process. Development of open-source process models facilitating TEA and LCA could also be key. Recently, the DOE National Energy Technology Laboratory (NETL) released a guidance toolkit for LCA of CO₂ utilization that included guidance documents, training materials, templates, and an open database. This could serve as a model for developing a similar type of toolkit for mineralization to ensure consistent application of LCA and TEA for future projects.

Developing Monitoring, Reporting, and Verification Standards

Protocols or frameworks for MRV are imperative for carbon mineralization technologies to participate in voluntary and compliance carbon markets and to secure tax credits. Carbon mineralization, however, is not reflected in existing MRV protocols or frameworks. A lack of MRV standards or guidelines may cause high compliance costs. Currently, technologies for monitoring carbon stored by mineralization are not well developed, which could make it difficult to develop standards. Federal 45Q credits, for example, depend on having an EPA-approved MRV plan, which requires extensive modeling and monitoring of CO₂.

Developing MRV standards should be an essential component of the carbon mineralization RD&D portfolio. In addition, methodologies for MRV should be tested at the early stage of field tests. The DOE Regional Carbon Sequestration Partnership (RCSP) Initiative (see section on Implementation, below) tested monitoring technologies at the stage of small-scale field projects and developed optimized MRV design from its large-scale field laboratories.

Creating an Enabling Policy Environment for Large-Scale Deployment

The policy framework governing carbon mineralization is unclear and poses a potentially significant impediment to the largescale deployment of carbon mineralization methods that successfully emerge in the RD&D process.

Regulatory Frameworks

Carbon mineralization methods—both ex situ an in situ—will need to comply with various federal and state environmental requirements, but many of these requirements were formulated without carbon mineralization in mind.

For in situ carbon mineralization, it is unclear how laws and regulations on underground CO₂ injection will be applied to in situ mineralization, since it is an untested area that differs substantially from geologic sequestration in saline formations, oil wells, etc. This includes federal and state regulations on siting and permitting, MRV requirements, property rights, and long-term liability.

Ex situ carbon mineralization would be subject to a different set of regulatory requirements, perhaps more complex than for in situ methods. For example:

- → Mineralization on any publicly owned land would require a permit. Many federal land management agencies, such as the Department of the Interior (DOI) Bureau of Land Management and the Department of Agriculture (USDA) Forest Service, have specific Resource Management Plans that determine acceptable uses of agencymanaged land. Given that mineralization is not included in these plans, it might not be permitted.
- → Using ground rock at large scale may fall within requirements of the Environmental Protection Agency (EPA) Clean Air Act, such as those pertaining to fugitive emissions or prevention of significant deterioration.
- → Use of alkaline industrial waste use for mineralization could be subject to federal and state regulations on waste

disposal, including permitting requirements, which could create uncertainty for project developers.

→ Surface runoff from ex situ mineralization activities could be classified as a non-point source effluent under the Clean Water Act, triggering federal and state regulation.

Finally, subseafloor mineralization could fall within the purview of international ocean agreements, such as the United Nations Convention on Law of the Sea, the London Convention on ocean dumping and the London Protocol. (The legal and regulatory challenges of marine CDR are explored in greater depth in another report in this series, Uncharted Waters: Expanding the Options for Carbon Dioxide Removal in the Oceans.)

Financial Incentives

Eligibility for federal or state financial incentives is another area of substantial uncertainty affecting large scale deployment of carbon mineralization methods. For example, in situ carbon mineralization, while producing results comparable to geologic sequestration, faces uncertainty about eligibility for statutory incentive programs that apply to traditional geologic sequestration, such as federal 450 tax credit and the California Low Carbon Fuel Standard (LCFS). In particular, the MRV provisions of these programs are not tailored to mineralization, which could make it hard for projects to obtain credits. In addition, the 45Q program's 2024 deadline for commencement of project construction could present a challenge for nascent technologies such as mineralization.

Mineralization pathways—both in situ and ex situ—are also generally not included in carbon markets that use offsets, whether compliance markets (e.g., cap-and-trade systems in California and the Regional Greenhouse Gas Initiative) or voluntary markets. Further development of LCA, TEA, and MRV protocols could help position mineralization as a candidate for these markets or future ones like them.

The difficulties associated with navigating the patchwork of potentially applicable laws and regulations, as well as eligibility for financial incentives, could be a major hindrance to the development of large-scale mineralization projects. Further policy analysis and follow-on policy actions will be needed to address these uncertainties.

Implementation: Funding, Organization, and Management

The September 2019 EFI report *Clearing the* Air recommended a carbon mineralization RD&D portfolio to enhance the understanding of the feasibility and potential of carbon mineralization as a CDR technology option. The report proposed \$700 million of funding from four federal agencies-Department of Energy (DOE), Department of Interior (DOI), Environmental Protection Agency (EPA), and the National Science Foundation (NSF)-over a ten-year period. The report also proposed a \$2 billion demonstration project fund that also could be used to support large-scale demonstrations of carbon mineralization selected on a competitive basis. Mineralization-related pathways were also included in the terrestrial and biological, coastal and oceans, and CO₂ utilization portfolio areas. The full set of portfolio recommendations can be found in Appendix A. Building upon these recommendations, this section provides additional options for policy actions to enhance and accelerate deployment of carbon mineralization technology. A combination of actions is needed to scale up the technology given the various opportunities and challenges described above.

Implementation of a RD&D enterprise could be initiated by Presidential Executive Order. Congressional authorizing legislation would ultimately be desirable; historically, such as in the case of the U.S. Global Change Research Program, Congress acted on authorizing legislation for new interagency science and technology initiatives promptly in response to executive branch-proposed initiatives. Legislation could also provide multi-year authorizations to guide future appropriations. Congress may wish to consider additional options for implementation, such as establishing a guasi-governmental entity to manage a broad CDR initiative and a dedicated funding source. In 2020, bipartisan groups in both houses of Congress introduced the Carbon Removal, Efficient Agencies, Technology Expertise (CREATE) Act, which followed the recommendation from Clearing the Air that the National Science and Technology Council (NSTC) establish a new Committee on Large-Scale Carbon Management. The CREATE Act proposes a "geologic" working group, with representatives from DOE, DOI, NSF, and EPA.

Regional Collaboration Hubs

A multi-phase program starting with building regional infrastructure can accelerate mineralization RD&D. Because the feasibility of mineralization pathways varies greatly by region in the United States, establishing regional infrastructure and finding mineralization opportunities within specific regions should be the first step to support for the deployment of carbon mineralization technologies. Taking a regional approach can also help develop collective strategies to address land-use concerns, environmental constraints, and garnering political buy-in.

The Regional Carbon Sequestration Partnership (RCSP) and the Carbon Storage Assurance Facility Enterprise (CarbonSAFE) initiatives offer examples of federally funded regional approaches to large-scale carbon management (Figure X). The DOE created a network of seven RCSPs and started characterizing each region's potential for carbon sequestration in 2003. This led to the completion of nineteen small-scale field projects, and seven large-scale field laboratories. Building upon the success of the RCSP, the DOE initiated CarbonSAFE, a program aiming to develop the projects that will be ready for CCUS system deployment between 2025 and 2030. The program provides funding from the pre-feasibility assessment stage to permitting and construction of a storage complex. The first phase of CarbonSAFE was completed after funding thirteen projects, and currently, the second phase, a two-year initiative of storage complex feasibility, is being implemented.

This experience can be extended to carbon mineralization. The first step should be building regional infrastructure including a network of professionals in academia, industry, government, and National Laboratories through adopting a similar program to the RCSP and CarbonSAFE programs, focusing on the regions with high mineralization potential. Collaboration with industry is important because industry's knowledge and experience will contribute to the RD&D efforts, and eventually provides the pathway to large scale deployment. These regional partnerships could also mirror the RCSP and CarbonSAFE experience by funding multi-institution collaborative projects and instituting a stage-gated process, wherein only the most promising projects are funded as they move through the RD&D process. Another advantage of the regional approach could be the creation of designated field labs that can support multiple field-scale demonstration experiments necessary for scaling up CDR.

FIGURE 15

Co-benefits of Carbon Mineralization



This figure shows previous DOE-sponsored regional collaboration efforts for sedimentary carbon sequestration. Shaded states and white dots show the RCSP partnerships: Big Sky Carbon Sequestration Partnership (BSCSP), Midwest Geological Sequestration Consortium (MGSC), Midwest Regional Carbon Sequestration Partnership (MRCSP), Plains CO₂ Reduction Partnership (PCOR), Southeast Regional Carbon Sequestration Partnership (SECARB), Southwest Regional Partnership on Carbon Sequestration (SWP), and West Coast Regional Carbon Sequestration Partnership (WESTCARB). CarbonSAFE projects that reached the pre-feasibility stage and feasibility stage are shown in yellow and red, respectively. A similar program for mineralization, with regional hubs and stage-gated funding, could be a boon to scaling up regional collaboration and field testing. Source: EFI, 2020. Compiled using data from the National Energy Technology Laboratory.

Incorporating Mineralization into Existing RD&D Programs

Existing federal research programs can help develop carbon mineralization technology. Carbon mineralization can be an agenda item in existing research programs in the DOE, DOI, and the USDA. Multiple parts of DOE could participate in mineralization RD&D. The EFI *Clearing the Air r*eport proposed adding mineralization as a technology mission responsibility for the Office of Fossil Energy R&D (which already hosts carbon capture, utilization, and storage programs), and revitalizing and expanding the cross-DOE Subsurface Science, Technology and Engineering Research, and Development (SubTER) initiative to cover both geologic sequestration and mineralization. DOE could also help address numerous fundamental science questions for mineralization through collaborative programs that bring together government, academia, and national laboratories, such as the Office of Science Energy Frontier Research Center program. The DOE Advanced Manufacturing Office also participates in a multiagency effort called the National Network for Manufacturing Innovation, a network of manufacturing institutes bringing industry, academia, and federal entities together. While mineralization does not clearly fit into any of the existing institutes, NNMI could provide a good model for collaboration with industry.

ERWC could also be incorporated into USDA's RD&D programs. The Clearing the Air Report suggested that ERWC RD&D could be supported by the USDA Agricultural Research Service. It could also be included as a research area for the Agriculture Advanced R&D Authority (AGARDA), a new agency for cutting-edge research modeled on the Department of Defense, Defense Advanced Research Projects Agency (DARPA) and the DOE Advanced Research Projects Agency— Energy (ARPA-E).

Within DOI, the U.S. Geologic Survey (USGS) could be the primary RD&D performer for mineralization. But given the potential benefits to mining industry, carbonation of mine tailings could also be incorporated into the Technology Development Transfer (TDT) program of the Office of Surface Mining Reclamation and Enforcement (OSMRE). TDT supports developing new technologies and communicating the technologies to users and could be a great way to move mineralization from the lab to the field.

International RD&D Collaboration

International collaboration is imperative for scaling up carbon mineralization technology and promoting global application. Carbon mineralization is location-specific and as such is potentially suitable for a number of specific regions worldwide. International collaboration and coordination are needed to find the regions with high carbon mineralization potential and to build infrastructure in those regions. The Carbfix project is an example of international collaboration of public entities and academia. The project aims to make their technology economically viable and applicable throughout Europe (and beyond). The U.S. could incorporate mineralization into existing international collaboration mechanisms, especially bilateral cooperation with Canada, which is home to significant mineralization research. The September 2019 EFI Clearing the Air Report proposed using Mission Innovation and the InterAcademy Partnership as venues for expanding international collaboration in CDR RD&D.

Appendix A

Clearing the Air Funding Levels for Mineralization RD&D

TABLE X

Carbon Mineralization RD&D Portfolio (\$millions)

Portfolio Element	Funding Agency	Funding Organization or Office	Year 1	5-Year Total	10-Year Total	
	4.10 Research and Assessments					
<u>4.11 Fundamental</u> <u>research</u>	NSF	GEO	\$2	\$46	\$121	
	DOE	SC (BES)	\$2	\$36	\$86	
4.12 Resource	DOI	USGS	\$2	\$22	\$47	
<u>assessments</u>	DOE	FE	\$0	\$20	\$20	
4.10 Subtotal, Research and Assessments			\$6	\$124	\$274	
4.20 Field Experiments						
4.21 Pilot studies of ex situ mineralization	DOE	FE	\$2	\$23	\$42	
	EPA	ORD	\$2	\$16	\$29	
4.22 Pilot studies of in situ mineralization	DOE	FE	\$2	\$65	\$148	
	NSF	GEO	\$1	\$16	\$32	
4.23 Tailings and waste mineralization	DOI	USGS	\$1	\$12	\$24	
	EPA	ORD	\$1	\$8	\$15	
4.20 Subtotal, Field Experiments			\$9	\$140	\$290	
4.30 Environmental Studies						
4.31 Environmental impacts of	EPA	ORD	\$1	\$19	\$44	
mineralization products	DOI	USGS	\$1	\$19	\$44	
4.32 Environmental and social impacts of	NSF	GEO	\$2	\$18	\$38	
expanded mining for mineralization	DOI	USGS	\$1	\$5	\$10	
4.30 Subtotal, Environmental Studies			\$5	\$61	\$136	

Portfolio Element	Funding Agency	Funding Organization or Office	Year 1	5-Year Total	10-Year Total
		5.30 Ocean Alkalinit	y Modification		
<u>5.31 Fundamental</u> <u>research</u>	NSF	GEO	\$2	\$31	\$71
	DOE	SC (BER)	\$2	\$28	\$63
5.32 Applied alkalinity	DOC	NOAA (OAR)	\$0	\$65	\$175
techniques	NSF	GEO	\$0	\$25	\$65
5.30 Subtotal, Alkalinity Modification			\$4	\$149	\$374
7.10 Carbonation Conversion for CO2 Utilization					
7.11 Fundamental research	DOE	SC (BES)	\$2	\$22	\$47
	NSF	MPS	\$3	\$23	\$48
7.12 Integrated process design	DOE	FE	\$2	\$22	\$42
	NSF	ENG	\$2	\$14	\$26
7.13 Alkalinity source pathways	DOE	EERE (AMO)	\$3	\$15	\$27
	DOI	USGS	\$3	\$15	\$27
7.14 Construction materials	DOE	EERE (BTO)	\$3	\$15	\$30
	DOC	NIST	\$2	\$10	\$19
7.15 Transportation infrastructure materials	DOT	FHWA	\$2	\$37	\$57
7.10 Subtotal, Carbonation Conversion			\$22	\$173	\$323
Other Mineralization					
3.26 Reactive minerals in agricultural soils	USDA	ARS	\$3	\$15	\$30
	TOTAL		\$49	\$662	\$1,427

GEO = Directorate for Geosciences. SC = Office of Science. BES = Basic Energy Sciences Program. FE = Office of Fossil Energy. ORD = Office of Research and Development. BER = Biological and Environmental Research Program. MPS = Directorate for Mathematical and Physical Sciences. ENG = Directorate for Engineering. EERE = Office of Energy Efficiency and Renewable Energy. AMO = Advanced Manufacturing Office. BTO = Building Technologies Office. NIST = National Institute for Standards and Technology. DOT = Department of Transportation. FHWA = Federal Highway Administration. ARS = Agricultural Research Service. Source: EFI, 2019.

Appendix B

Examples of Federally Funded Mineralization RD&D

While much of the significant mineralization research has taken place outside the U.S., there have been several domestic projects funded by the federal government. In an analysis by EFI and the Bipartisan Policy Center (BPC) for the report Carbon Removal: Comparing Historical Federal Research Investments with the National Academies' Recommended Future Funding Levels, which covered federal spending from Fiscal Years 1993 through 2019, EFI and BPC found carbon mineralization projects at DOE's ARPA-E, Office of Fossil Energy R&D, and Office of Science; the National Science Foundation's Geosciences Directorate, and Department of Agriculture's National Institute for Food and Agriculture.

Specific examples of federally backed research identified in Clearing the Air include:

Wallula, Washington. The Wallula Basalt Pilot Demonstration Project, located in southeastern Washington, was an in situ mineralization project that began in 2009 as part of DOE's Regional Carbon Sequestration Partnership Initiative. During the span of three weeks from June to July 2013, the project injected a total of nearly 1 ktCO₂ into continental basalt formations, which led to the successful mineralization of CO₂ over a twoyear period. The project was reportedly the first to provide field evidence of in situ mineralization using free phase supercritical CO₂ in a flood basalt reservoir.^{46,47,48}

Cascadia Basin. The Carbon Storage Assurance Facility Enterprise (CarbonSAFE) Initiative, the DOE/NETL carbon sequestration research program, is currently funding a prefeasibility study for offshore carbon mineralization in the Cascadia Basin near Washington and British Columbia.⁴⁹ This project is seeking to capture and sequester 50 MtCO₂ from concentrated point sources over a 20-year period and inject the CO₂ into offshore basalt reservoirs 200 miles off the Pacific Coast, where it would mineralize into calcium carbonate.⁵⁰ Project goals include technical (e.g., site characterization and monitoring) and nontechnical (e.g., regulatory and liability frameworks) assessments of the proposed injection site.⁵¹

DOE Research on CO₂ Utilization. Some of the original development of ex situ mineralization using calcium- and magnesium-rich silicate minerals was supported at Los Alamos National Laboratory in the 1990s, with follow-on work performed by NETL.⁵² Carbon mineralization currently has been identified by DOE as one of the four research efforts for CO₂ utilization pathways.⁵³ DOE projects have included a project testing the viability of CO₂-injected concrete compared with traditional concrete, for use in a Hawaii Department of Transportation road construction project.⁵⁴ The CO₂ feedstock being used is from Hawaii Gas, which is injected into ready-mix concrete, where it becomes mineralized and reportedly improves the strength of the material. DOE also funded 74 percent of a project use alkaline industrial wastes from iron and steel production to serve as reactive feedstocks for carbon mineralization using CO₂ captured from coalfired power plants. Carbonate minerals produced through this process were used for the development of construction materials.⁵⁵

Abbreviations

Са	Calcium
Carbon- SAFE	Carbon Storage Assurance Facility Enterprise
CCUS	Carbon Capture, Utilization and Storage
CDR	Carbon Dioxide Removal
CO ₂	Carbon Dioxide
CW	Saturated Water
DOE	Department of Energy
DOI	Department of the Interior
EPA	Environmental Protection Agency
ERWC	Enhanced Rock Weathering and Carbonation
Fe	Iron
Gt	Gigaton
Gton	Gigaton
LCA	Life Cycle Analysis
LCFS	Low-Carbon Fuel Standard
Mg	Magnesium
MRV	Monitoring, Reporting, and Verification
MVA	Monitoring, Verification, and Accounting
Mt	Megaton
N ₂	Dinitrogen
Na	Sodium
NETL	National Energy Technology Laboratory
NSF	National Science Foundation
NSTC	National Science and Technology Council
O ₂	Oxygen
RCSP	Regional Carbon Sequestration Partnerships
RD&D	Research, Development, and Demonstration
TDT	Technology Development Transfer
TEA	Techno-economic analysis
UIC	Underground Injection Control
UM	Ultramafic

USDA	U.S. Department of Agriculture
USGS	United States Geological Survey

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