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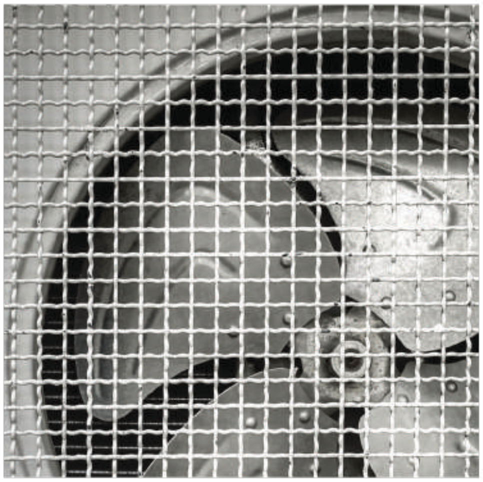

Clearing the Air

A Federal RD&D Initiative and Management Plan for Carbon Dioxide Removal Technologies

ENERGY FUTURES INITIATIVE

About EFI

The Energy Futures Initiative (EFI), established in 2017 by former Secretary of Energy Ernest J. Moniz, is dedicated to addressing the imperatives of climate change by driving innovation in energy technology, policy, and business models to accelerate the creation of clean energy jobs, grow local, regional, and national economies, and enhance energy security. We are fact-based analysts who provide our funders with unbiased, practical real-world energy solutions.

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Acronyms and Abbreviations

ACT	Accelerating Carbon Capture and Storage Technologies
AGARDA	Agriculture Advanced Research and Development Authority
AMO	Advanced Manufacturing Office
AR5	Fifth Assessment Report
ARL	Army Research Laboratory
ARPA-E	Advanced Research Projects Agency-Energy
ARRA	American Recovery and Reinvestment Act
ARS	Agricultural Research Service
BECCS	bioenergy with carbon capture and sequestration
BER	Biological and Environmental Research
BES	Basic Energy Sciences
BETO	Bioenergy Technologies Office
BIO	Directorate for Biological Sciences
BPM	best practice manual
BRAIN	Brain Research through Advancing Innovative Neurotechnologies
BRDI	Biomass Research & Development Initiative
BSCSP	Big Sky Carbon Sequestration Partnership
BTO	Building Technologies Office
$Ca(OH)_2$	calcium hydroxide
$CaCO_3$	calcium carbonate
CaO	lime
CarbonSAFE	Carbon Storage Assurance Facility Enterprise
CBD	Convention on Biological Diversity
CBO	Congressional Budget Office

CCAFS	Climate Change, Agriculture, and Food Security
CCUS	carbon capture, utilization, and sequestration
CDR	carbon dioxide removal
CDRA	Carbon Dioxide Removal Assembly
CED	Clean Energy Dialogue
CERC	Clean Energy Research Center
CERN	European Organization for Nuclear Research
CES	Cooperative Extension Service
CGIAR	Consultative Group for International Agricultural Research
CH_4	methane
CO	carbon monoxide
COAST	Coastal and Ocean Acidification Stressors and Threats
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
CO_2-EOR	enhanced oil recovery using CO_2
CO_2U	carbon dioxide utilization
CO_3^{2-}	carbonate ion
COP15	15th Conference of the Parties (Copenhagen Agreement)
COP21	21st Conference of the Parties (Paris Agreement)
CPI	Consumer Price Index
CSLF	Carbon Sequestration Leadership Forum
DAC	direct air capture
DACS	direct air capture with storage
DARPA	Defense Advanced Research Projects Agency
DAS	Deputy Assistant Secretary
DIC	dissolved inorganic carbon

DOC	Department of Commerce
DOD	Department of Defense
DOE	Department of Energy
DOI	Department of the Interior
DOT	Department of Transportation
EERE	Office of Energy Efficiency and Renewable Energy
EEZ	exclusive economic zone
EFRC	Energy Frontier Research Center
EGR	enhanced gas recovery
ENG	Directorate for Engineering
EOP	Executive Office of the President
EOR	enhanced oil recovery
EPA	Environmental Protection Agency
EPAct	Energy Policy Act
ESA	European Space Agency
ESAAB	Energy Systems Acquisition Advisory Board
ESD	Earth Sciences Division
EU	European Union
EW	enhanced weathering
FC&FP	Freedom CAR and Fuel Partnership
FE	Office of Fossil Energy
FEED	Front-End Engineering Design
FFAR	Foundation for Food and Agriculture Research
FFRDC	Federally Funded Research and Development Center
FHWA	Federal Highway Administration
FIA	Forest Inventory and Analysis
FOA	funding opportunity announcement

FOB	forward operating base
FRED	Federal Reserve Economic Data
GCAM	Global Change Assessment Model
GEO	Directorate for Geosciences
GESAMP	Joint Group of Experts on the Scientific Aspects of Marine Environmental Exploration
GHG	greenhouse gas
GHGRP	Greenhouse Gas Reporting Program
GMO	genetically modified organism
Gt	gigaton (billion metric tons)
H_2	hydrogen
H_2CO_3	carbonic acid
H_2S	hydrogen sulfide
ha	hectare
HCl	hydrochloric acid
HCO_3^-	bicarbonate ion
HFC	hydrofluorocarbon
HGP	Human Genome Project
HNLC	High-Nutrient Low-Chlorophyll
HTLS	high-temperature liquid solvent
HUD	Housing and Urban Development
IAM	integrated assessment model
IAP	InterAcademy Partnership
IARPC	Interagency Arctic Research Policy Committee
ICEF	Innovation for a Cool Earth Forum
IEA	International Energy Agency
IEAGHG	International Energy Agency Greenhouse Gas Research and Development Programme

IP	intellectual property
IPCC	Intergovernmental Panel on Climate Change
ISS	International Space Station
IUCN	International Union for Conservation of Nature
kg	kilogram
KIFES	Korean Iron Fertilization Experiment in the Southern Ocean
km	kilometer
KOH	potassium hydroxide
KOSMOS	Kiel Off-Shore Mesocosms for Ocean Simulations
kt	kiloton (thousand metric tons)
kW	kilowatt
LCA	lifecycle analysis
LGU	Land-Grant University
LiOH	lithium hydroxide
LP	London Protocol
LTSS	low-temperature solid sorbent
LULUCF	land use, land-use change, and forestry
MARINER	Macroalgae Research Inspiring Novel Energy Resources
MgC	megagram of carbon
MgO	magnesium oxide
MGSC	Midwest Geologic Sequestration Consortium
Mha	million hectares
MI	Mission Innovation
MODIS	Moderate Resolution Imaging Spectroradiometer
MOU	Memorandum of Understanding
MPS	Directorate for Mathematical and Physical Sciences

MRCSP	Midwest Regional Carbon Sequestration Partnership
MRV	monitoring, reporting, and verification
Mt	megaton (million metric tons)
MVA	monitoring, verification, and accounting
MW	megawatt
N_2	nitrogen
N_2O	nitrous oxide
NaOH	sodium hydroxide
NASA	National Aeronautics and Space Administration
NASEM	National Academies of Sciences, Engineering, and Medicine
NATCARB	National Carbon Sequestration Database and Geographic Information System
NDC	Nationally Determined Contribution
NET	negative emissions technology
NETL	National Energy Technology Laboratory
NF_3	nitrogen trifluoride
NIFA	National Institute for Food and Agriculture
NIST	National Institute for Standards and Technology
NITRD	Networking and Information Technology Research and Development
NNI	National Nanotechnology Initiative
NNMI	National Network for Manufacturing Innovation
NOAA	National Oceanic and Atmospheric Administration
NOx	nitrogen oxides
NRCS	Natural Resources Conservation Service
NRI	National Resources Inventory
NRL	Naval Research Laboratory
NSF	National Science Foundation

NSTC	National Science and Technology Council
NTTAA	National Technology Transfer and Advancement Act
NYDF	New York Declaration on Forests
O&M	organization and management
OAM	ocean alkalinity modification
OAR	Oceanic and Atmospheric Research
OCAP	Organic Carbon Dioxide for Assimilation of Plants
OCO-2	Orbiting Carbon Observatory-2
OECD	Organisation for Economic Co-operation and Development
OIF	ocean iron fertilization
OMB	Office of Management and Budget
ORD	Office of Research and Development
OSPAR	Oslo and Paris Conventions
OSTP	Office of Science and Technology Policy
PCOR	Plains CO_2 Reduction Partnership
PFC	perfluorocarbon
PNGV	Partnership for a New Generation of Vehicles
ppm	parts per million
PRD	Priority Research Decision
R&D	research & developmnet
RCI	Rotterdam Climate Initiative
RCSP	Regional Carbon Sequestration Partnerships
RD&D	research, development, and demonstration
RDD&D	research, development, demonstration, and deployment
ROOTS	Rhizosphere Observations Optimizing Terrestrial Sequestration
ROZ	residual oil zone
SBE	Directorate for Social, Behavioral, and Economic Sciences

SC	Office of Science
SCC	social cost of carbon
SEAB	Secretary of Energy Advisory Board
SECARB	Southeast Regional Carbon Sequestration Partnership
SES	Division of Social and Economic Sciences
SF_6	sulfur hexafluoride
SO_2	sulfur dioxide
SOC	soil organic carbon
SubTER	Subsurface Science, Technology, Engineering, Research and Development
SWAMP	Sustainable Wetlands for Adaptation and Mitigation Program
SWP	Southwest Regional Partnership on Carbon Sequestration
tCO_2	metric ton of CO_2
TCP	Technology Collaboration Programme
TEA	techno-economic analysis
UIC	Underground Injection Control
UN	United Nations
UNCLOS	United Nations Convention on the Law of the Sea
UNFCCC	United Nations Framework Convention on Climate Change
USACE	U.S. Army Corps of Engineers
USAID	U.S. Agency for International Development
USDA	U.S. Department of Agriculture
USFS	U.S. Forest Service
USGCRP	U.S. Global Change Research Program
USGS	U.S. Geological Survey
WESTCARB	West Coast Regional Carbon Sequestration Partnership

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CLEARING THE AIR: TECHNOLOGICAL CARBON DIOXIDE REMOVAL RD&D INITIATIVE

SUMMARY REPORT

Net-zero carbon dioxide (CO_2) emissions is not credibly achievable by midcentury without major contributions from negative-carbon technologies. Such technologies will also make possible, in the long term, a reversal of ever increasing greenhouse gas (GHG) concentrations in the atmosphere, thereby reducing the impact of past actions.

Concerns about the inadequacy of collective emissions mitigation efforts, a growing body of scientific evidence, and current emissions trajectories are reflected in the actions of many foreign governments, including many U.S. states and cities, in their movement towards "net-zero" emissions targets to balance GHG emissions with an equivalent amount of carbon removal and sequestration. The growing number of national, state, and subnational entities that have committed to net-zero emissions puts additional pressure on innovators to develop a range of technologies that go beyond the scope of conventional mitigation options.

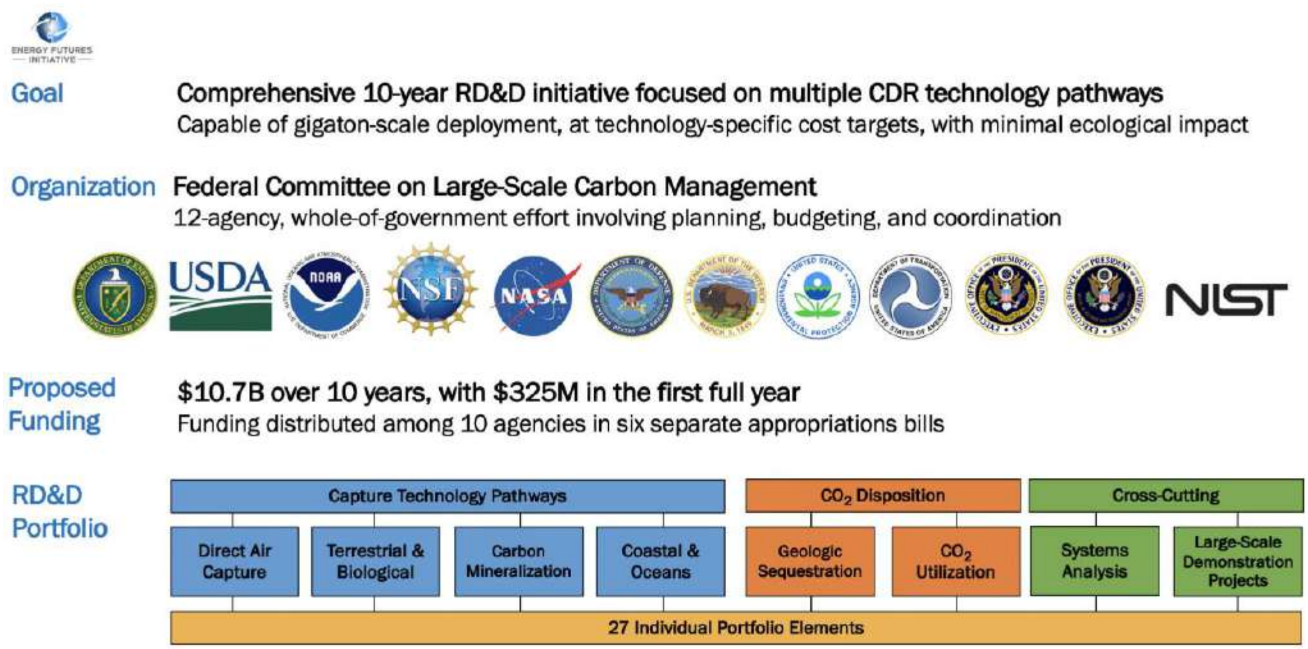
This report provides a set of recommendations and detailed implementation plans for a comprehensive, 10-year, $10.7 billion research, development, and demonstration (RD&D) initiative in the United States to bring new pathways for technological carbon dioxide removal (CDR) to commercial readiness (Figure S-1).

The CDR RD&D initiative encompasses a broad range of technological pathways and technologically-enhanced natural processes that can remove CO_2 from the environment including direct air capture (DAC); technologically-enhanced carbon uptake in trees, plants, and soils; capture and isolation of CO_2 in coastal and deep ocean waters; and carbon mineralization in surface and subsurface rock formations. Geologic sequestration and CO_2 utilization will also be included in the CDR RD&D initiative to provide CO_2 disposition options for CDR pathways such as DAC and bioenergy with carbon capture and sequestration (BECCS).

The wide range of scientific challenges requires a whole-of-government approach that reaches the mission responsibilities and research expertise of 12 federal departments and agencies, with the Department of Energy (DOE), Department of Agriculture (USDA), and the National Oceanic and Atmospheric Administration (NOAA) playing key roles. The planning, budgeting, execution, and performance aspects of the CDR RD&D initiative will require effective coordination led by the Office of Science and Technology Policy (OSTP) and the Office of Management and Budget (OMB) within the Executive Office of the President (EOP). At an international level, the CDR RD&D initiative should seek to collaborate with similar efforts in other countries under an expanded Mission Innovation (MI) initiative, which was launched at the 21st Conference of the Parties (COP21) in 2015.

Figure S-1

Overview of CDR RD&D Initiative



The CDR RD&D initiative is proposed to span 10 years and involve multi-agency collaboration and coordination.
Source: EFI, 2019.

Imperative for Carbon Dioxide Removal

Technological CDR provides policymakers with additional optionality and flexibility to both complement measures to reduce future CO_2 emissions as well as reduce atmospheric CO_2 concentrations resulting from past actions.

The need for CDR to augment mitigation measures has become increasingly evident for several reasons. The evolving climate science indicates the need to move toward a more stringent temperature limit of 1.5°C rather than 2°C, current GHG emissions trajectories are not on track to achieve current mitigation commitments, and many countries (including at the subnational level in the United States) are consequently moving to net-zero emissions targets by midcentury. While ambitions are increasing, current actual performance is falling short. As of 2018, two-thirds of the major carbon-emitting countries were not on track to meet the Paris target of 2°C,[1] and even if fully implemented, the Nationally Determined Contributions would achieve only one-third of the needed emissions reductions for a least cost pathway to 2°C.[2] Meanwhile, global CO_2 emissions rose 1.6 percent in 2017.[3] Preliminary estimates for 2018 suggest that global CO_2 emissions rose again at a rate of more than 2 percent.[4] The U.S. is no exception. In 2018, its CO_2 emissions from fossil fuel combustion rose 2.7 percent while economywide emissions likely increased by 1.5 to 2.5 percent.[5] CDR can play a key role in this effort by providing policymakers with a broader suite of options to address current and historical emissions. Net-zero emissions will not be achieved without substantial contributions from CDR.

CDR pathways extract CO_2 that has already been emitted into the environment and thus reduce atmospheric CO_2 concentrations. Atmospheric CO_2 concentrations have been increasing at a rate of 2-3 parts per million (ppm) per year,[6] with a commensurate rate of warming of 0.2°C per decade. Consequently, the planet will likely be committed to the lower temperature target of 1.5°C by as early as 2030.[7] Concerns about the current emissions trajectory and the imminence of crossing the 1.5°C threshold in little more than a decade are reflected in the actions of many governments and their movement towards net-zero emissions targets. CDR can thus compensate for residual emissions in difficult-to-decarbonize sectors like aviation that may be too difficult or expensive to eliminate from the economy, as well as address the problem of historical emissions created by the lack of past action on climate change. Removing CO_2 that previously was emitted to the atmosphere could assist in lowering CO_2 concentrations and help stabilize the climate at safer levels.

Strategic Framework for the Technological CDR RD&D Initiative

The proposed technological CDR RD&D initiative is both goal-focused and time-focused.

The ***overarching goal*** of the CDR RD&D initiative is to provide policymakers a suite of technological CDR approaches that can safely augment the natural carbon cycle to complement mitigation efforts and reduce atmospheric CO_2 concentrations.

The ***strategy*** to achieve this overarching goal is to implement a comprehensive 10-year CDR RD&D initiative that will demonstrate the commercial readiness of multiple technological and technologically-enhanced CDR pathways that can be deployed at or near gigaton scale.

The ***strategic elements*** necessary to enable successful achievement of the goal are summarized in Box S-1. Several of these elements—the scope of technology options, the span of innovation support, cost targets, and deployment scale—merit further elaboration.

Box S-1

Strategic Elements of the Carbon Dioxide Removal RD&D Initiative

- An effectively coordinated “whole-of-government” approach in addressing and coordinating CDR research needs;
- Incorporation of CDR into the strategic research mission objectives of the participating federal departments and agencies in a manner that creates synergy and complementarity with other national goals that can garner broad acceptance and be readily translated into specific projects with measurable progress and outcomes;
- A comprehensive and robust portfolio that:
    1.) Reflects the full range of potential CDR pathways;

2.) Spans the full innovation spectrum from fundamental research to demonstration at scale;
3.) Addresses near-, mid-, and longer-term research opportunities; and
4.) Incorporates regional variation among technological CDR approaches.

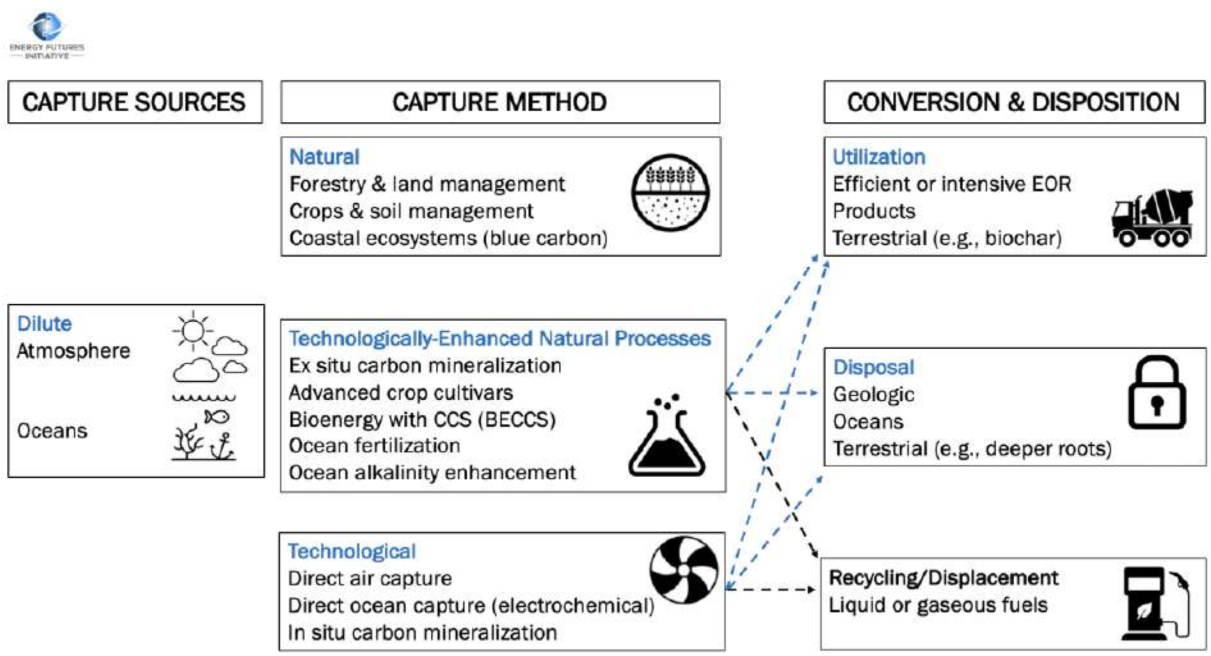
- Clearly defined technology-specific cost objectives and commercial application potential;
- Carefully defined research protocols to fully address and promote collateral environmental and resource benefits and minimize any adverse environmental impacts;
- A logical and transparent initiative structure, with clearly defined management roles and responsibilities, and supporting budget plans, that can garner broad-based acceptance and be readily translated into specific projects with measurable progress and outcomes;
- Engagement with the international scientific community to accelerate the pace of RD&D progress and promote the application of CDR technologies on a global scale;
- A budget planning process reflecting the long-term nature of research projects, interagency coordination needs, and specific budget line item allocations;
- Effective and efficient utilization of the nation's technology innovation infrastructure; and
- Disciplined program management and accountability, including stage-gated processes and independent evaluations of program performance, with sufficient flexibility to change course when informed by research outcomes.

Scope of Technological CDR Approaches

The three broad approaches to CDR, illustrated in Figure S-2, are **natural** , **technologically-enhanced natural processes** (or hybrid), and **technological** CDR from the atmosphere and oceans. Natural CDR includes pathways such as afforestation, reforestation, soil carbon sequestration, and coastal ecosystem carbon uptake ("blue carbon"). Natural CDR pathways remove carbon from the atmosphere at gigaton (Gt) scale, but are currently insufficient to offset anthropogenic emissions and thus cannot keep the carbon cycle in a net-neutral balance. The natural carbon cycle can be enhanced for example by expanding forested areas, avoiding deforestation, and preserving and expanding wetlands. These pathways already are the subject of considerable research studies and policy discussion, and the potential scale of expansion ultimately is limited by competing uses of land for food and fiber production and human habitat. The potential for, and issues related to, expansion of natural systems are not addressed in this study.

Figure S-2

Selection of Pathways for CDR from Dilute CO_2 Sources



There are a variety of natural, technologically-enhanced natural processes, and technological pathways that can facilitate CDR through the capture of CO_2 from dilute sources. Source: EFI, 2019.

The functioning of natural systems, however, can be technologically enhanced in various ways. Technologically-enhanced natural processes include elements of both natural and technological CDR and include pathways such as ex situ carbon mineralization, advanced crop cultivars, ocean alkalinity enhancement, and BECCS. The technologically-enhanced CDR options (other than BECCS) also have the advantage or providing both capture and sequestration in the same process.

A third broad approach is direct technological capture, including DAC and electrochemical separation of CO_2 from seawater. These pathways do require some form of sequestration or utilization in order to achieve permanent disposition of the captured CO_2. Since some of these technological CDR pathways can capture CO_2 in a relatively pure form, there are a range of CO_2 utilization options that might be available.

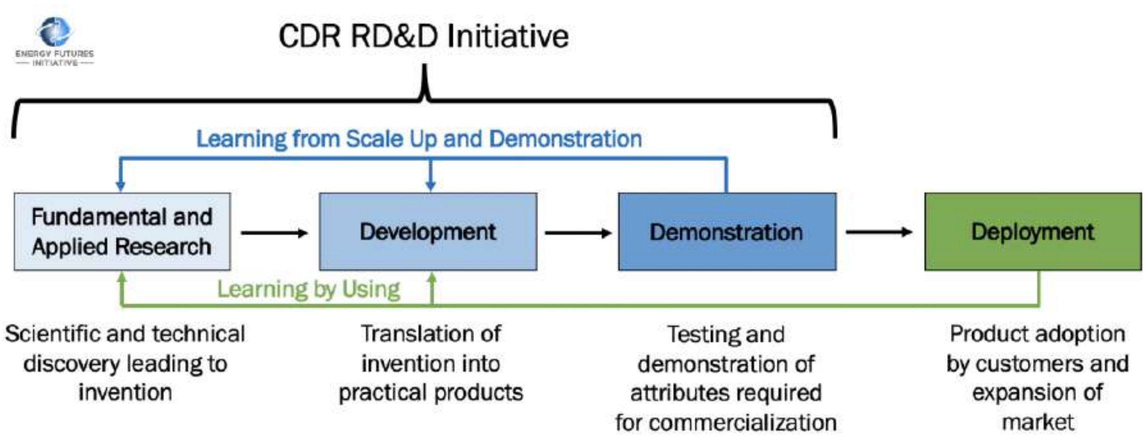
It is extremely important to note that CDR is distinct from geoengineering; the former involves the management of GHG emissions to address climate change, while the latter involves techniques that modify climate such as the management of solar radiation, but do not affect CO_2 fluxes or atmospheric concentrations. Geoengineering options are not considered in this study.

The individual technological CDR options within the scope of this RD&D initiative include those based on technology (not land-use change), result in net-negative emissions, require substantial RD&D, and are not being sufficiently advanced at present. The CDR RD&D initiative does not include geoengineering (e.g., solar radiation management), climate adaptation (e.g., modifying the built environment to accommodate a changed climate), or deployment policies (e.g., carbon standards or carbon pricing).

Span of Innovation

The CDR RD&D initiative will support all stages of the innovation process: fundamental and applied research, technology development, and demonstration at scale (Figure S-3), with a selection and prioritization of projects and activities informed by estimates of cost reduction and deployment potential. These research processes can take a substantial amount of time from proof-of-concept through successful full-scale demonstration, the dynamics of which are often difficult to predict. This is partly due to the highly non-linear nature of the innovation process, which often involves feedbacks from technology scale up, demonstrations, and learning by using that promote continuous improvement from invention to diffusion.

Figure S-3
Focus of CDR RD&D Initiative



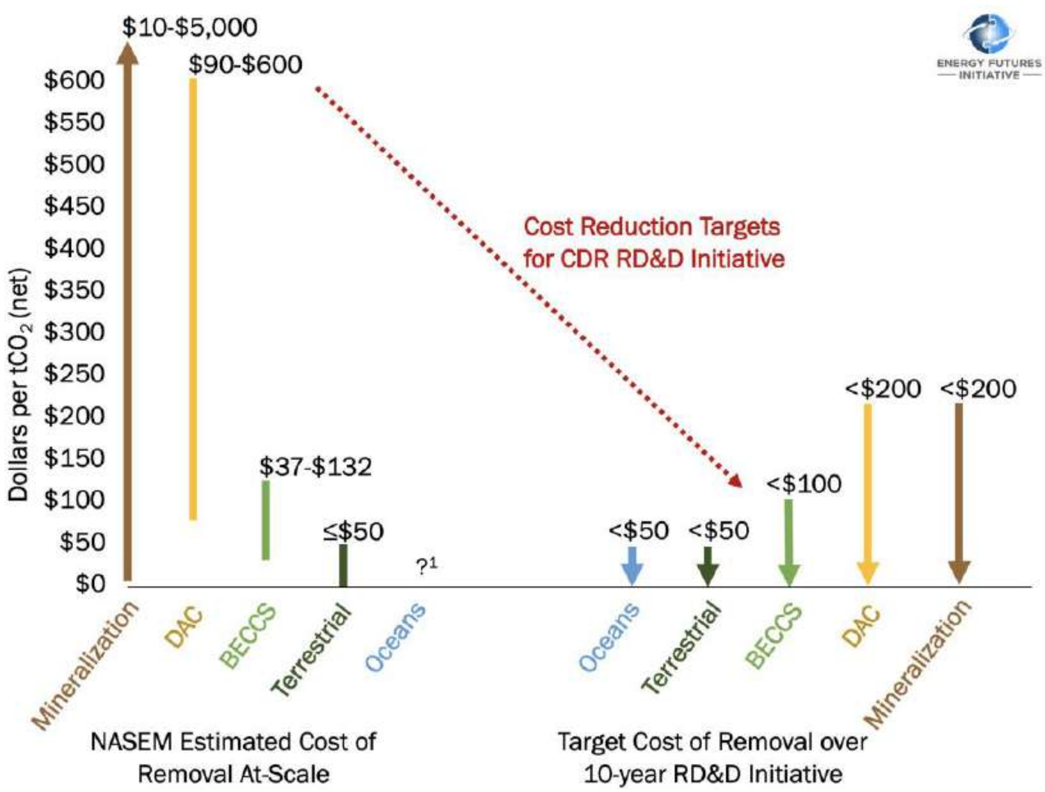
The process of moving innovations into the marketplace generally follows these four stages; however, this process can be non-linear as a result of feedbacks stemming from technology scale up, demonstrations, and learning by using. Source: EFI, 2019.

The core objectives supporting this RD&D initiative fall into two categories: potential for scale and technology cost. These categories follow from the considerations of the need for CDR in climate strategy. In order to have a material impact on climate outcomes, technological pathways for CDR must achieve certain relevant scales at acceptable economic costs so they can be deployed within climate-relevant timeframes. The candidate technologies must simultaneously be mapped to efforts at various stages of the RD&D pipeline, considering the needs for fundamental research, applied technology development, and pilot-scale demonstrations.

Technology-Specific Cost Objectives

The ultimate challenge in setting the RD&D cost objective is to strike a balance between the necessary (bringing costs down to where policy or market factors can drive deployment) and the realistic (establishing a target that can potentially be achieved). The proposed programmatic cost objective is to drive down the cost of multiple CDR technology pathways (at material scale) to technology-specific cost targets (Figure S-4)[8] defined as dollars per tCO_2 (net), where the use of net tons reflects the fact that it is only meaningful from a climate perspective to use a full lifecycle analysis of the CO_2 removal amount (including emissions due to energy or materials consumption in the removal

Figure S-4
CDR RD&D Initiative Cost Targets



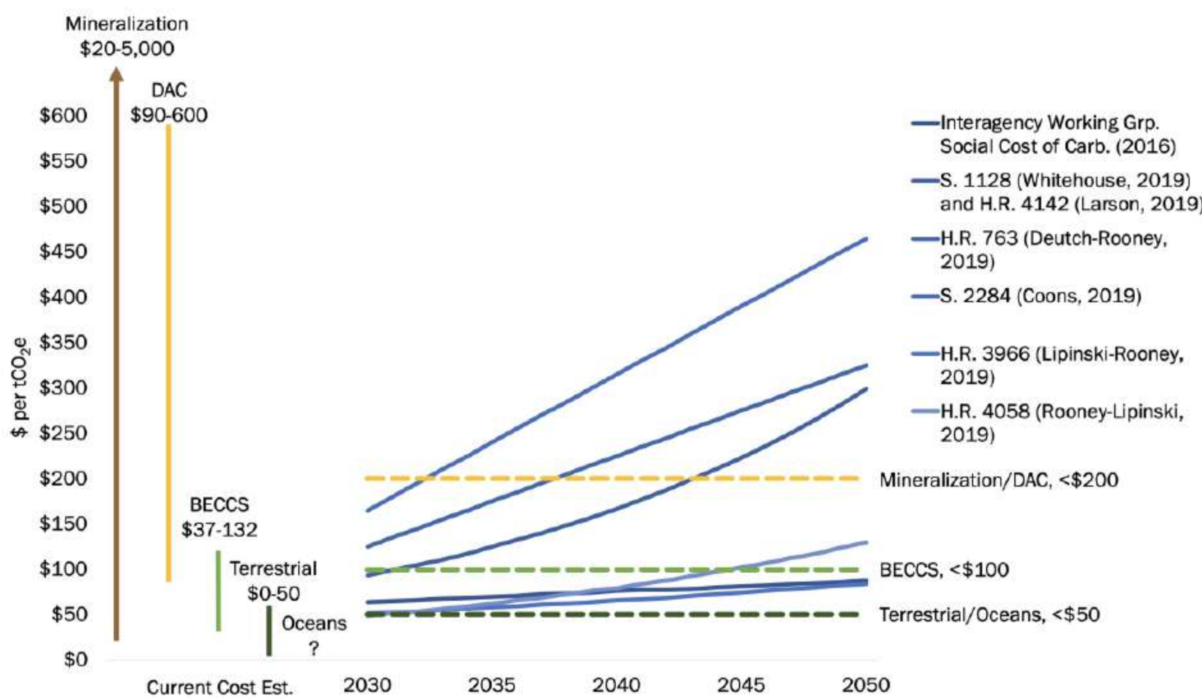
The CDR RD&D initiative cost targets are technology-specific given the high degree of cost uncertainties for various CDR capture technology pathways. [1]Cost estimates were available for blue carbon but not for other oceans-related CDR pathways. Source: EFI, 2019. Compiled using data from the National Academies of Sciences, Engineering, and Medicine.

process). The cost targets are technology-specific, and will narrow the range of cost uncertainties reported in the literature[9] that are defined by large variations within and across CDR technologies. There will also be a need to establish a rigorous process for estimating costs on an equal footing across the range of energy technologies.

The CDR RD&D initiative does not encompass deployment policies or measures, but the selection of technology options for RD&D support is informed by deployment potential. There currently is no comprehensive U.S. policy that directly or indirectly places a price on carbon. The cost targets for technological CDR approaches is guided in part by estimates of technology potential and market potential. One indicator of market potential is the possible range of carbon prices in legislative proposals currently pending in Congress. Figure S-5[10,11,12] compares proposed carbon pricing policies from the 116th Congress and the social cost of carbon to both the NASEM estimated costs for CDR removal at scale and target costs of removal over the 10-year CDR RD&D initiative. This comparison shows that a CDR RD&D initiative that demonstrates multiple pathways at the proposed cost targets can successfully lead to a major CDR deployment program under a range of carbon pricing proposals currently in Congress.

Figure S-5

Benchmarking the Cost of CDR Technologies, Now and 2030



RD&D-driven cost decreases, as well as price support in the form of carbon pricing, could both be necessary to achieve CDR deployment on the required scale. Source: EFI, 2019. Compiled using data from the National Academies of Sciences, Engineering, and Medicine; Interagency Working Group on the Social Cost of Carbon; C2ES.

Deployment Scale Objective

To be effective, technological CDR ultimately needs to be deployed at very large scale. The 2018 National Academies of Sciences, Engineering, and Medicine (NASEM) report entitled *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda* identified the need for CDR at a scale of approximately 10 billion metric tons ($GtCO_2$) per year globally by midcentury and 20 $GtCO_2$ per year globally by 2100 to achieve climate goals while accounting for economic growth. Capturing carbon from the environment at that scale would require the creation of new industries comparable in size to the steel, concrete, and petroleum industries of today.[13] For example, 1 $GtCO_2$, when liquefied during subsurface sequestration, is nearly 9 billion barrels of supercritical CO_2, equivalent to twice the current annual U.S. domestic oil production.

It is worth noting in the context of material scale that three of the major economic sectors in the United States emitted CO_2 at or near the gigaton scale through fossil fuel combustion in 2017: transportation (1.8 $GtCO_2$); electricity (1.7 $GtCO_2$); and industry (0.8 $GtCO_2$).[14] Achieving a similar scale through CDR will require the active participation of private sector entities. Therefore, an important feature of any comprehensive effort to develop and deploy CDR pathways at material scale will be a strategic view of how to incentivize industries to actively support and adopt CDR into their business practices.

Modeling and scientific studies point toward the need to deploy technological CDR methods at or near gigaton scale per year in order to provide a material contribution to meeting science-based climate goals. This benchmark should be considered as a guideline; there may be innovative or disruptive ideas for technological CDR that could have niche applications.

Portfolio Structure for the CDR RD&D Initiative

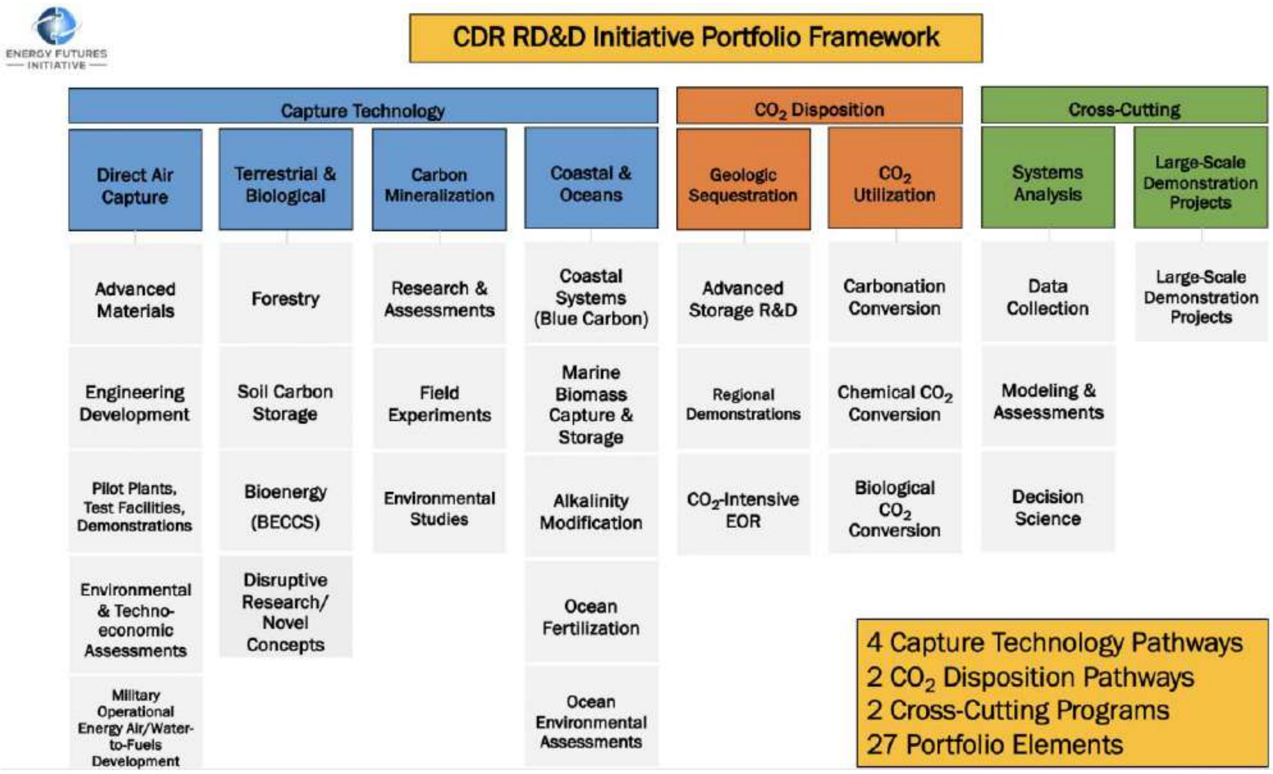
The proposed technological CDR RD&D portfolio framework consists of:

- Four capture technology pathways (DAC, terrestrial and biological, carbon mineralization, coastal and oceans). For the terrestrial and biological, carbon mineralization, and many coastal and oceans CDR pathways, sequestration is an integral part of the capture mechanism;
- Two CO_2 disposition pathways (geologic sequestration, CO_2 utilization). The two CO_2 disposition pathways are needed primarily to support DAC, BECCS, and oceans direct capture options; and
- Two cross-cutting programs (systems analysis, large-scale demonstration projects) that provide holistic or common services applicable to all of the CDR pathways.

Figure S-6 illustrates the portfolio design. The organization of the four capture technology pathways largely stems from those discussed in the NASEM report, but were expanded to include CDR in the deep oceans. Each of the capture technology pathways and CO_2 disposition pathways contain specific RD&D needs and challenges at different stages of the research process, which are explained in detail in the subsequent chapters. In total, the RD&D portfolio comprises 27 separate elements.

Figure S-6

CDR RD&D Initiative Portfolio Framework



The CDR RD&D portfolio consists of four capture technology pathways, two CO_2 disposition pathways, and two cross-cutting programs. Source: EFI, 2019.

Direct Air Capture (DAC)

DAC uses heat and electricity to separate CO_2 from ambient air with various sorbent or solvent materials. DAC processes are energy intensive; low-cost, carbon-free process heat is a key requirement. Current cost estimates for DAC vary widely and are subject to considerable uncertainty. Little is known about its longevity under real-world conditions. However, DAC has a very large potential scale for CDR. The overarching RD&D objective for DAC is to reduce the cost and energy use and improve the performance and durability of DAC technologies to be a viable option for CDR. The components of the RD&D portfolio include: (1) fundamental research on the development of new sorbent and solvent materials; (2) applied research and development on components and system-level integration; (3) full-system scale up and manufacturing research; (4) research on cost, lifecycle emissions, and environmental impacts; and (5) applied technology development of air-to-fuels and seawater-to-fuels systems for military use at forward operating bases and at sea.

Terrestrial and Biological CDR

Terrestrial and biological pathways include increased growth of trees to store carbon as living or dead woody biomass (afforestation and reforestation), increased storage of carbon in the soil by crops and other herbaceous plants (soil carbon), and BECCS. Forest-related techniques require improved monitoring systems and expanded utilization and disposal options for woody biomass; soil carbon techniques require improved monitoring systems, the development of high-carbon-input crop cultivars, and better understanding of soil treatments; BECCS requires advances in biomass supply (including algae), as well as conversion to liquid fuels and electricity with carbon capture. Terrestrial and biological techniques are relatively mature, but their potential scale for CDR is limited by land availability and long-term permanence. The overarching RD&D objective for terrestrial and biological CDR is to develop new approaches for enhanced carbon uptake in trees, plants, and soils, in a manner consistent with advancing traditional food and fiber mission objectives. The components of the RD&D portfolio include: (1) enhanced monitoring systems, integrating modeling, and frontier techniques for forest carbon storage; (2) fundamental and applied research on carbon-relevant soil properties, soil carbon monitoring, advanced cultivars, biochar and reactive mineral impacts in agricultural soils, optimizing cultivation systems for carbon, and predictive modeling tool development; and (3) enhanced methods for biomass supply and pre-treatment (including algal biomass), and advanced technologies for biomass conversion to fuel, biochar, and biopower. High-risk, high-reward research on advanced CDR technologies relevant to agriculture will also be supported through the Agriculture Advanced Research and Development Authority (AGARDA).

Carbon Mineralization

CO_2 naturally reacts with a variety of minerals to form carbonates (such as calcite), a process that leads to long-term solid storage of carbon. These reactions cause natural weathering of rock formations over thousands of years; carbon mineralization CDR techniques seek to accelerate this process, by using various sources of minerals and exposing them to CO_2 in a variety of ways. Challenges for these techniques include identifying sufficient supplies of reactive minerals, minimizing energy and transport costs for CO_2 exposure and carbonate disposal, and understanding environmental impacts from the process. While relatively immature, carbon mineralization techniques have very large potential scale and may have low costs. The overarching RD&D objective for carbon mineralization is to enhance the understanding of the feasibility and potential for carbon mineralization as a CDR technology pathway. The components of the RD&D portfolio include: (1) fundamental research on geochemistry and rock physics to improve understanding of reaction rates and potential scale of CDR; (2) resource assessments to identify sustainable sources of reactive minerals; (3) applied research and field tests of surface and subsurface carbon mineralization methods (including mine tailings and industrial waste); and (4) research on environmental impacts.

Coastal and Oceans CDR

The oceans interact extensively with the atmosphere, and currently absorb a quarter of anthropogenic CO_2 emissions directly from air.[15] Coastal CDR techniques (also referred to as "blue carbon") envision encouraging the growth of plants in coastal environments such as salt marshes, mangroves, and seagrass meadows, and subsequent natural burial of their biomass in coastal soil. Ocean CDR techniques aim to accelerate the absorption of atmospheric CO_2 by the oceans, storing it as dissolved bicarbonate and/or carbon exported to the deep ocean; other techniques focus on cultivating macroalgae at sea and using the resulting biomass for a variety of purposes, accompanied by CO_2 capture and storage. These techniques are all relatively immature, with some being almost entirely untested. There is little information about the potential costs, but the theoretical scale is extremely large, reflecting the fact that the oceans naturally regulate planetary atmospheric CO_2 levels over millennia. The overarching RD&D objective for coastal and oceans techniques is to develop a better understanding of carbon removal processes in coastal areas and deep ocean waters to provide the basis for determining feasibility of future CDR implementation measures. The components of the RD&D portfolio include: (1) fundamental research and resource assessment for blue carbon coastal techniques; (2) regional field trials and database development for coastal CDR; (3) applied research on aquatic biomass cultivation, harvesting, and conversion; (4) fundamental research and small-scale applied field trials of ocean alkalinity modification; (5) fundamental research and preparation for small-scale applied field trials of ocean iron and macronutrient fertilization; and (6) fundamental research and modeling on environmental impacts from ocean and coastal CDR techniques.

Geologic Sequestration

Sequestration of CO_2 in geologic formations is a critical enabling technology for CDR; without validated, at-scale sequestration capability, removed CO_2 cannot be permanently kept out of the atmosphere. Techniques for geological sequestration are relatively well understood, although new approaches beyond saline aquifer storage are in development. Key issues include accurate and low-cost resource characterization, monitoring, and at-scale demonstration. The overarching RD&D objective for geologic sequestration is to determine the potential for large-scale (at or near Gt scale) geologic sequestration as a permanent storage option for captured carbon. The components of the RD&D portfolio include: (1) applied research on a range of advanced storage topics including reduction of seismic risk, improved site monitoring, secondary trapping, and CO_2 fate and transport simulation; (2) augmenting the existing DOE CarbonSAFE program by adding additional sites and accelerating the timetable for full site characterization; (3) regional large-scale CO_2 injection demonstrations at multiple sites characterized under CarbonSAFE; and (4) applied research and demonstration of techniques to co-optimize CO_2 injection and oil production in enhanced oil recovery (CO_2-EOR).

CO_2 Utilization

There are multiple technology pathways currently under development to utilize CO_2 for economically beneficial purposes. The largest of these by current volume is CO_2-EOR, but others include the production of liquid fuels, building materials, plastics, commodity chemicals, and advanced materials; accelerating plant and algal growth; and food & beverage production. Many of these techniques remain energy intensive or cost prohibitive. While the feasible potential scale of CO_2 utilization will not reach the total required for CDR as discussed above, utilization can provide revenues to compensate for the costs of early CDR deployment and help with technology development. The overarching RD&D objective for CO_2 utilization is to accelerate development of innovative carbon conversion processes and new carbon-based materials through carbon mineralization, chemical, and biological conversion. The components of the RD&D portfolio include: (1) fundamental and applied research on carbonation reactions and process integration with CO_2 capture; (2) resource assessment on alkalinity sources for carbonation; (3) applied research and demonstration of CO_2-based construction materials for buildings and roads; (4) fundamental research and systems integration for chemical conversion of CO_2 including catalyst development and reactor design; (5) fundamental research on engineered organisms for biological CO_2 conversion and bioprospecting; and (6) applied research on valorization of co-products from biological CO_2 conversion.

Cross-Cutting Programs

The portfolio design highlights activities that span all CDR pathways and disposition options. An expanded carbon data collection effort is proposed to develop comprehensive lifecycle data on carbon flows in the economy. Independent techno-economic assessments will provide the capability to periodically assess technological CDR alternatives on a common basis with the credibility of a third-party perspective. The integrated carbon systems modeling program will assess systems-level impacts of large-scale CDR deployment, reflecting environmental, social, and economic issues. The decision science program will assess socio-economic issues, such as risk analysis and societal acceptance, associated with large-scale deployment of CDR approaches such as geological sequestration.

The proposed CDR RD&D portfolio includes a major cross-cutting element for large-scale demonstration projects. The CDR technology demonstration program is proposed as a cross-cutting initiative because it incorporates an innovative program design. Specifically, the CDR technology demonstration program:

- Will be a technology-neutral program, supported by a separate fund; major technology demonstration programs are not budgeted separately within each CDR pathway portfolio;
- Will support demonstration projects competitively, based on threshold qualification criteria; not all CDR technologies will qualify for large-scale demonstration;

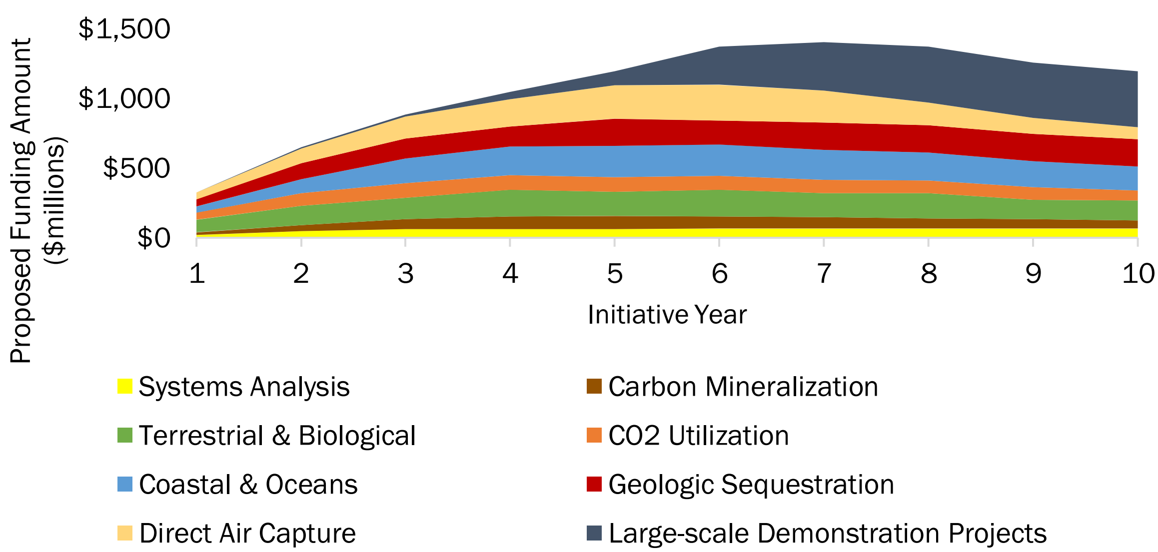
- Will be initiated several years after the start of the CDR research programs, to take advantage of early research results and not commit prematurely to technology concepts that may need further maturation;
- Will be operated with flexible and innovative cost-sharing arrangements to take maximum advantage of the Section 45Q tax credits and emphasize incentives for demonstration project performance; and
- Will be managed centrally by a new demonstration program office with robust project management expertise.

Recommended Budget Planning Estimates

Budget planning estimates were developed for each of the 27 portfolio elements. One or more agencies were identified to lead the RD&D work within each element, and the budget planning estimates reflect the proposed scope of work for that element.

The total RD&D initiative budget is estimated at $10.7 billion over the proposed 10-year span of the program. The proposed funding level for the first full year of the initiative is $325 million, with total initiative funding allocated among 10 federal departments and agencies. The total budget planning estimate for the first five years is $4,100 million (38 percent); the estimate for the second five years is $6,600 million (62 percent) but is contingent upon the evaluation of progress over the first five years (Figure S-7). The annual funding level ramps to $325 million in Year 1, reaches a sustained funding level of more than $1 billion per year in Year 4, peaks at $1,404 million in Year 7, and averages $1,320 million in the latter five years.

Figure S-7
CDR RD&D Initiative Proposed Total Funding by Year

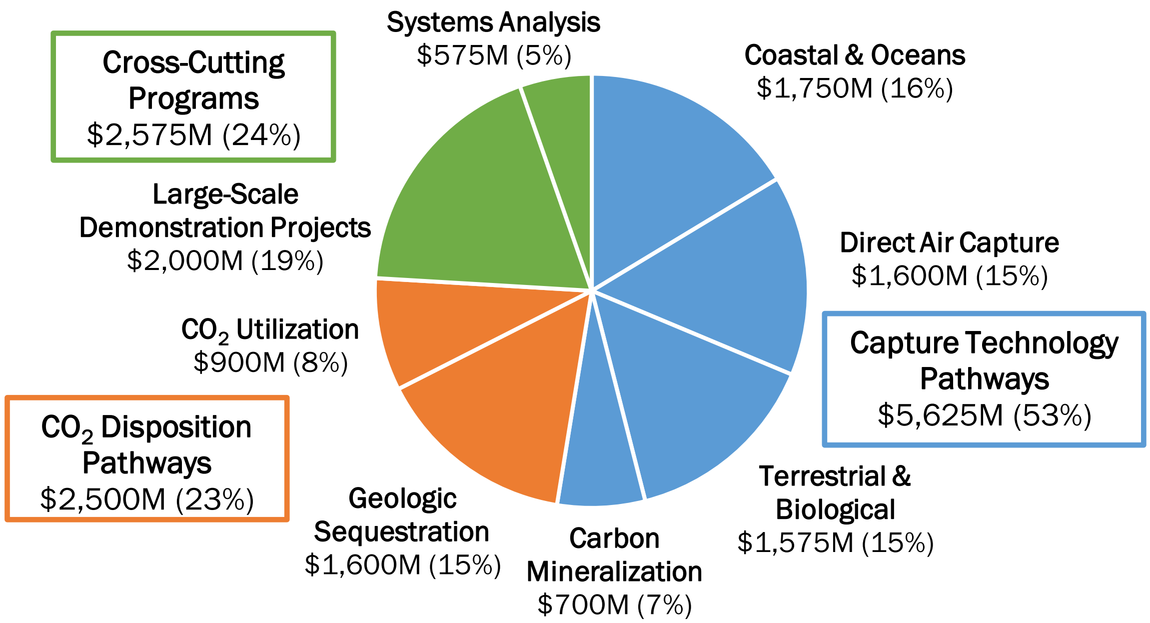


Proposed funding ramps to $325 million in Year 1 and peaks at $1,404 million in Year 7. Source: EFI, 2019.

The distribution of funding by portfolio component is illustrated in Figure S-8. Funding for the four capture technology pathways totals $5,625 million over 10 years (53 percent), while funding for the two CO_2 disposition pathways and two cross-cutting programs totals $2,500 million (23 percent) and $2,575 (24 percent), respectively.

Figure S-8

CDR RD&D Initiative Proposed Total Funding by Portfolio Categories



Proposed funding is divided between four capture technology pathways, two CO_2 disposition pathways, and two cross-cutting programs. Source: EFI, 2019

Achieving a diversified RD&D portfolio is essential, for several reasons. First, the alternative CDR pathways have widely varying degrees of technological maturity; the differences were clearly highlighted in the NASEM report. In short, it is too soon to declare a "winner." Second, because of the complexity of the carbon cycle, it is critical to understand the movement and interactions of carbon among the atmosphere, terrestrial biosphere, and oceans in response to removal of carbon in any one ecosystem. Third, while the various elements in the technological CDR portfolio may have Gt-scale deployment potential, there will be technology-specific limitations on deployment due to many factors. The NASEM report articulate the major factors, including land use and other environmental constraints, energy requirements, and public support and institutional issues.[16] Finally, CDR pathways have strong regional characteristics that need to be reflected in the CDR RD&D initiative. The feasibility of carbon mineralization will be dependent upon regional geology or locations of other reactive feedstock material; geologic sequestration locations are dependent upon subsurface geology, and in turn will affect the siting of BECCS and DAC facilities. The availability of carbon-free, low-cost energy sources for process heat will be critical to the economic feasibility of certain DAC technologies; atmospheric humidity and other environmental conditions will be critical to the operational performance of DAC (these differences are discussed in more detail in Chapter 2). These regional variations suggest that regionally-focused technological CDR RD&D programs may serve as an effective implementation strategy.

Dedicated funding allocations of up to 5 percent of the proposed budget planning estimates are recommended for novel, unconventional, and potentially disruptive technological CDR approaches that are not otherwise assumed within the scope of the RD&D portfolio elements. Advanced Research Projects Agency-Energy (ARPA-E), which is not specifically earmarked within the recommended RD&D portfolio, can play an important role. The standup of AGARDA within USDA also can be especially helpful. The fundamental and applied R&D program offices in DOE, USDA, NOAA, and other agencies also should seek to allocate funds to be positioned to flexibly respond to new ideas that might emerge over the course of the RD&D initiative.

The CDR RD&D initiative will involve proposed funding for 27 offices or organizations across 10 federal agencies, with a prominent role for DOE, USDA, and NOAA. DOE is proposed to receive more than $4.8 billion in funding (45 percent of the total), while USDA, NOAA, and the National Science Foundation (NSF) are each proposed to receive over $900 million. Funding would be enacted through six appropriations bills: Agriculture; Commerce, Justice, Science; Defense; Energy and Water; Interior and Environment; Transportation, Housing and Urban Development (HUD). Further details on allocations of the proposed budget planning estimates are provided in Chapter 9.

Federal Agency Organization and Management

The broad scope of the technological CDR RD&D initiative requires a whole-of-government approach involving numerous federal agencies that work in a coordinated manner to bring the alternative technological CDR pathways to commercial readiness. The proposed RD&D portfolio identifies research responsibilities for 10 federal departments and agencies, along with the participation of OSTP and OMB for the purposes of planning, budgeting, execution, and performance-tracking for the CDR RD&D initiative (Figure S-9).[a]

Achieving effective coordination in portfolio planning, budgeting, performance management and evaluation, and reporting to Congress, the scientific community, and the public will be challenging. This challenge is not unique; the federal government has successfully implemented other interagency science and technology initiatives in the past, and the lessons learned can serve to guide the technological CDR RD&D initiative.

[a] A previous analysis identified a baseline of nine federal agencies that historically supported RD&D activities related to CDR, which could help provide a framework for a federal CDR RD&D initiative. Individual RD&D projects related to CDR were funded in 23 separate appropriations accounts contained in five different appropriations bills.

Figure S-9

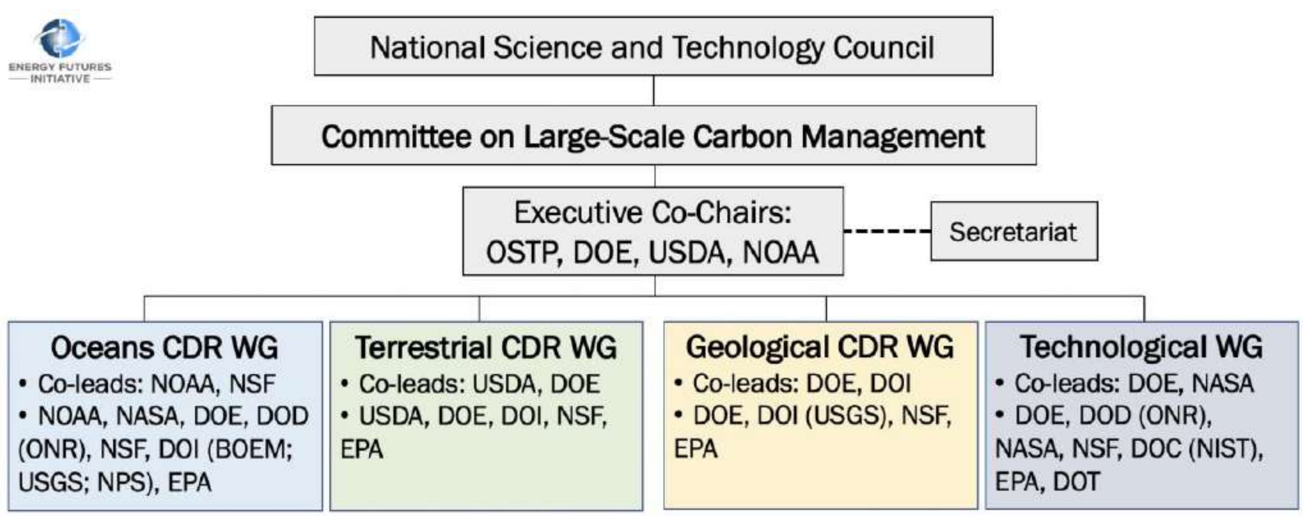
Federal Participation in CDR RD&D Initiative

Federal participation in the CDR RD&D initiative includes 10 agencies and EOP. Source: EFI, 2019.

Best practices were identified through a survey of lessons learned by experts involved in the implementation of prior federal RD&D initiatives. Drawing from this assessment, the recommended organizational framework for the technological CDR RD&D initiative is outlined in Figure S-10.

Figure S-10

Interagency Integration and Coordination



The CDR RD&D initiative would be governed by a new entity within the National Science and Technology Council. Source: EFI, 2019.

The proposed initiative would be governed by a new entity, the ***Committee on Large-Scale Carbon Management***, to be established within the National Science and Technology Council (NSTC). The new committee would be co-chaired by an Executive Committee comprised of the OSTP Associate Director for Science, and senior officials from DOE, USDA, and NOAA. Co-leadership is essential to reflect the key roles and responsibilities of these organizations in the overall planning of the initiative.

The Committee would have a broad set of responsibilities including:

- Developing a technological CDR RD&D strategic plan;
- Overseeing task forces responsible for more detailed RD&D road-mapping;
- Coordinating budget planning with the agencies and budget review with OMB;
- Identifying candidate CDR technologies for large-scale demonstration;
- Overseeing independent evaluations of program performance; and
- Providing an annual report to Congress and the public.

It is recommended that OMB assist in the coordination of the technological CDR RD&D initiative by conducting an annual budget crosscut review. The budget crosscut would have two principal objectives: ensure that budget proposals from the program offices with technological CDR RD&D responsibilities are integrated with the overall budget for each participating department and agency, and ensure that the various OMB staff review and act on agency budget proposals for technological CDR RD&D elements in a holistic fashion. The OMB budget crosscut would be provided to Congress as part of the President's budget. The crosscut process can thus act as the "glue" to ensure that the CDR RD&D initiative is implemented in a fully integrated manner.

In short, the roles and responsibilities of OSTP and OMB are essential to make the interagency technological CDR RD&D initiative function effectively. Implementation of these recommendations could be initiated by Presidential Executive Order. Congressional authorizing legislation would ultimately be desirable; historically, Congress has acted on authorizing legislation for new interagency science and technology initiatives promptly in response to Executive Branch proposed initiatives.

The programmatic roles and responsibilities for each of the 10 departments and agencies are identified at a high level in the proposed CDR RD&D portfolio design. This serves as the starting point for further delineation of organization and management responsibilities within each agency. As discussed further in the chapters that follow, the technological CDR RD&D portfolio elements comprise a combination of augmentation of existing research programs as well as the establishment of new ones. This in turn will require a combination of new coordination processes and structural changes in individual agencies.

Three federal agencies in particular—DOE, USDA, and NOAA within the Department of Commerce (DOC), are proposed to be responsible to lead major elements of the CDR RD&D initiative. These three agencies have extensive existing research infrastructure and relatively large research and development (R&D) budgets that will require some realignment in order to effectively incorporate CDR RD&D into their mission objectives. NSF also is proposed to have significant research responsibilities within the CDR RD&D

initiative, but these new research activities are readily incorporated into the existing NSF organizational and program structure.

The recommended organizational structural and process changes for DOE, USDA, and NOAA are discussed in more detail in Chapter 9. The key recommendations include:

- DOE: Establish an interim organization for Large-Scale Carbon Management within the Office of Fossil Energy, headed by a new Deputy Assistant Secretary selected on the basis of scientific qualifications appointed for a term basis. Longer term, Congress should consider re-establishing the Office of Under Secretary for Science and Energy, which would provide a more appropriate longer-term organizational home for the CDR program.
- NOAA: Incorporate CDR as a new strategic objective within its Oceans Research Plan and establish a new Office of Ocean Technologies within the Office of Oceanic and Atmospheric Research, headed by the Chief Scientist.
- USDA: Incorporate CDR as a new strategic element within the Department's research focus, incorporate CDR in appropriate existing research programs across the Department, and designate the Under Secretary for Research, Education, and Economics as the lead coordinator for all CDR-related research activities. USDA also should stand up the newly authorized AGARDA and assign CDR a high priority for this organization.

International Collaboration on Technological CDR RD&D

CDR is a critical tool for addressing past problems by removing CO_2 from the environment previously emitted from anthropogenic sources. It is thus a global challenge and an international responsibility. Other countries are currently sponsoring research on technological CDR approaches. This report recommends a major new U.S. initiative. This effort can and should catalyze additional efforts among other countries; collectively, these efforts can be more efficient and effective.

Climate change is a global challenge, and the scale of CDR needed to meet that challenge—100 to 1,000 $GtCO_2$ on a global level cumulatively removed by 2100 according to the Intergovernmental Panel on Climate Change (IPCC)[17]—is more than one country can feasibly address within its own borders. Additionally, CDR pathways typically have few geographic requirements and can be carried out in nearly any country. Coordinating effort is also important because innovation in CDR technologies and approaches could be accomplished more effectively and rapidly if countries create durable RD&D collaborative frameworks that facilitate pooling of both intellectual and monetary resources. The implementation process emerging from the 2015 Mission Innovation initiative appears to have the characteristics needed to make effective and efficient international collaboration in technological CDR a reality.

There are also facets of CDR that will specifically require international collaboration because they could have legal and regulatory impacts that cross borders. Several CDR pathways involve practices that are already governed by international law, such as ocean fertilization[b] or biological sequestration with genetically modified organisms.[c] Other pathways pose issues that are common to any country contemplating deployment of geologic sequestration. These include technical issues, such as induced seismicity, as well as legal and regulatory issues, such as monitoring, reporting, and verification (MRV) for sequestered carbon. Common legal and regulatory frameworks around these issues, built upon a shared understanding of the science and technology base, will be essential to ensure effective deployment of CDR on a gigaton scale globally.

Another important component of building durable international collaboration efforts is establishing ground rules for the management and sharing of intellectual property (IP). Safeguarding U.S. IP is crucial to stimulating innovation around CDR; without those protections, the economic motivation for innovation could be diminished. At the same time, knowledge-sharing across international borders is important to global deployment of CDR methods. The federal government will need to work closely with international partners to find the appropriate balance between protecting the IP of CDR innovators while ensuring that all countries have the opportunity and incentives to deploy CDR at the needed Gt-scale. The resolution of an appropriate policy for international collaboration in CDR IP is a complex issue beyond the scope of this report; it is, however, important that CDR IP rights and sharing policies be addressed as part of the implementation process for the proposed technological CDR RD&D initiative and discussed in the appropriate international fora.

Value Added from the Proposed CDR RD&D Initiative

The proposed initiative is designed to offer significant value in several ways:

- The proposed initiative is highly focused to deliver commercial-ready CDR innovations within a decade to address the mounting climate crisis. A $10.7 billion investment is small compared to the potential range of economic damage resulting from unchecked climate change.
- The CDR technological pathways provide additional optionality and flexibility to help limit temperature increases in the most cost-effective manner possible, as well as reverse atmospheric CO_2 concentrations resulting from past emissions.
- CDR RD&D innovations can also benefit other national research objectives in ocean ecosystems and fisheries restoration and management, forest and agriculture productivity, and resource conservation; and national security.
- The large-scale deployment potential for CDR innovation offers significant economic benefits in terms of new industries and new jobs on a global scale.

All of these factors shape the value proposition for a new federal CDR RD&D initiative.

[b] The London Convention/Protocol applies to this topic. The U.S. is a signatory to both agreements.
[c] The Cartagena Protocol applies to this topic, although the U.S. is not a party to this agreement.

1 https://www.pbl.nl/node/65210
2 https://www.unenvironment.org/resources/emissions-gap-report-2017
3 https://www.globalcarbonproject.org/carbonbudget/18/files/Norway_CICERO_GCPBudget2018.pdf
4 https://www.globalcarbonproject.org/carbonbudget/18/files/Norway_CICERO_GCPBudget2018.pdf
5 https://rhg.com/research/final-us-emissions-estimates-for-2018/
6 https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide
7 https://www.ipcc.ch/sr15/chapter/summary-for-policy-makers/
8 https://www.nap.edu/catalog/25259/negative-emissions-technologies-and-reliable-sequestration-a-research-agenda
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11 https://19january2017snapshot.epa.gov/sites/production/files/2016-12/documents/sc_co2_tsd_august_2016.pdf
12 https://www.c2es.org/site/assets/uploads/2019/07/carbon-pricing-proposals-in-the-116th-congress.pdf
13 http://web.mit.edu/chemistry/deutch/policy/2018-ResOppCO2Utiliz-Joule.pdf
14 https://www.epa.gov/sites/production/files/2019-04/documents/us-ghg-inventory-2019-main-text.pdf
15 https://sos.noaa.gov/datasets/ocean-atmosphere-co2-exchange/
16 https://www.nap.edu/catalog/25259/negative-emissions-technologies-and-reliable-sequestration-a-research-agenda
17 https://www.ipcc.ch/sr15/chapter/spm/

Part I
Framing & Initiative Overview

CHAPTER 1.
TECHNOLOGICAL CARBON DIOXIDE REMOVAL:
WHY, HOW, AND WHAT

There is increasing interest in technological carbon dioxide removal (CDR) as an essential element to address the mounting climate crisis. As used in this report, *technological* CDR refers to a portfolio of approaches to technologically enhance the functioning of natural carbon dioxide (CO_2) removal systems or directly remove CO_2 from the environment. CDR approaches are also referred to as negative emissions technologies (NETs) in other studies.

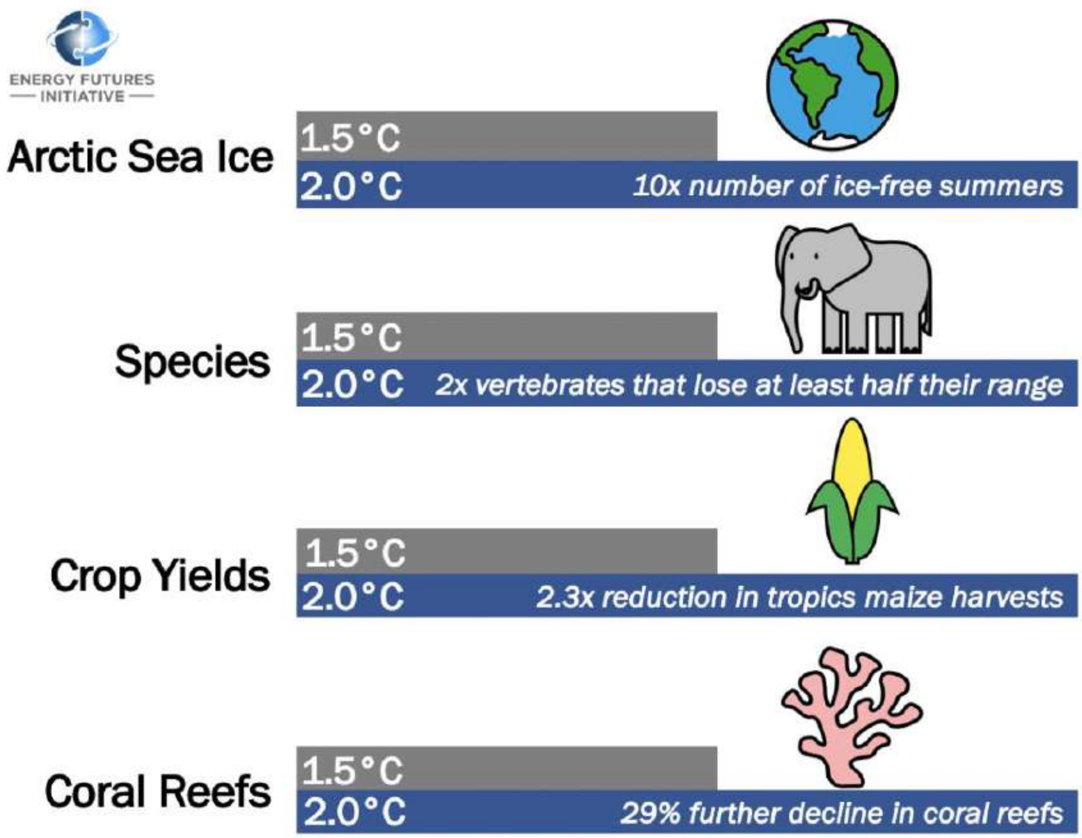
Why is Technological CDR Essential?

Major carbon-emitting countries are not on track to meet the targets they agreed to in Paris; growing evidence highlights the need to move from a 2°C to 1.5°C warming limit; and many governments are responding by adopting “net-zero” emissions targets to balance GHG emissions with an equivalent amount of carbon removal and sequestration. This is where CDR comes into play. Achieving global net-zero emissions is simply not credible without major carbon-negative contributions at considerable scale. Investment in CDR is essential.

Since 1992, there has been increasing ambition in the international community focused on measures to reduce GHG emissions, leading to the Paris Agreement in 2015, where 195 countries committed to “holding the increase in global average temperature to well below 2 degrees Celsius above pre-industrial levels and pursuing efforts to limit the temperature increase to below 1.5 degrees Celsius above pre-industrial levels”;[1] 185 of the 195 parties have since ratified the Paris Agreement.[2]

More recent evidence shows that the 2°C goal adopted in Paris may be insufficient to avert serious climate change damage. The Intergovernmental Panel on Climate Change (IPCC) recently highlighted the significant differences in impacts on the planet’s ecosystems between a 1.5°C and a 2°C temperature rise (Figure 1-1).[3,4] The IPCC Special Report on Global Warming of 1.5°C underscores the fact that every tenth of a degree Celsius matters.

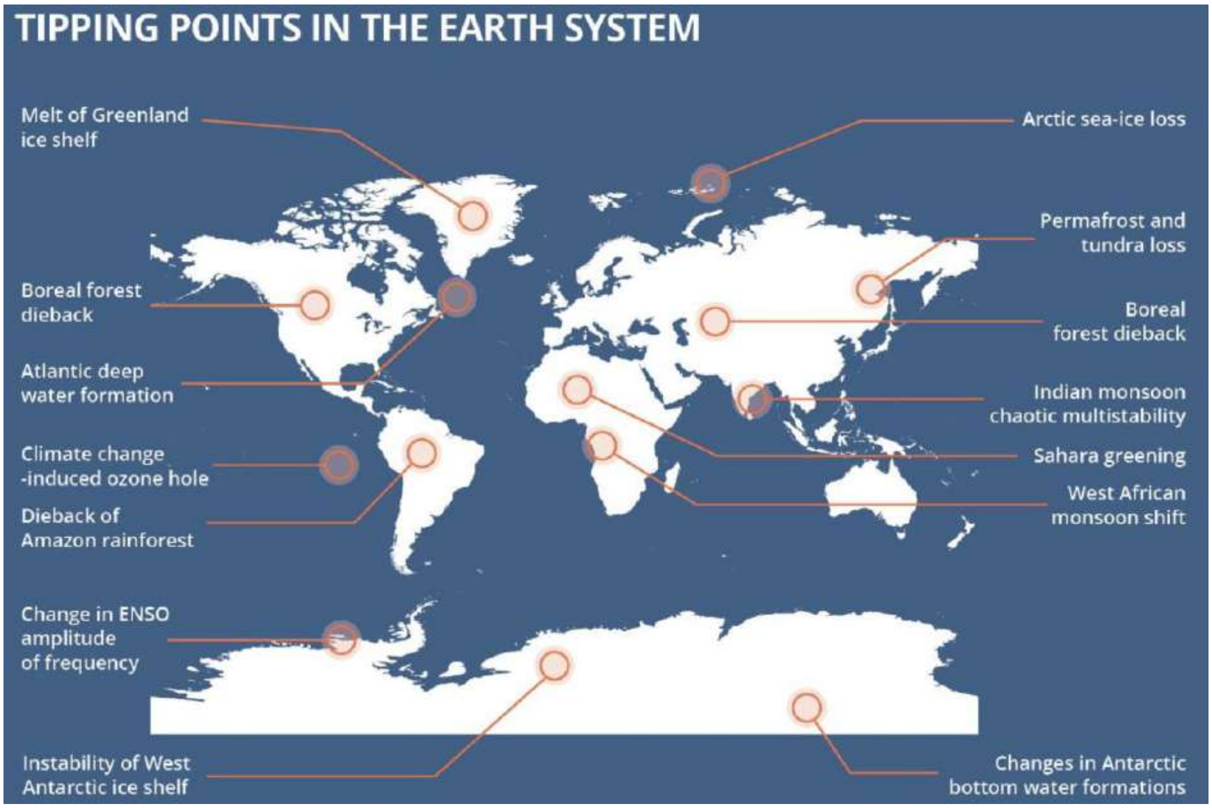
Figure 1-1
Comparing Impacts of 1.5°C and 2°C Warming Scenarios



IPCC projects significant differences in environmental impacts under 1.5°C and 2°C warming scenarios. Source: EFI, 2019. Compiled using data from IPCC and WRI (2018).

Not only is more ambition required to meet a 1.5°C warming goal, but action is required at a faster pace. There are indications that the impacts of warming are occurring at a faster rate than projected, with indications of potential tipping points in major environmental ecosystems. There are a number of global ecosystems potentially vulnerable to tipping points (Figure 1-2);[5] one of these—the Bering Sea—is illustrated in Figure 1-3.[6] These impacts to natural ecosystems make the natural, built, and social systems more vulnerable to unpredictable cascading events and impacts.

Figure 1-2
Potential Climate Change Tipping Points



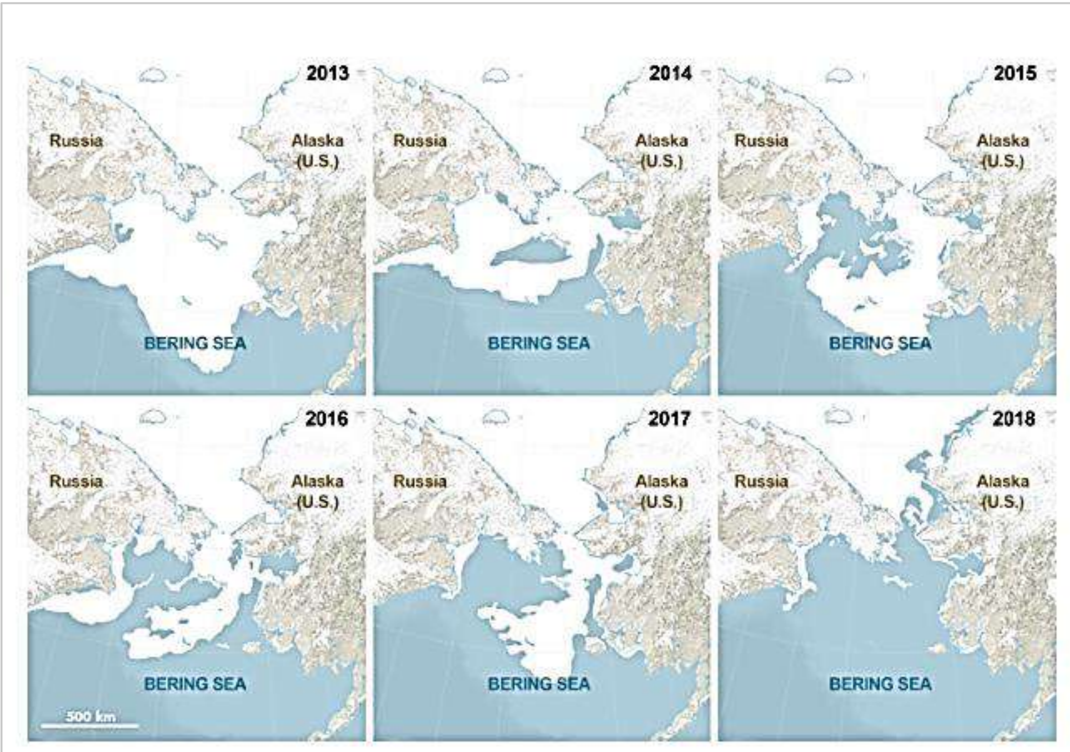
There are numerous potential climate change tipping points in Earth systems science. Source: Rockstrom, Global Challenges Foundation.

Current policies and programs to reduce GHG emissions are lagging at a time when increased ambition is being called for. Updated projections indicate that 2030 emissions reductions will fall short of the national commitments made during the Paris Agreement. As of 2018, two-thirds of the major carbon-emitting countries, including the United States, were not on track to meet the targets they agreed to in Paris.[7]

Recent data shows that over the past several years, global CO_2 emissions continue to increase, suggesting that current actions have yet to reach the scale needed to bend the emissions curve. In 2018, U.S. CO_2 emissions from fossil fuel combustion rose 2.7 percent while economywide emissions increased by 1.5 percent to 2.5 percent.[8]

Figure 1-3

Changes in Sea Ice in the Bering Sea: An Example of a Climate Change Tipping Point



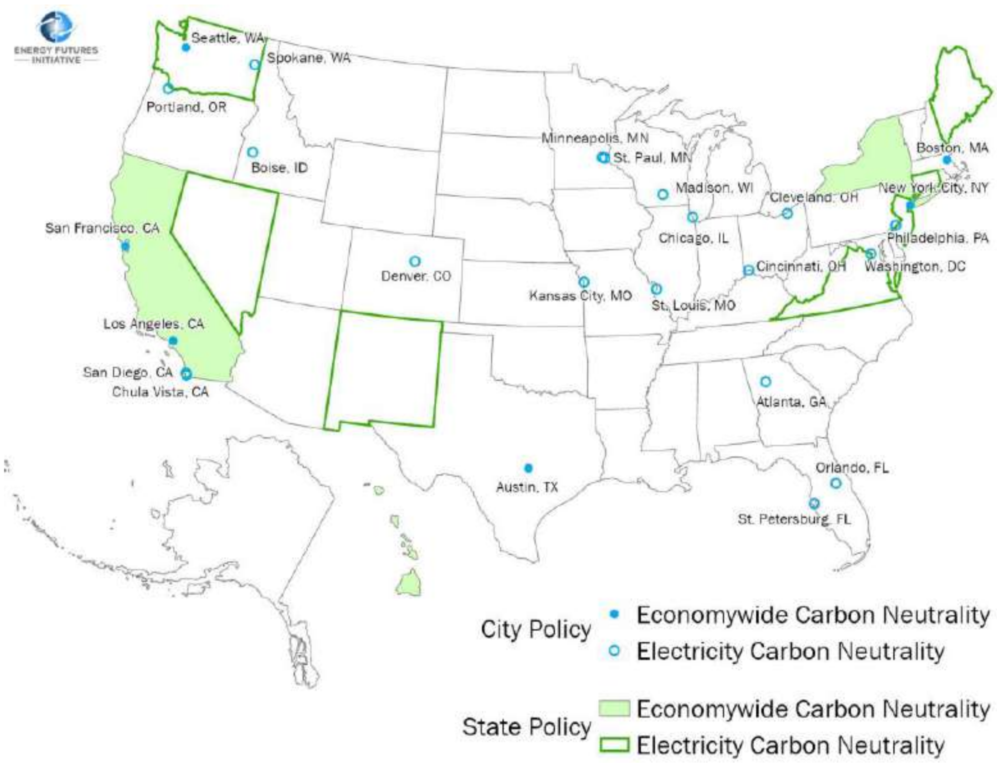
Using data from the National Snow and Ice Data Center, this series shows the maximum ice extent in the Bering Sea during April for the years 2013 through 2018. The year 2018 set the record for the least amount of sea ice dating back to 1850. Source: NASA Earth Observatory, Joshua Stevens.

Concerns about the inadequacy of collective efforts, a growing body of scientific evidence suggesting we are approaching climate tipping points, and current emissions trajectories have motivated further actions by many governments to move toward “net-zero” emissions targets by midcentury. Achieving net-zero emissions will require negative emissions from CDR to augment emissions reductions, compensating for residual emissions in difficult-to-decarbonize sectors like aviation that may be too difficult or expensive to eliminate from the economy. CDR is an essential component for any net-zero emissions scenario.

Ten U.S. states and 25 cities, which covers more than 30 percent of the U.S. population, have adopted net-zero emissions goals (either economywide or specific to the power sector) by midcentury (Figure 1-4). On the global level, the United Kingdom (UK), France, Portugal, Sweden, and some island nations have adopted net-zero emissions goals, and the European Union (EU) is currently considering a European-wide goal.

Figure 1-4

Net-Zero Climate Targets in the United States, September 2019



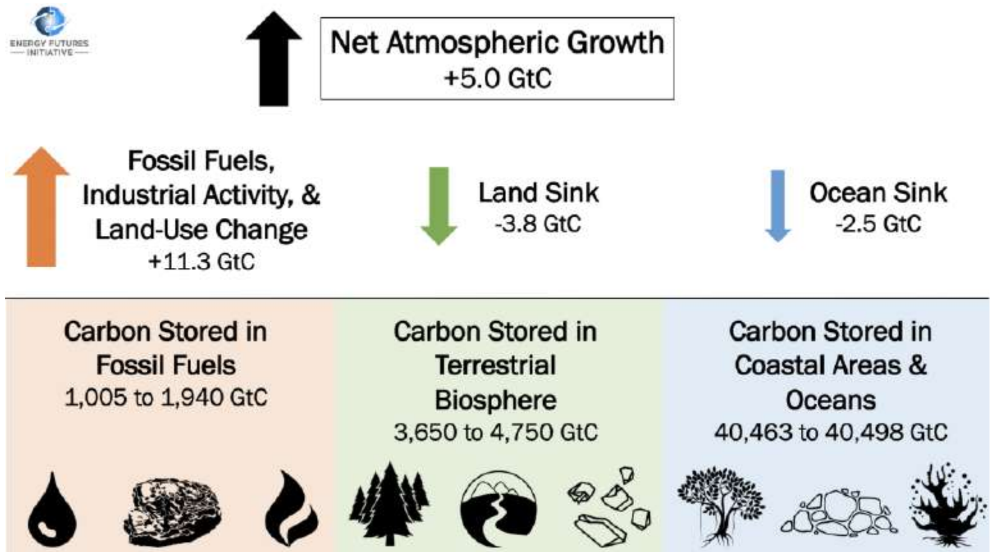
At least ten states and more than two dozen cities have adopted net-zero emissions targets across the United States. Note: Data as of September 2019. Source: EFI, 2019.

How Can Technological CDR Assist the Natural Carbon Cycle?

To understand more precisely what CDR is and its value for meeting both the Paris targets and net-zero emissions, it should be considered in the context of the global carbon cycle—the continuous exchange of carbon among the atmosphere, terrestrial biosphere, and oceans through both natural (e.g., photosynthesis and respiration) and anthropogenic (e.g., fossil fuel combustion) processes (Figure 1-5).[9,10]

Over long time periods, the carbon cycle has maintained a relative balance of carbon fluxes among these different systems and storage mediums. However, human activity has stressed the carbon cycle through the combustion of fossil fuels and land-use change, which has resulted in an imbalance of carbon fluxes and increasing accumulation of carbon within these storage systems. Of the total historical CO_2 emissions from human activities, about 45 percent has remained in the atmosphere, 30 percent has diffused into the oceans, and 25 percent has been absorbed by the terrestrial biosphere.[11]

Figure 1-5
Carbon Stocks and Flows in the Global Carbon Cycle, 2017



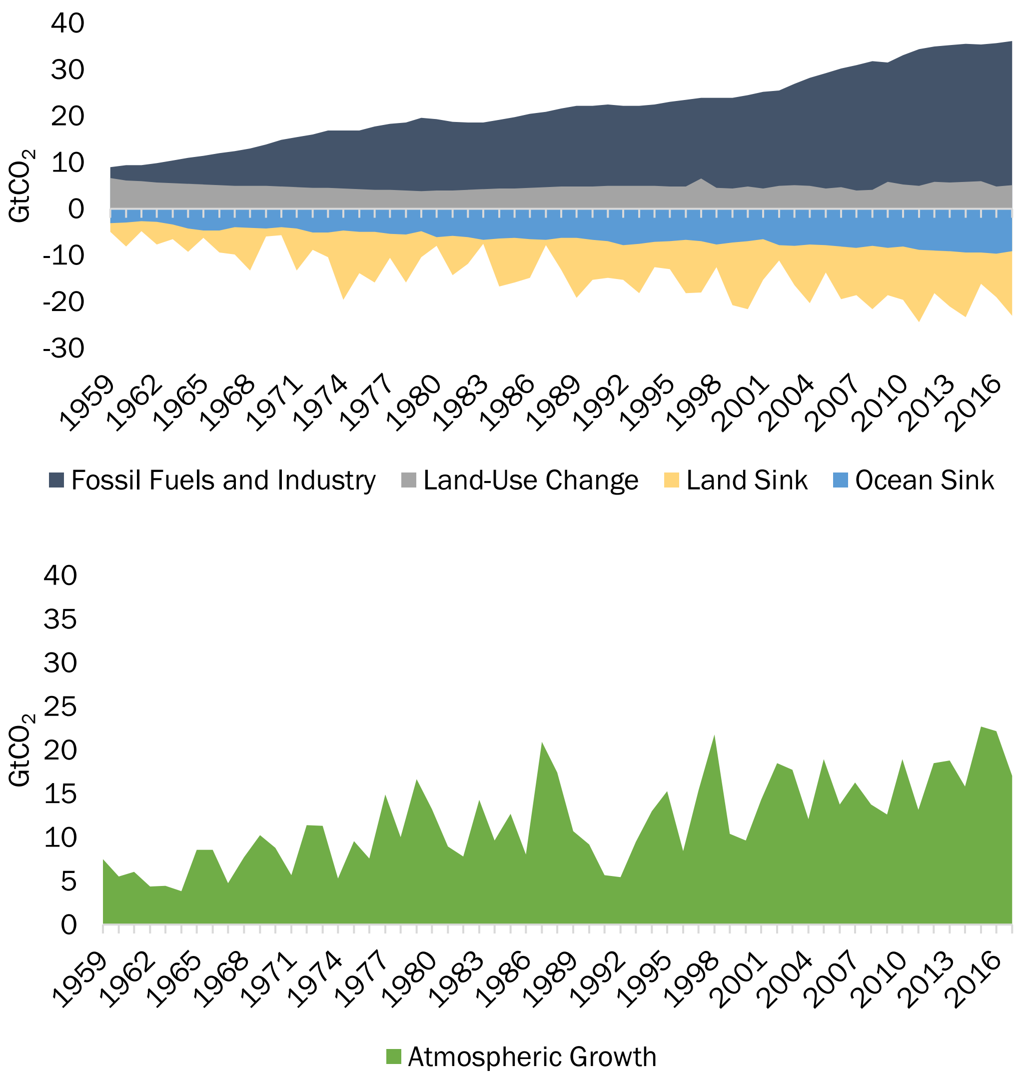
The global carbon cycle involves the exchange of carbon among the atmosphere, terrestrial biosphere, and oceans. Estimated carbon fluxes for the year 2017 correspond to the arrows; all other values represent estimated carbon stocks. Note: 1 GtC is equivalent to 3.664 $GtCO_2$. Source: EFI, 2019. Compiled using data from Global Carbon Project, 2018. Graphics from Noun Project.

The cumulative anthropogenic flux of CO_2 through the combustion of fossil fuels, industrial activity, and land-use change is a major perturbation of the global carbon cycle and the dominant driver of climate change. From 1959 to 2017, global CO_2 emissions from fossil fuels and industry increased from approximately 9.0 $GtCO_2$ in 1959 to 36.2 $GtCO_2$ in 2017, while CO_2 emissions from land-use change remained relatively steady at approximately 4.9 $GtCO_2$ per year. Over this 59-year period, the combustion of fossil fuels and industrial activity resulted in an estimated cumulative anthropogenic flux of 1,286.9 $GtCO_2$ along with an additional anthropogenic flux of 287.2 $GtCO_2$ from land-use change. Figure 1-6[12] illustrates how the rising levels of anthropogenic emissions has not been offset by the rate of natural CO_2 absorption, resulting in a net increase in atmospheric concentrations. These cumulative net fluxes of CO_2 emissions over time have led to corresponding increases in atmospheric CO_2 concentrations. The elevated concentration of CO_2 in the atmosphere, rather than the net flux rate in any given year, is the major determinant of subsequent warming. This underscores the importance of decreasing emissions immediately and to the maximum possible extent so as to avert the further rate of increase in atmospheric concentration levels.[13]

Technological CDR has the potential to help rebalance the global carbon cycle and reduce atmospheric CO_2 concentrations by increasing the amount of CO_2 that is removed from the atmosphere for permanent sequestration within the terrestrial biosphere, surface and subsurface geological formations, and oceans. Technological CDR can enhance natural carbon absorption (e.g., modifying biological species to increase the rate of carbon uptake and storage) or directly capture CO_2 in the atmosphere. Technological CDR can therefore counteract anthropogenic CO_2 fluxes from fossil fuel combustion and land-use change by reducing excess carbon stocks that have accumulated in the environment.

Figure 1-6

Global Emissions Sources, Sinks, and Net Atmospheric Accumulation, 1959-2017 ($GtCO_2$)



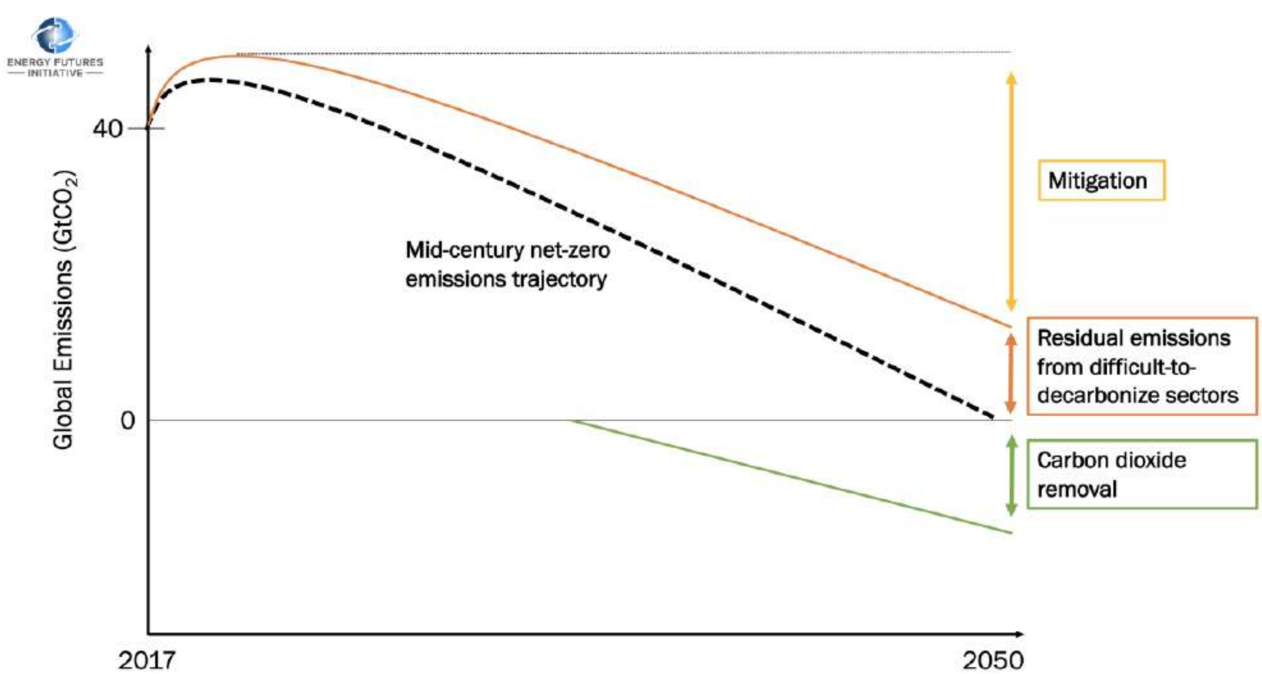
Anthropogenic CO_2 emissions stem from fossil fuels, industrial activity, and land-use change. The terrestrial biosphere (land sink) and oceans absorb a proportion of the emitted CO_2 from the atmosphere, while a considerable proportion remains in the atmosphere. Source: EFI, 2019. Compiled using data from the Global Carbon Project, 2018.

How Can Technological CDR Complement GHG Emissions Mitigation Actions?

Technological CDR can complement GHG emissions mitigation measures to reach net-zero emissions and reduce atmospheric CO_2 concentrations, which have been increasing at a rate of 2-3 parts per million (ppm) per year[14] with a commensurate rate of warming of 0.2°C per decade. Consequently, the planet will likely be committed to the lower temperature target of 1.5°C by as early as 2030.[15] Achieving net-zero emissions will be nearly technically impossible and economically prohibitive if relying solely on the mitigation technologies and strategies commercially available today. Accelerating the pace of innovation in energy technologies, policies, and business models is essential for expanding the potential for mitigation; opening the aperture to include technological CDR expands the suite of options for policymakers to address climate change. It can provide more flexibility and optionality in policy planning, which could ease the transition to a low-carbon and ultimately carbon-neutral economy while minimizing transition costs and providing greater assurance that science-based climate goals can be met in a timely manner. The complementary nature of mitigation and technological CDR is illustrated in Figure 1-7.

Figure 1-7

Complementary Nature of Mitigation and Carbon Dioxide Removal



This illustration shows how technological CDR can play a complementary role to mitigation in order to achieve midcentury climate targets. Source: EFI, 2019.

The development of CDR technologies could also offer opportunities for economic competitiveness through the formation of new export markets, the ability to achieve co-benefits with other science and technology objectives (such as greater food productivity), and risk management from the economic damages incurred by climate change ($450 billion has been spent for federal disaster assistance since 2005—including $91 billion in 2018 alone—due to weather and climate events).[16]

What Is the Scale Required for Technological CDR Deployment?

The scale of technological CDR needed to complement mitigation strategies to achieve science-based climate targets depends upon a wide range of factors, including the scale and cost of mitigation programs, rate of technological innovation, and willingness to accept uncertainty in modeling projections. Modeling studies by the IPCC indicate that the range of technological CDR to complement mitigation measures and natural carbon absorption to meet a 1.5°C temperature target is between 100 and 1,000 $GtCO_2$ removed from the atmosphere (cumulative) by 2100.[17] The 2018 National Academies of Sciences, Engineering, and Medicine (NASEM) report stated that technological CDR will need to be deployed at a scale to achieve CO_2 removal at a rate of 20 $GtCO_2$ per year by the end of the century.[18] This scale is daunting when considering that a CDR-deployment program at gigaton scale will place it in the same size as the domestic petroleum industry or the global steel industry (Figure 1-8).[19,20,21,22]

Figure 1-8
CDR at the Gigaton Scale

CDR at gigaton scale will require the emergence of a new commercial industry on a scale comparable to petroleum, steel, and other major industrial sectors. Source: EFI, 2019. Compiled using data from the U.S. Energy Information Administration; World Steel Association; and U.S. Environmental Protection Agency.

How Can a Portfolio of Technological CDR Pathways Contribute to Large-Scale Deployment?

Bioenergy with carbon capture and sequestration (BECCS) is currently the principal technological approach considered for CDR. BECCS has typically been the approach incorporated into the modeling of various climate strategies, but it has become apparent that BECCS alone cannot provide the needed scale for technological CDR (Box 1-1).

Box 1-1

The Potential Contribution of BECCS to CDR

Modeling studies by the IPCC and others have identified the contribution needed from technological CDR measures to complement emissions reductions. These modeling studies typically used BECCS as the principal alternative for CDR, since the technology performance and cost estimates are relatively well known.[23] The modeling analyses, utilizing integrated assessment models (IAMs),[24] have largely excluded other technological and technologically enhanced CDR measures, including direct air capture (DAC), carbon mineralization, and coastal and oceans capture, as these technologies have not been fully tested; and cost, performance, and scaling potential are not well defined. Reliance on BECCS alone, however, will be insufficient to achieve the level of CDR necessary to stay below the 1.5-degree Celsius target, due in part to the major land requirements—25 percent to 80 percent of current global cropland—that would be required for CDR on the scale needed of approximately 12 $GtCO_2$ per year.[25] The NASEM report reached a similar conclusion regarding BECCS, stating that, at best, existing approaches for CDR can be safely scaled to perhaps half the needed scale but will require "unprecedented adoption" at high cost.[26]

A number of other technological CDR approaches have been identified by the science community with varying degrees of research and development (R&D) support and technical readiness, but not at the technological maturity needed for large-scale commercial deployment. Expanded research, development, and demonstration (RD&D) efforts are needed to bring these additional technological CDR approaches to the stage of commercial readiness.

In view of the technical, cost, and other uncertainties, a portfolio approach is needed. The various alternative approaches for CDR—and the resulting options for disposition of the CO_2 once captured—are illustrated in Figure 1-9. This portfolio of options can augment the natural carbon absorption cycle in two ways: (1) by enhancing the capacity of natural systems to absorb CO_2 (e.g., technologically-enhanced or hybrid removal approaches) or (2) by directly absorbing CO_2 through chemical capture technologies (e.g., DAC and marine electrochemical capture). It is extremely important to note that technological CDR is distinct from geoengineering; CDR removes CO_2 from the environment in a manner that averts climate change impacts, while geoengineering involves the direct manipulation of sunlight hitting the earth, leading to changes in weather and climate without addressing the imbalance in the carbon cycle (Box 1-2). To borrow an analogy from health, geoengineering treats only the symptoms of the CO_2 "disease," while CDR seeks to repair the underlying causes.

Box 1-2

Carbon Dioxide Removal is Not Geoengineering

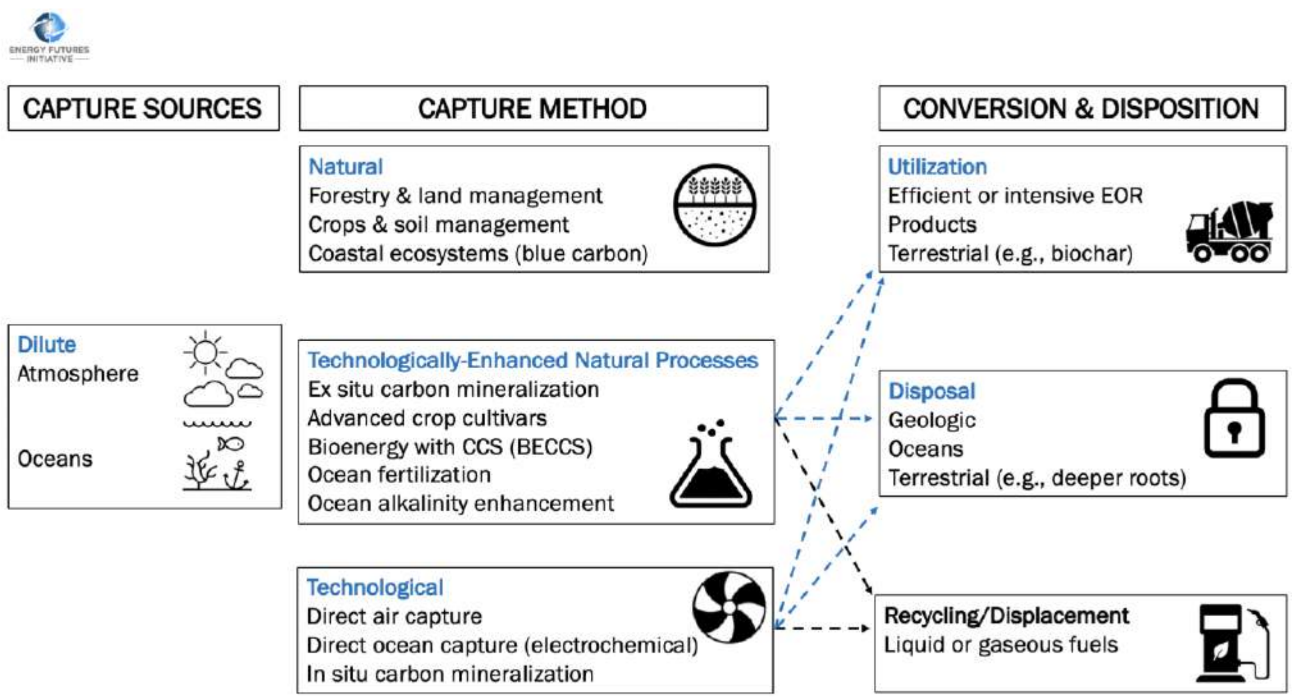
CDR is distinct from geoengineering concepts. The CDR pathways addressed in this report focus on removing CO_2 from the environment by either (1) technologically enhancing the operation of natural processes or (2) removing the CO_2 via chemical capture processes. Geoengineering typically refers to measures to directly modify weather or climate through means that do not address the carbon cycle, such as reducing the incidence of solar radiation on the Earth and thus increasing planetary albedo and reducing temperatures.

The *IPCC Special Report on Global Warming of 1.5 °C* describes the differences between the two concepts as follows: those that remove CO_2 from the environment (CDR) and those that alter the Earth's balance of solar radiation (solar radiation modification). This report addresses the former; it makes no recommendations with respect to the latter. Some stakeholder groups may seek to conflate the two concepts, leveraging possible public concern about the risks of large-scale geoengineering as an argument against CDR research. CDR is a necessary complement to a broad array of clean energy technologies, and any RD&D projects should be carefully prescribed within protocols set by the federal government and international scientific community.

The 2018 NASEM report provided the most detailed catalog of a portfolio of technological CDR approaches (other than deep oceans-based CDR), identifying the uncertainties associated with costs, scaling potential, and negative impacts (e.g., environmental, social, biogeophysical) of different CDR pathways (Table 1-1).[27,28] The report (which refers to technological CDR as NETs) concluded that some CDR pathways are relatively mature, while others have large potential but are immature. As a result, the principal recommendation of the report was that the United States "launch a substantial research initiative to advance NETs as soon as practicable" that would address several objectives: increase carbon removal potential and reduce costs and negative impacts across a variety of NETs; give particular attention to DAC and carbon mineralization, which have a nearly unlimited capacity for CDR; and simultaneously pursue research that enables CDR, such as geologic sequestration.[29]

The NASEM report, along with other recent scientific studies, have laid the foundation for the design of a CDR RD&D initiative. In view of the uncertainties and immaturity of some technological CDR approaches, optionality among the various types of CDR pathways will be critical to achieving material impact while minimizing potential negative impacts. The need for additional measures to address science-based climate goals, together with the broad national benefit that would result from technological CDR, provide justification for a federal role to advance a portfolio of technological CDR options through a new federal RD&D initiative.

Figure 1-9
Alternative Pathways for Carbon Dioxide Removal, Conversion, and Disposition



There are a variety of natural, technologically-enhanced natural processes, and technological pathways that can facilitate CDR through the capture of CO_2 from dilute sources. Source: EFI, 2019.

Table 1-1
CDR Pathway Characteristics Given Current Technology and Level of Understanding

Pathways	Implementation Cost at Scale ($/t$CO_2$)	Scaling Potential: Removal Rate ($GtCO_2$/yr.)	Scaling Potential: Removal Capacity ($GtCO_2$)	Potential Negative Impacts and Limitations
Afforestation, Reforestation, and Forest Management	$15 to $50	**U.S.**: 0.25 to 0.60 **Global**: 2.5 to 9.0	**U.S.**: 15 to 38 **Global**: 1,125 to 1,570	Warming effect at high latitudes; streamflow reduction in low-rainfall areas; land availability and competition with other productive land uses such as food and fiber; biodiversity loss (monocultures)
Agricultural Soil Management	$0 to $50	**U.S.**: 0.25 **Global**: 3.0	**U.S.**: 7 **Global**: 90	May increase N_2O emissions
Bioenergy with Carbon Capture and Sequestration (BECCS)	$70 (Electricity)	**U.S.**: 0.5 to 1.5	N/A	Land availability and competition with other

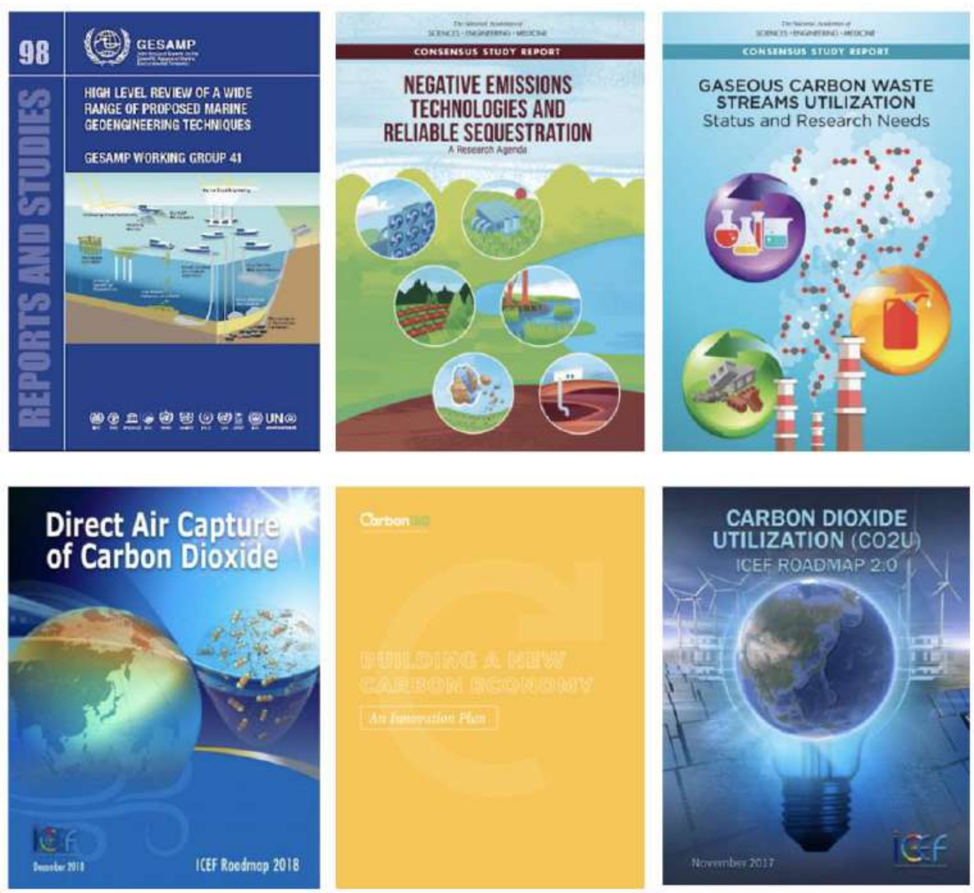
	$37 to $132 (Fuels)	**Global**: (3.5 to 5.2) to (10 to 15)		productive land uses such as food and fiber; biodiversity loss; changes in albedo; fertilizer pollution
Carbon Mineralization: Surficial Existing Tailings	$10 to $20	**U.S.**: 0.001 **Global**: 0.02 to 0.20	**U.S.**: <1 **Global**: 10	Water and air contamination
Carbon Mineralization: Surficial Mining and Grinding	$50 to $500	Unknown	Unlimited	Water and air contamination
Carbon Mineralization: Produce Alkaline Water from Calcite	<$10	N/A	N/A	N/A
Carbon Mineralization: In Situ Basalt and Peridotite	$20 to $5,000	Unknown	Unlimited	Groundwater contamination; induced seismicity
Coastal (Blue Carbon)	$10	**U.S.**: 0.024 to 0.050 **Global**: 0.13 to 0.80	**U.S.**: 0.26 to 4.0 **Global**: 8 to 65	Land availability and competition; sea-level rise
Direct Air Capture (DAC)	$90 to $600	Large	N/A	Large thermal and electrical energy requirements and associated emissions
Source: EFI, 2019. Compiled using data from the National Academies of Sciences, Engineering, and Medicine, 2018; Fuss et al., 2018.				

How Should a Federal Technological CDR RD&D Initiative be Designed to Deliver Large-Scale Deployment Options?

The NASEM report was the principal, but not the only, scientific report calling for the need for a technological CDR RD&D effort. There have been several other important reports on this topic (Figure 1-10); together, they provide the scientific grounding for the design of a new federal RD&D program. This report takes the NASEM and other reports as its starting point. The recommendations in this report provide the programmatic framework for designing a major new federal RD&D initiative for technological CDR approaches.

Figure 1-10

Selection of Recent Literature Concerning CDR



The proposed CDR RD&D portfolio design is drawn from existing literature. Source: EFI, 2019.

Strategic Framework for the CDR RD&D Initiative

A viable technological CDR RD&D initiative requires a focused goal, clear strategy, comprehensive portfolio, well-defined agency roles and responsibilities, adequate resources, and disciplined management. Each of these is described in turn in the following chapters in this report. The starting point for this effort can be summarized below.

The ***overarching goal*** of the CDR RD&D initiative is to provide policymakers a suite of technological CDR approaches that can safely augment the natural carbon cycle to complement mitigation efforts and reduce atmospheric CO_2 concentrations.

The ***strategy*** to achieve this overarching goal is to implement a comprehensive 10-year CDR RD&D initiative that will demonstrate the commercial readiness of multiple technological and technologically-enhanced CDR pathways that can be deployed at or near gigaton scale.

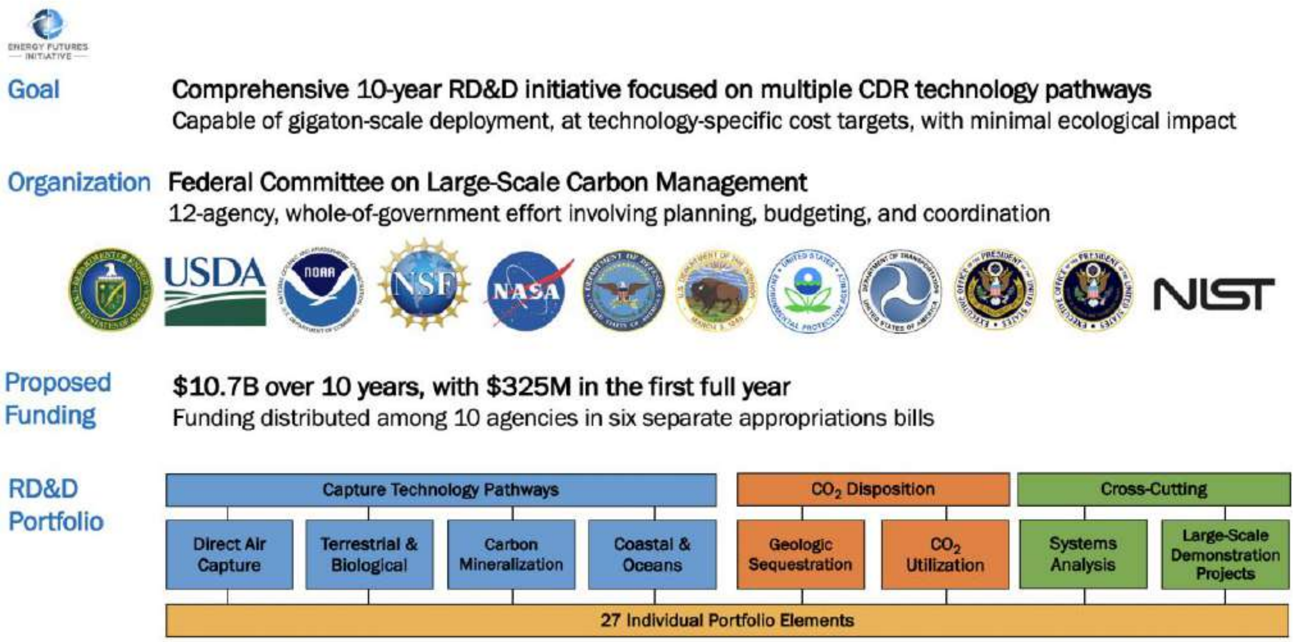
The ***strategic elements*** necessary to enable successful achievement of the goal are summarized below. Several of these elements—the scope of technology options, the span of innovation support, cost targets and deployment scale—merit further elaboration.

The strategic elements of the CDR RD&D initiative include:

- An effectively coordinated "whole-of-government" approach in addressing and coordinating CDR research needs;
- Incorporation of CDR into the strategic research mission objectives of the participating federal departments and agencies in a manner that creates synergy and complementarity with other national goals that can garner broad acceptance and be readily translated into specific projects with measurable progress and outcomes;
- A comprehensive and robust portfolio that:
    1. Reflects the full range of potential CDR pathways;
    2. Spans the full innovation spectrum from fundamental research to demonstration at scale;
    3. Addresses near-, mid-, and longer-term research opportunities; and
    4. Incorporates regional variation among technological CDR approaches.
- Clearly defined technology-specific cost objectives and commercial application potential;
- Carefully defined research protocols to fully address and promote collateral environmental and resource benefits and minimize any adverse environmental impacts;
- A logical and transparent initiative structure, with clearly defined management roles and responsibilities, and supporting budget plans, that can garner broad-based acceptance and be readily translated into specific projects with measurable progress and outcomes;
- Engagement with the international scientific community to accelerate the pace of RD&D progress and promote the application of CDR technologies on a global scale;
- A budget planning process reflecting the long-term nature of research projects, interagency coordination needs, and specific budget line item allocations;
- Effective and efficient utilization of the nation's technology innovation infrastructure; and
- Disciplined program management and accountability, including stage-gated processes and independent evaluations of program performance, with sufficient flexibility to change course when informed by research outcomes.

The organization, budget planning estimate, and RD&D portfolio structure for the CDR RD&D initiative is illustrated in Figure 1-11.

Figure 1-11
Carbon Dioxide Removal RD&D Initiative



Source: EFI, 2019.

Starting from the strong foundation provided in the scientific literature illustrated in Figure 1-10, a stepwise **methodology** was followed in organizing and defining the CDR RD&D portfolio:

1. Identifying all CDR pathways that have been reviewed by credible scientific organizations, including reports by NASEM,[30,31] the Innovation for a Cool Earth Forum (ICEF),[32,33] and the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP).[34]
2. Surveying credible estimates for the potential scale and cost of each CDR pathway, and whether the threshold for scale (at or near gigaton scale per year globally) and cost (technology-specific) could plausibly be met.
3. Reviewing the RD&D needs for each CDR pathway to determine if there is a sufficient need for further RD&D in order to make a material contribution to CDR (as opposed to only a primary need for deployment support).
4. Mapping the RD&D needs for the remaining CDR pathways to the federal agency (or agencies) and office/organization that have the most relevant authorization and expertise.
5. Developing detailed budget planning estimates over 10 years for each of the individual budget line items.

Organization of the Report

Subsequent chapters of this report discuss each of these components in more detail. The report includes an expansive research portfolio, organizational and management arrangement, and detailed budget planning estimates for the proposed CDR RD&D initiative. More specifically:

- Chapter 2 examines the role of DAC in the CDR RD&D initiative and profiles specific RD&D needs and priorities;
- Chapter 3 examines the role of various terrestrial and biological CDR techniques in the CDR RD&D initiative and profiles specific RD&D needs and priorities;
- Chapter 4 examines the role of carbon mineralization in the CDR RD&D initiative and profiles specific RD&D needs and priorities;
- Chapter 5 examines the role of various coastal and oceans CDR techniques in the CDR RD&D initiative and profiles specific RD&D needs and priorities;
- Chapter 6 examines the role of geologic sequestration in the CDR RD&D initiative and profiles specific RD&D needs and priorities;
- Chapter 7 examines the role of CO_2 utilization in the CDR RD&D initiative and profiles specific RD&D needs and priorities;
- Chapter 8 examines the role of cross-cutting programs in the CDR RD&D initiative, including the roles of systems analysis and large-scale demonstration projects;
- Chapter 9 examines the proposed budget estimates and interagency organization and management arrangements for the CDR RD&D initiative; and
- Chapter 10 examines the important role of international collaboration to help advance the field of CDR and support the RD&D initiative.

The appendix provides detailed budget planning estimates for the CDR RD&D portfolio. Separately, EFI will publish supplemental working papers that address several topics in greater depth. These will include a discussion of the current U.S. Department of Agriculture (USDA) research program infrastructure, a more in-depth discussion of genomic and algal research opportunities for CDR, and a lessons-learned assessment of the performance of past federal interagency RD&D initiatives in other technology areas.

1 https://unfccc.int/sites/default/files/english_paris_agreement.pdf
2 https://unfccc.int/process/the-paris-agreement/status-of-ratification
3 https://www.ipcc.ch/sr15/
4 https://www.wri.org/blog/2018/10/half-degree-and-world-apart-difference-climate-impacts-between-15-c-and-2-c-warming
5 https://globalchallenges.org/our-work/annual-report/annual-report-2017/climate-tipping-points
6 https://www.noaa.gov/stories/unprecedented-2018-bering-sea-ice-loss-repeated-in-2019
7 https://www.pbl.nl/node/65210
8 https://rhg.com/research/final-us-emissions-estimates-for-2018/
9 https://www.icos-cp.eu/GCP/2018
10 https://www.globalcarbonproject.org/carbonbudget/18/infographics.htm
11 https://earthobservatory.nasa.gov/features/CarbonCycle
12 https://www.icos-cp.eu/GCP/2018
13 https://www.mitpressjournals.org/doi/abs/10.1162/DAED_a_00182
14 https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide
15 https://www.ipcc.ch/sr15/chapter/summary-for-policy-makers/
16 https://www.gao.gov/assets/700/699605.pdf

17 https://www.ipcc.ch/sr15/chapter/summary-for-policy-makers/
18 https://www.nap.edu/catalog/25259/negative-emissions-technologies-and-reliable-sequestration-a-research-agenda
19 https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=MCRFPUS2&f=M
20 https://www.worldsteel.org/en/dam/jcr:f9359dff-9546-4d6b-bed0-996201185b12/World%2520Steel%2520in%2520Figures%25202018.pdf
21 https://www.epa.gov/sites/production/files/2019-04/documents/us-ghg-inventory-2019-main-text.pdf
22 https://www.fhwa.dot.gov/policyinformation/statistics/2017/vm1.cfm
23 https://www.iass-potsdam.de/sites/default/files/files/fact_sheet_carbon_dioxide_removal.pdf
24 https://www.nap.edu/read/25259/chapter/6
25 https://www.imperial.ac.uk/media/imperial-college/grantham-institute/public/publications/briefing-papers/BECCS-deployment---a-reality-check.pdf p. 3
26 https://www.nap.edu/catalog/25259/negative-emissions-technologies-and-reliable-sequestration-a-research-agenda
27 https://www.nap.edu/login.php?record_id=25259
28 https://iopscience.iop.org/article/10.1088/1748-9326/aabf9f
29 https://www.nap.edu/download/25259
30 https://www.nap.edu/catalog/25259/negative-emissions-technologies-and-reliable-sequestration-a-research-agenda
31 https://www.nap.edu/catalog/25232/gaseous-carbon-waste-streams-utilization-status-and-research-needs
32 https://www.icef-forum.org/pdf2018/roadmap/ICEF2018_DAC_Roadmap_20181210.pdf
33 https://www.icef-forum.org/pdf2018/roadmap/CO2U_Roadmap_ICEF2017.pdf
34 http://www.gesamp.org/publications/high-level-review-of-a-wide-range-of-proposed-marine-geoengineering-techniques

Part II
RD&D Portfolio Design

CHAPTER 2.
DIRECT AIR CAPTURE

Technical methods to remove CO_2 directly from air have been known for decades and are currently used to maintain breathable air on board submarines[1] and spacecraft (Box 2-1).[2,3] However, these use cases are highly specialized and relatively cost-insensitive, so they use technology that is not appropriate for very large-scale deployment. The idea of using direct CO_2 removal from air as a climate strategy was first proposed in 1999 by K.S. Lackner et al.[4] and is now known generically as DAC.

Broadly, DAC technology uses heat and electricity to separate ambient air into a concentrated stream of CO_2 and a stream of CO_2-depleted air. This by itself is not a complete carbon removal system and must be coupled with a disposition pathway, either utilization or sequestration of the removed CO_2. The lifecycle impacts of these options can be quite different, so the overall potential removal of DAC needs to be evaluated in combination with CO_2 disposition. While DAC with storage (often called DACS) results in the largest net CO_2 removal, DAC with utilization is attractive because of revenue from the sale of utilization products and has thus been the focus of most commercial DAC activity to date.

The intense recent interest in DAC as a CDR technology is driven by several factors, including the large theoretical potential for removal (when coupled with sequestration) and the relatively small ecological impacts associated with large-scale deployment. This chapter describes DAC technology types, estimates of cost and removal potential, relevant legislative activity, and RD&D needs.

Box 2-1

Carbon Dioxide Removal for Spacecraft

As astronauts breathe on board spacecraft, the concentration of CO_2 in the cabin air can rise, and if unmitigated can reach dangerous levels. All human spaceflight therefore uses technologies to remove excess CO_2 as part of the life-support system. Beginning with the Mercury missions (1958-1963), NASA used lithium hydroxide (LiOH) canisters, which were designed for one-time use, to remove CO_2. For longer-duration missions such as Skylab, NASA developed CO_2-removal technology based on molecular sieves, which were reusable and vented the removed CO_2 to space. The International Space Station (ISS) currently uses two advanced molecular-sieve-based CO_2-removal devices (Carbon Dioxide Removal Assembly, CDRA), one of which can convert removed CO_2 back to oxygen. NASA has developed a CO_2 Removal Roadmap to guide technology development for even longer-duration CO_2-removal systems for use on future missions to Mars. While aspects of spacecraft CO_2 removal are relevant to CDR DAC technology, the performance requirements and costs are substantially different.[5,6]

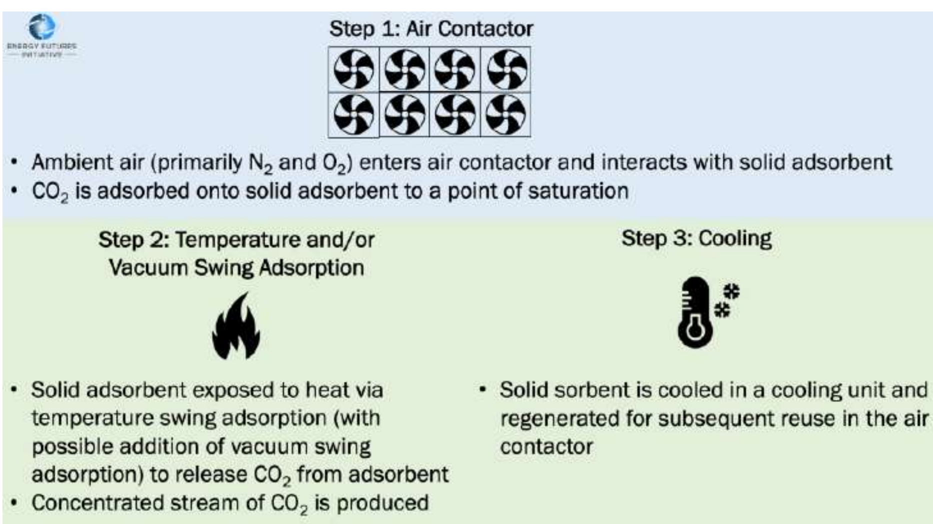
Technical Description of Direct Air Capture

There are three main categories of DAC: cryogenic, membrane, and chemical.[7,8] Cryogenic DAC takes advantage of the fact that CO_2 has a different freezing temperature than other gases in the air and can be separated by cooling air below this temperature, as occurs during the operation of cryogenic oxygen separation facilities.[9,10] Membrane DAC uses ionic exchange and reverse osmosis membranes to separate CO_2 from air and seawater, as occurs during typical seawater desalination. To date, these two categories have received very limited research attention as pathways for CDR.

Much more attention has been focused on chemical DAC, which uses various sorbents to remove CO_2 from the air in a process that can be reversed using heat, pressure, or moisture. Chemical DAC systems operate on a capture-regenerate cycle in which CO_2 is removed from ambient air and later released in concentrated form for utilization or storage. There are currently two primary techniques that are under development: low-temperature solid sorbent (LTSS) and high-temperature liquid solvent (HTLS).

LTSS DAC (Figure 2-1)[11] currently uses amines as the sorbent, supported on porous structures known as air contactors. Fans move ambient air through these contactors, and the amines adsorb CO_2. Once they are saturated, the air flow is stopped and the amines are heated to 80°C to 120°C in order to release CO_2 in concentrated form (approximately 99 percent pure). This CO_2 is then removed for compression and pipeline transport or utilization. The primary companies developing LTSS are Climeworks, based in Switzerland, and Global Thermostat, based in the United States.

Figure 2-1
Basic Steps in DAC Process for Solid Sorbent-Based Systems

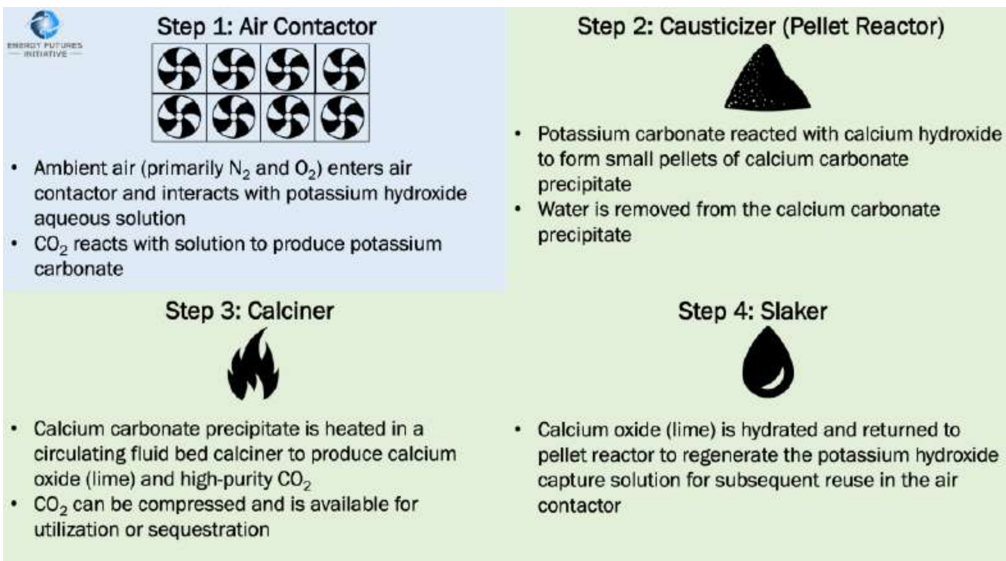


The two major components of a solid sorbent-based DAC system include adsorption (blue) and desorption (green). Source: EFI, 2019. Compiled using data from the National Academies of Sciences, Engineering, and Medicine.

HTLS DAC (Figure 2-2)[12,13] is based on an aqueous liquid solution of potassium hydroxide (KOH), which is distributed across an air contactor structure. Fans move ambient air through this structure to contact the liquid, and CO_2 is absorbed into the solution, forming potassium carbonate. The solution is then reacted with calcium hydroxide ($Ca[OH]_2$) to form calcium carbonate ($CaCO_3$), which in turn is fed to a calciner to liberate concentrated CO_2 (approximately 99 percent pure) and regenerate $Ca(OH)_2$. The calciner operates at 900°C and represents a substantial portion of the overall energy consumption of the system. The only company currently developing HTLS is Carbon Engineering, based in Canada.

Figure 2-2

Basic Steps in DAC Process for Liquid Solvent-Based Systems



The two major components of a liquid solvent-based DAC system include the air contactor (blue) and regeneration facility (green). Approximately 75 percent of the CO_2 that enters the air contactor is captured by the solvent. Source: EFI, 2019. Compiled using data from Carbon Engineering and the National Academies of Sciences, Engineering, and Medicine.

Some attention has also been focused on developing membrane DAC systems based on a moisture-swing process (Box 2-2).[14] This uses an amine-based anion exchange membrane that absorbs CO_2 when dry and releases it when exposed to moisture, at a relatively low concentration (3 percent to 5 percent). The companies known to be developing this form of DAC are Infinitree LLC, based in the United States, and Silicon Kingdom Holdings, based in Ireland.[15]

Box 2-2

Moisture-Swing DAC

Dublin-based Silicon Kingdom Holdings announced in 2019 that it would commercialize DAC technology developed at Arizona State University in the research group led by Prof. Klaus Lackner. The technology is based on anion exchange membranes, which have a strong affinity for CO_2, and a stronger affinity for water. The membranes are mounted on vertical supports and exposed to ambient air through natural wind (no fans are used). CO_2 adsorbs onto the membranes until they reach saturation, at which point they are folded into a chamber with high humidity, driving off the CO_2 as water molecules adsorb onto the membrane surface. The CO_2 is removed for disposal or utilization, and the membranes are re-extended and exposed to air again. This moisture-swing adsorption (MSA) system only works in dry environments, where water on the membrane surface evaporates after air exposure, enabling further CO_2 adsorption. The energy requirements for this system are far lower than other DAC technologies because no heat is required for regeneration, but the water requirements are substantially higher. Silicon Kingdom Holdings has announced it intends to build a 36 ktCO_2 per year plant based on this technology, possibly as early as 2020.[16]

Utilization and Sequestration of CO_2 Captured by DAC

High-purity CO_2 from DAC can be utilized for a variety of purposes or stored. Carbon Engineering is pursuing making synthetic liquid fuel using removed CO_2 ("air-to-fuels")[17] and providing CO_2 for enhanced oil recovery (EOR).[18] Climeworks is pursuing markets in food and beverage, greenhouses, materials, aviation fuels, and related sectors.[19,20] Global Thermostat is also pursuing markets in food and beverage, greenhouses, materials, EOR, and related sectors.[21,22] Table 2-1[23] profiles several DAC companies and the technology characteristics of their DAC systems.

A focus on CO_2 utilization pathways by these companies is understandable, given the need to develop revenue streams. In the absence of a price on carbon, it appears likely that DAC companies will work to sell removed CO_2 for utilization to the maximum extent possible. While the Section 45Q tax credit provides some economic benefits from sequestration, utilization markets appear to remain highly attractive for the private sector. The potential scale of CO_2 utilization remains uncertain (CO_2 utilization opportunities are discussed in greater detail in Chapter 7).

Table 2-1
Technology Characteristics of DAC Companies

Company	Location	Capture Type		Capture Method			Regeneration Temperature
		Liquid Solvent	Solid Sorbent	Absorption	Adsorption (Temperature Swing)	Adsorption (Moisture Swing)	
Carbon Engineering	Canada	✓		✓			900°C
Antecy B.V.	Netherlands		✓		✓		80-100°C
CLIMEWORKS Capturing CO_2 from air	Switzerland		✓		✓		100°C
globalthermostat a carbon negative solution	United States		✓		✓		85-95°C
hydrocell	Finland		✓		✓		70-80°C
INFINITREE	United States		✓			✓	Moisturizing
skytree	Netherlands		✓			✓	Moisturizing at 80-90°C

There are several DAC companies globally, most of which employ solid sorbent-based capture systems. Note that Antecy B.V. was acquired by Climeworks in September 2019. Source: EFI, 2019. Compiled using data from Fasihi et al., 2019.

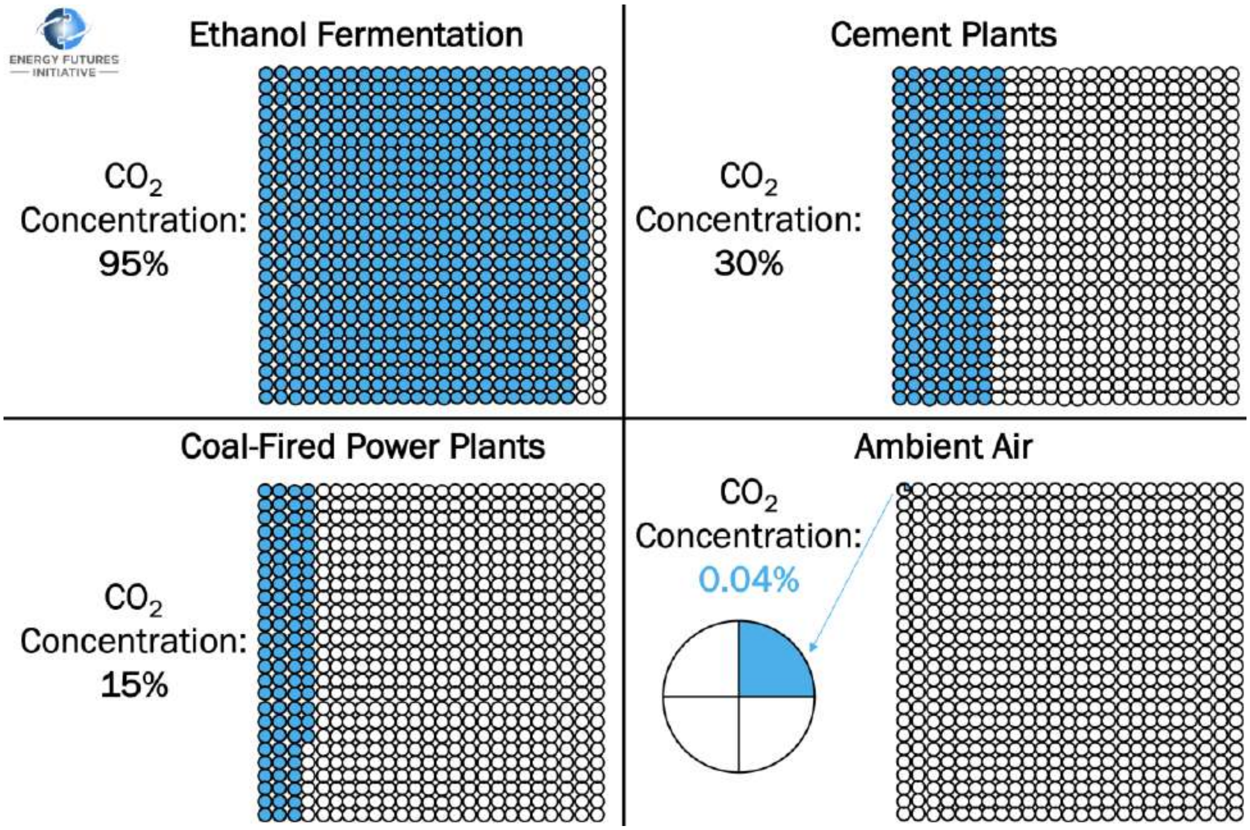
Energy Intensity of Direct Air Capture

DAC is energy intensive and thus energetically challenging for two reasons: the energy requirements to process large amounts of ambient air in order to recover dilute quantities of CO_2 in ambient air, and the energy required to separate the captured CO_2 from the sorbent.

The concentration of CO_2 in the atmosphere is only 0.04 percent, meaning that separating CO_2 from ambient air to high purity through DAC can be more difficult and energy intensive compared to separation from more concentrated sources[24] such as fossil fuel power plants and industrial facilities (Figure 2-3).[25,26,27,28,29] For DAC, the dilute nature of CO_2 requires the processing of large volumes of ambient air to remove a material amount of CO_2. For example, annual per capita emissions in the United States were 20 tCO_2 in 2010; if this same amount of CO_2 were to be removed from the atmosphere, it would require processing a volume of air equivalent to an American football field and 10 meters high per American per day.[30] Moving such large volumes of air requires significant amounts of electricity to process the ambient air. Energy requirements can be reduced by reducing the ambient air flow rates, but this may require larger contractor areas in order to capture CO_2 at a comparable rate.

Figure 2-3

CO_2 Concentration in Dilute (Ambient Air) Versus Concentrated Sources

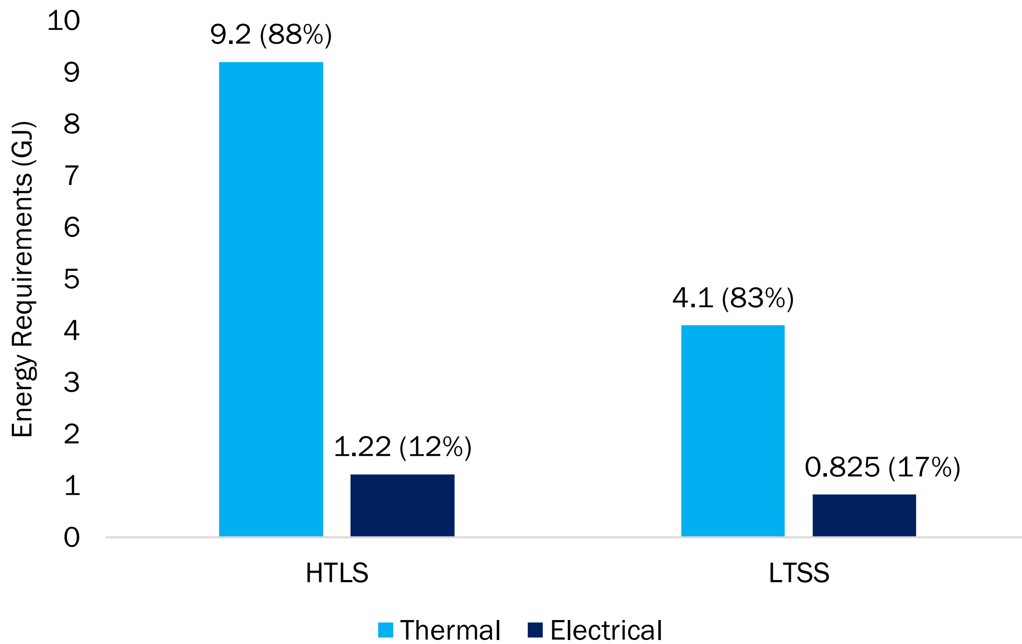


Technological CDR from the atmosphere is challenging due in part to the dilute nature of CO_2 in ambient air as compared to other CO_2 emissions from power plants and industrial sources. Sources: EFI, 2019. Compiled using data from Davis et al., 2018; National Academies of Science, Engineering, and Medicine, 2018; Scripps Institution of Oceanography, 2019; State CO_2-EOR Deployment Work Group, 2017; and Wolk, 2009.

The larger energy requirement for DAC is process heat. Separation of the captured CO_2 and regeneration of the sorbent agent requires heat energy to break the chemical bonds that formed as the CO_2 was absorbed. The heat energy challenge is complicated by the fact that sorbent performance characteristics and regeneration energy requirements are inversely related. In technical terms, current CO_2 sorbents have either high-rate constants and high-binding enthalpy or low-rate constants and low enthalpy.[31] Technology solutions that reduce heat energy requirements thus may involve large contact areas with resulting higher capital costs. While LTSS DAC requires less energy than HTLS stems, in both cases, heat energy comprises in excess of 80 percent of total energy requirements (Figure 2-4).[32] NASEM estimates HTLS requires 7.7 to 10.7 GJ of thermal energy and 0.74 to 1.7 GJ of electrical energy per ton of CO_2 removed; the equivalent values for LTSS DAC are 3.4 to 4.8 GJ (thermal) and 0.55 to 1.1 GJ (electrical) per ton of CO_2 removed.[33]

Figure 2-4

Energy Requirements for HTLS and LTSS DAC Systems



Energy requirements for both HTLS and LTSS DAC systems are dominated by thermal energy. Values reflect the midpoint of the range given by NASEM. Source: EFI, 2019. Compiled using data from Davis et al., 2018; the National Academies of Science, Engineering, and Medicine.

It is helpful to put the significant heat energy requirements for DAC in context relative to current U.S. energy demand. If current LTSS DAC technology (which has lower energy requirements than current HTLS technology) were deployed at the scale of 1 $GtCO_2$ per year, and the thermal energy were supplied entirely by electrical resistive heating, it would require 1,368 billion kWh of electrical energy per year, equivalent to 33 percent of all 2018 U.S. electricity generation and 1.9 times all 2018 U.S. renewable electricity generation.[34]

There are RD&D opportunities to reduce energy requirements. As noted by NASEM, current technology for both HTLS and LTSS DAC systems require far more energy than the theoretical minimum of 0.45 GJ per tCO_2, meaning there is a large amount of headroom for engineering improvements before beginning to approach fundamental limits. Higher-performance sorbent materials and better heat integration at the systems level could significantly improve the energy efficiency of DAC. Further, the energy requirements of DAC could be reduced if the CO_2 from DAC is produced at lower purity, which may be suitable for several utilization applications.[35]

An additional approach to reduce DAC costs is to locate DAC facilities adjacent to sources of low-cost thermal energy. One study currently underway is investigating waste heat from geothermal electric power plants, boiler steam from nuclear power plants, and stranded natural gas currently being flared. In addition to quantifying the total potential from these energy sources, the study intends to identify specific U.S. locations where this thermal energy is available, as favorable for siting early DAC facilities.[36,37]

Consideration of DAC energy requirements must consider not only total energy demand but also the source of the energy, as the net CO_2 removal impacts of DAC will be impacted by the carbon content of the energy sources being considered. While there are a number of options for providing carbon-free electricity to support DAC, providing low-carbon or carbon-free heat remains a significant technical challenge[38] for HTLS DAC given its requirement for high-quality heat. For example, using natural gas to provide heat, when accompanied by CO_2 capture for the associated emissions, is a low-carbon option and is currently being pursued as one pathway for HTLS. Waste heat and/or curtailed renewable electricity may provide some of the energy for DAC.[39] J. Wohland et al. estimate that DAC powered by excess renewable electricity in Europe could scale to 500 $MtCO_2$ per year of removal.[40]

Focused RD&D on reducing DAC energy requirements is a high priority for further RD&D. Providing that energy in the form of low- or zero-carbon energy for DAC also will be necessary. This should be considered primarily on an economic basis as an integrated part of the overall system cost, rather than viewed as an independent factor in the potential scalability of DAC. The falling cost of renewables, particularly solar, presents one possibility for providing large amounts of renewable electricity for DAC in the future at lower cost.

Potential Scale of Direct Air Capture

The NASEM report noted that DAC has “no fundamental physical limit” for achieving CDR, and thus its potential scale is likely to be determined by geographic location and cost factors.[41] Potential geographic considerations for the siting of DAC plants include the available energy mix (e.g., low- or high-quality thermal energy), carbon intensity of available electrical and thermal energy (important for lifecycle assessments of net carbon removal), water availability, and proximity to geologic sequestration opportunities and enabling infrastructure (e.g., CO_2 pipelines).[42] Potential scale of geologic sequestration also needs to be considered a potential limiting factor (see Chapter 6 for a further discussion of geologic sequestration). One assessment illustrates how DAC could play a prominent role in helping to meet U.S. climate goals (Box 2-3).

Box 2-3

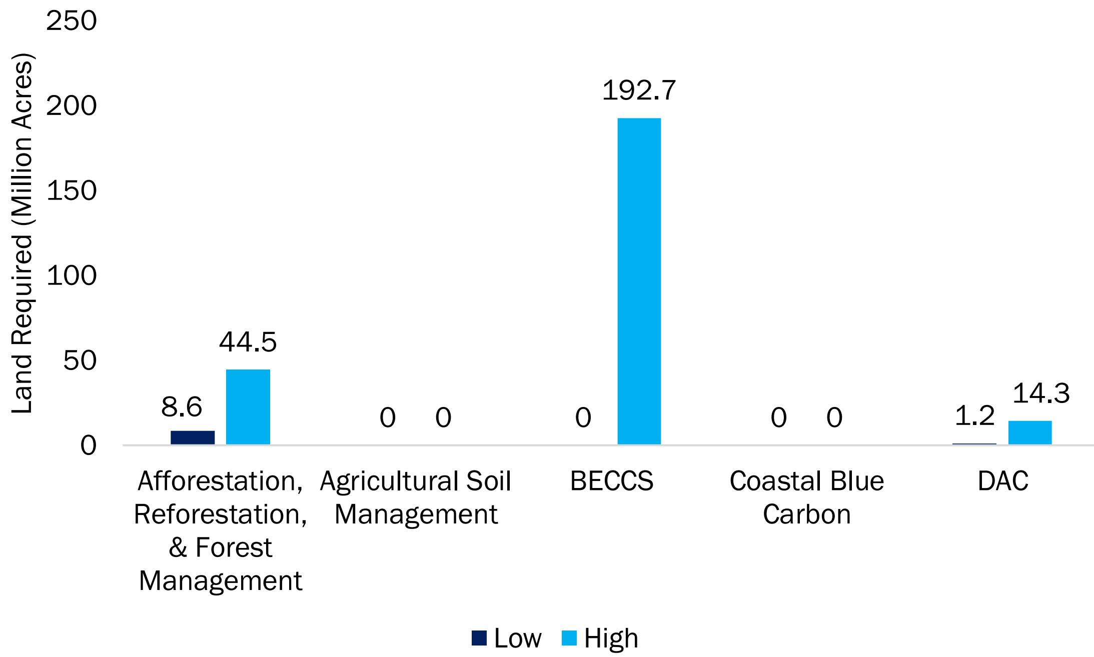
Potential Role for DAC in Meeting U.S. Climate Goals

A 2019 Rhodium Group report found that the scale of DAC deployment required to meet U.S. midcentury carbon removal requirements was at least 9 $MtCO_2$ per year by 2030. This scale of DAC deployment was predicated on the United States achieving net-zero emissions by 2045, which would require CDR through DAC at an estimated level of 560 to 1,850 $MtCO_2$ (depending on the availability of other CDR pathways). A less ambitious climate mitigation scenario of achieving an 83 percent reduction in GHG emissions by 2050 was found to still require CDR to help offset residual emissions that could either be too difficult or expensive to eliminate from the economy, of which DAC could be required at a level of 740 $MtCO_2$ per year if other CDR pathways are unable to scale to necessary levels.[43] Achieving the more ambitious net-zero target by 2045 was found to require an estimated deployment scale of 689 to 2,258 megaton-scale plants, while the less ambitious target of an 83 percent reduction by 2050 could require up to 856 DAC plants. The analysis assumed a learning rate of 10 percent to 15 percent, capture-sequestration cost of \$191 to \$308 per tCO_2 for HTLS and \$142 to \$343 per tCO_2 for LTSS, and a break-even cost of \$236 per tCO_2 using a 30-year levelized median cost for the first plant.[44]

The physical infrastructure for DAC, including any dedicated energy generation facilities, has a significant footprint. The land requirements, however, are substantially smaller per ton of removal capacity than most other CDR pathways considered (Figure 2-5).[45] NASEM estimates that a 1 $MtCO_2$ per year DAC facility would require 550 to 800 acres (if powered by natural gas) and 1,355 to 2,450 acres (if powered by a gas/solar combination).[46] For the latter (conservative) case, this translates to a land-use intensity of 408 to 738 tCO_2 per acre per year. For comparison, afforestation/reforestation has an estimated land use intensity of 4.2 to 8.2 tCO_2 per acre per year, and agricultural practices to increase soil carbon have an estimated land use intensity of 0.3 to 0.7 tCO_2 per acre per year. Thus, DAC would remove approximately 100 to 1,000 times more CO_2 per acre than these other pathways. As noted by NASEM, the land use requirements would be even smaller if offshore wind energy were used rather than solar.

Figure 2-5

Land Use Requirements for Various CDR Pathways at Gigaton Scale in the U.S.

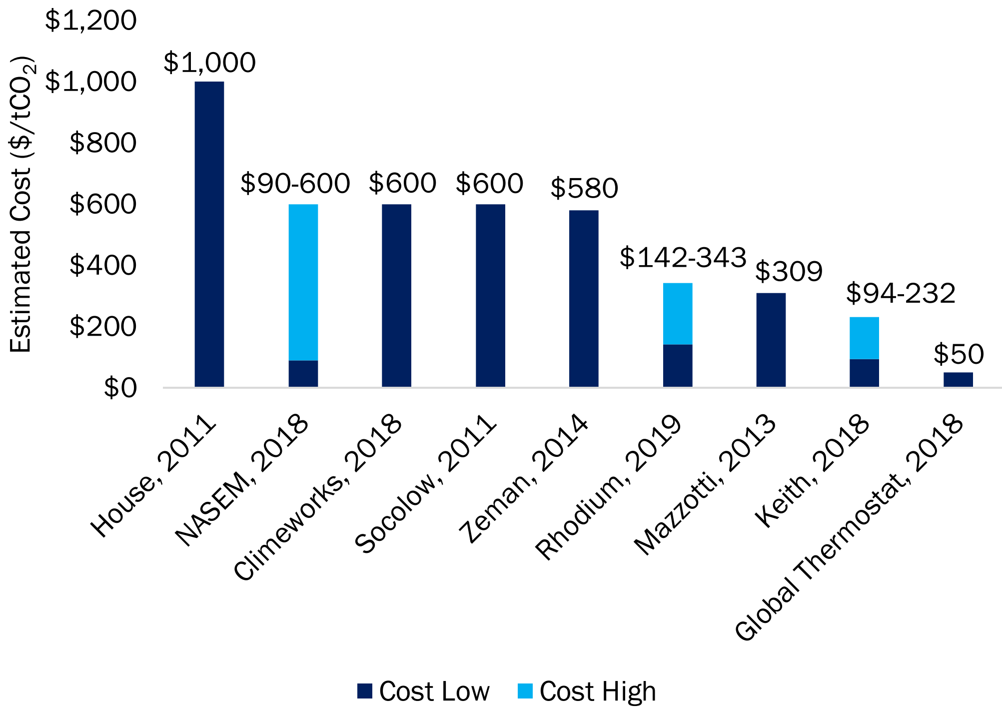


DAC has a relatively small land use requirement compared to several terrestrial and biological CDR pathways. Note: Values reflect the land use requirements for CDR at the scale of 1 GtCO2 per year. Source: EFI, 2019. Compiled using data from Carbon Engineering and the National Academies of Sciences, Engineering, and Medicine.

Costs of Direct Air Capture

Reported cost estimates for DAC technologies have varied widely (Figure 2-6). The assumptions used in the reported cost estimates are not fully transparent. Those that are reported incorporate different energy costs, projected performance improvements, contingency factors, and other parameters. (For example, some cost estimates exclude compression of the removed CO_2 to pipeline pressure which would add an additional $8 per tCO_2.)[47] They provide an indication of the size of the ballpark but should not be considered directly comparable. The first broad review of DAC, conducted by R. Socolow et al., concluded that a benchmark HTLS system would cost above $600 per tCO_2.[48] It did not assess costs of LTSS DAC. Without addressing a specific design, but reasoning from efficiencies achieved by existing gas separation technologies, K.Z. House et al. estimated that DAC costs would be on the order of $1,000 per tCO_2.[49] Other analyses have estimated costs ranging from $236 to $580 per tCO_2.[50,51,52]

Figure 2-6
Estimated Costs of DAC



There is a wide range of current estimated costs (and associated cost assumptions) for DAC. Due to differences in costing assumptions, individual cost estimates are not directly comparable but are indicative of the potential cost range. Source: EFI, 2019. Compiled using data from K.Z. House (2011), the National Academies of Sciences, Engineering, and Medicine (2018), Climeworks (2018), R. Socolow (2011), F. Zeman (2014), M. Mazzotti (2013), D. Keith (2018), and Global Thermostat (2018).

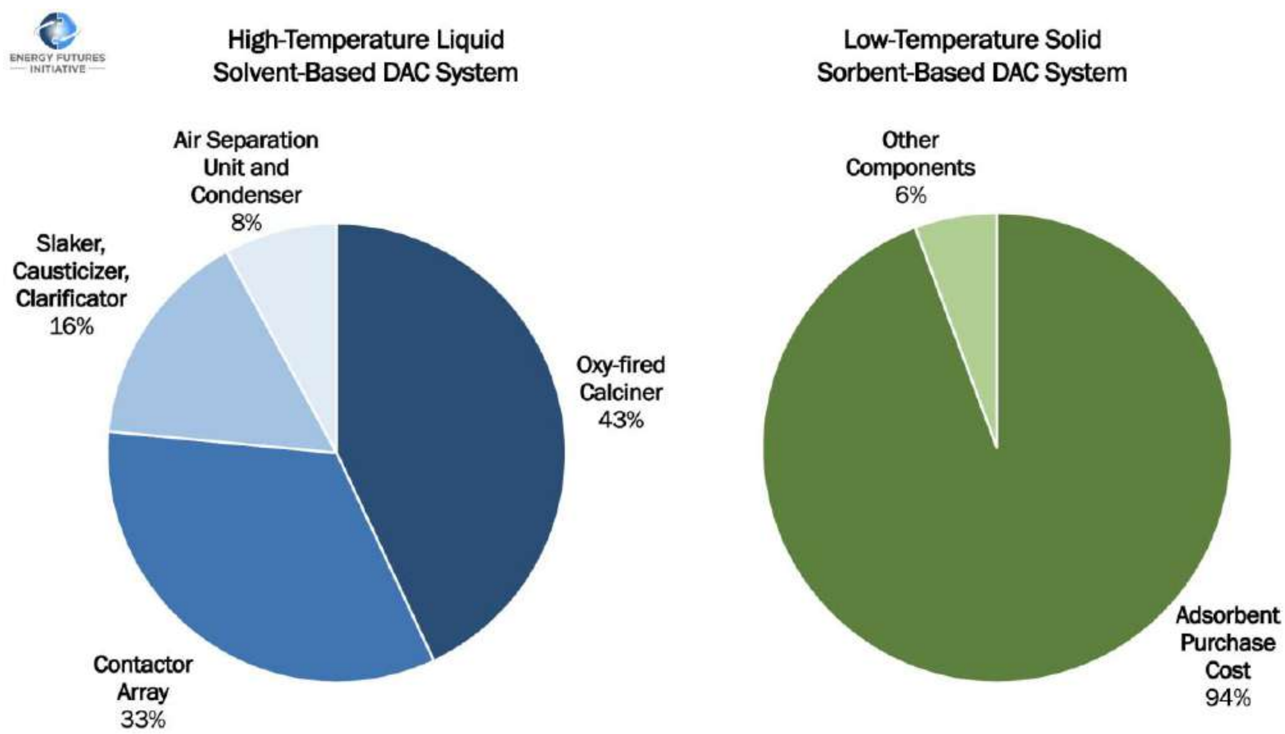
More recent cost estimates have tended lower but are still reflective of limited R&D experience and are not fully transparent. For example, D. Keith et al. reported a DAC design that is under development by Carbon Engineering with a levelized cost of $94 to $232 per tCO_2.[53] No other commercial DAC designs have been reported in the literature, although Climeworks has publicly stated that the cost of its technology is $600 per tCO_2,[54] while Global Thermostat has publicly stated that the cost of its technology is $50 per tCO_2.[55] Various projections about the future costs of DAC have also been offered; M. Fasihi et al. project that the cost of DAC with and without free waste heat could fall to 60 euros and 105 euros per tCO_2 by 2030 ($67 and $117 per tCO_2, respectively).[56]

The NASEM report presented updated cost estimates constructed on a common set of assumptions for both HTLS and LTSS DAC systems under various scenarios of energy provision. For HTLS, the net removal cost of a 1 $MtCO_2$ per year plant was estimated to be \$156 to \$419 per tCO_2; for LTSS, the net removal cost of a 1 $MtCO_2$ per year plant was estimated to be \$89 to \$877 per tCO_2. The ranges reflect uncertainty in technology costs and variation in the assumed energy source. The use of wind and solar power reduces the net cost of removal because of their low emissions profile, while the use of coal-fired power increases the net cost because of its high emissions profile.

The NASEM analysis also revealed important differences in the composition of capital costs between HTLS and LTSS DAC technologies (Figure 2-7).[57] For HTLS, capital costs are spread across multiple components, including the oxy-fired calciner (43 percent), the air contactor (33 percent), and the slaker, causticizer, and clarificator (16 percent). This implies that RD&D to reduce HTLS capital costs must target improvements in many different components, as well as systems integration.

Figure 2-7

Capital Cost Composition of HTLS and LTSS DAC Systems



Capital costs for HTLS DAC systems are distributed over multiple components. Capital costs for LTSS DAC systems are dominated by the cost for the sorbent. Source: EFI, 2019. Compiled using data from the National Academies of Sciences, Engineering, and Medicine.

By contrast, the NASEM analysis estimates that LTSS capital costs are dominated by the sorbent material (94 percent). This implies that RD&D to reduce LTSS capital costs should focus primarily on reducing sorbent material cost, as well as improving its durability and performance. Other components are correspondingly less important to address unless and until sorbent material costs can be substantially reduced.

There is a growing interest in the research community for innovation in DAC technologies. For example, recent published results have included a novel DAC technique using aqueous solutions of amino acids to capture CO_2 from air using low-quality heat,[58] and a novel application of electrochemical conversion that may significantly lower the thermal requirements of HTLS DAC.[59] Despite the extremely limited RD&D funding available, these early results suggest that a robust community of DAC researchers is beginning to form and would be prepared to substantially accelerate progress if funding support were available. Furthermore, there have been several legislative bills under consideration by the 116th Congress that would specifically impact DAC technology (Box 2-4).

Box 2-4

Legislative Proposals for Increased DAC R&D Funding

A number of bills related to DAC have been under consideration by the 116th Congress:

Enhancing Fossil Fuel Energy Carbon Technology (EFFECT) Act (S. 1201) was introduced by Sens. Joe Manchin, Lisa Murkowski, Shelley Moore Capito, Kevin Cramer, and Steve Daines in April 2019 and would authorize several RD&D programs at the Department of Energy (DOE) Office of Fossil Energy (FE), including one focused on DAC, BECCS, and other CDR technologies.[60]

Fossil Energy Research and Development Act (H.R. 3607) was introduced by Reps. Marc Veasey, David Schweikert, Conor Lamb, Lizzie Fletcher, and Eddie Bernice Johnson in July 2019 and would authorize several RD&D programs at FE, including one focused on DAC, BECCS, and other CDR technologies.[61]

Utilizing Significant Emissions with Innovative Technologies (USE IT) Act (S. 383 and H.R. 1166) was introduced by Sens. John Barrasso, Sheldon Whitehouse, Capito, Tammy Duckworth, Cramer, Tina Smith, Manchin, Thomas Carper, and Michael B. Enzi and Reps. Scott Peters, David B. McKinley, Veasey, Schweikert, and Cheri Bustos in February 2019 and would authorize RD&D at the Environmental Protection Agency (EPA) on DAC and CO_2 utilization.[62]

SEA FUEL Act (S. 1679) was introduced by Sens. Whitehouse, Jack Reed, and Dan Sullivan in May 2019 and would direct the Department of Defense (DOD) and the Department of Homeland Security (DHS) to pursue carbon capture from the atmosphere and oceans to convert it to clean fuels or other CO_2 utilization products.[63]

The Carbon Capture Prize Act (H.R. 3282) was introduced in June 2019 by Reps. Grace Meng, Anthony Brown, Matt Cartwright, Gilbert Cisneros, Yvette Clarke, Barbara Lee, Gregory Meeks, Jamie Raskin, Harley Rouda, Darren Soto, Thomas Suozzi, Nydia Velazquez, and Susan Wild and would establish a prize competition of up to $30 million for R&D related to DAC and the permanent sequestration of the captured CO_2.[64]

Recommended Direct Air Capture RD&D Portfolio

The overarching RD&D objectives for DAC are to reduce the cost and energy use and improve the performance and durability of DAC technologies. The available estimates in the peer-reviewed literature, although incomplete and subject to significant uncertainty, suggest nonetheless that there are RD&D opportunities that can achieve DAC technology at a cost at or below \$200 per net tCO_2 removed.

The overarching RD&D objectives for DAC are to reduce the cost and energy use and improve the performance and durability of DAC technologies.

Reducing the cost of DAC is the key to unlocking its potential. Current cost estimates have a significant degree of uncertainty, lack transparency in many cases, and reflect extrapolations from limited, short-duration testing of prototypes that in some cases are not fully integrated. Reaching a target of \$200 per net tCO_2 removed will require maturation of the technology to fully integrated at-scale systems with the additional benefit of learning by doing. Table 2-2 provides a further summary of the key cost uncertainties and research needs.

Table 2-2
Cost Estimate Uncertainties and RD&D Needs for DAC

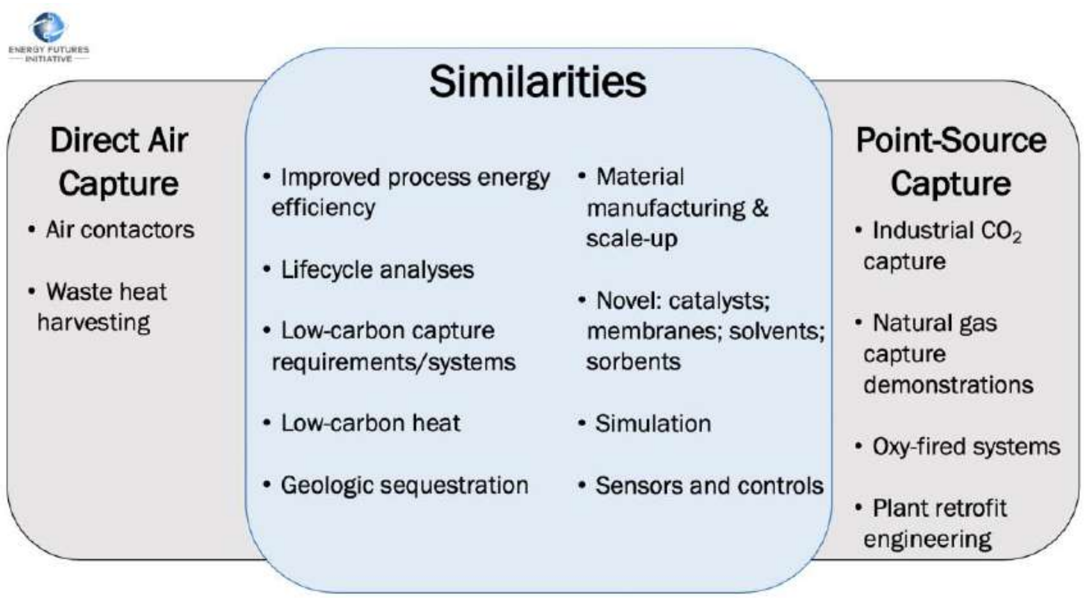
Cost Estimate Uncertainties	RD&D Needs
Cost estimates from literature may not fully incorporate the full balance of plant.	Proposed data acquisition program and comprehensive techno-economic assessment of current alternatives will provide a clearer and consistent basis for assessing innovation needs.
Assumptions regarding contingency allowances vary and may not follow standard engineering guidelines.	Techno-economic analysis will apply an appropriate and consistent approach to estimating contingencies.
Cost estimates are based on significant scale-up factors (from several tCO_2 to 100 $MtCO_2$ per year at commercial scale) and in some cases incorporate nth-of-a-kind plant learning rates.	Techno-economic analysis needs to distinguish between the cost of first-of-a-kind and nth plant. Construction and operation of additional pilot scale test facilities may be needed to validate the basis for initial commercial plants.
Capital cost estimates are sensitive to choice of materials and absorbers and assumptions regarding economies of mass manufacturing of DAC components. Cost assumptions and estimates at the component level may also involve uncertainties in addition to cost estimates at the systems level.	Additional RD&D opportunities to develop new absorber materials with improved properties (e.g., thermodynamics, kinetics, energy for regeneration), lower costs, and improved manufacturability.
DAC plants are energy intensive, and cost estimates are sensitive to energy requirements and energy costs (they should be assessed on the basis of industrial energy costs, not residential). There are cost uncertainties for low-	Additional RD&D needs to focus on ways to reduce energy requirements, particularly energy (work) requirements for air movement through DAC systems and heat requirements for regeneration of absorbents. Systems studies are needed to

carbon electrical and thermal energy, of which heat energy can constitute more than 80 percent of total energy requirements for DAC. Energy costs can vary by geography and can be impacted by infrastructure availability. The role of waste heat availability for DAC operations is difficult to assess due to its limited availability relative to the scale of removal needed.	identify opportunities for utilization of low-cost heat sources.
DAC operating performance is sensitive to weather and climate conditions; cost estimates may be based on optimal siting locations and operating conditions for DAC.	RD&D to test DAC components and sub-systems at regional test facilities under differing weather and climate conditions will enable better estimates of potential scope of deployment opportunities and operational performance.
Operations and maintenance (O&M) costs can be a considerable component of total cost for removal. Limited experience with initial DAC pilot plants may be insufficient to identify potential longer-term O&M cost sensitivities for larger systems.	RD&D is required to test long-term durability of DAC materials and equipment. Engineering integration studies can identify opportunities to optimize facility operations and minimize maintenance costs.
Cost estimates may be based on analogous technologies and systems rather than specific DAC plant designs, especially given the lack of DAC designs reported in the literature.	A proposed data acquisition program, larger-scale demonstration projects, and public dissemination of information could help researchers develop more robust cost estimates.
Cost estimates may not include associated issues such as land requirements and grid connections, in addition to infrastructure requirements for CO_2 management such as compression equipment, CO_2 pipelines, injection wells, and utilization facilities (e.g., chemical plants).	In general, these considerations are related to deployment and are outside the scope of the CDR RD&D initiative. However, larger-scale demonstration projects may help establish realistic values for these costs.
Cost estimates may ignore financing costs such as interest on debt and return on equity, or use artificially low values from well-established technologies such as coal-fired power plants.	In general, these considerations are related to deployment and are outside the scope of the CDR RD&D initiative. However, larger-scale demonstration projects may improve investor confidence and reduce the cost of capital.
Source: EFI, 2019.	

The recommended RD&D portfolio addresses these needs by organizing work in the following elements: (1) improved DAC materials, including sorbents, solvents, and membranes, (2) engineering development focused on technology performance and cost improvements, equipment manufacturing, and heat energy management, (3) integrated system scale-up and testing through pilot-plant stage, (4) cost, lifecycle, and environmental analysis, and (5) military operational applications. The proposed funding level for this capture technology pathway is $1,600 million over 10 years. Table 2-3 provides a detailed breakdown of the portfolio elements, agency roles, and budget planning estimates.

Although the applications differ greatly, there are a number of areas of common research needs between DAC and concentrated point-source technologies. Examples of common research needs and opportunities are highlighted in Figure 2-8.

Figure 2-8
Similarities and Differences Between DAC and Concentrated Point-Source Carbon Capture Research Focus Areas



There are a number of common research needs between DAC technologies and concentrated point-source carbon capture technologies. Source: EFI, 2019.

Recommended RD&D Portfolio Elements

DOE/FE has a long history of support for R&D and demonstration programs for carbon capture technologies for concentrated point sources of CO_2, including both power generation and industrial facilities. Congress has continued to fund DOE/FE R&D programs to advance carbon capture, utilization, and sequestration (CCUS) technologies, providing a total of $198 million in fiscal year 2019.[65] The DOE/FE expertise and experience in managing R&D programs for carbon capture technologies, centered at the National Energy Technology Laboratory (NETL), provides the appropriate springboard for DOE to actively lead the proposed DAC RD&D portfolio. Successfully advancing the technological frontiers of DAC will require contributions from other federal agencies as well, and the proposed portfolio identifies key roles for the EPA, National Science Foundation (NSF), National Institute of Standards and Technology (NIST) within the

Department of Commerce (DOC), and DOD. NSF and DOC/NIST manage research and testing that is foundational to all DAC technologies, while EPA is responsible for the ultimate application of DAC within the framework of the Clean Air Act (CAA) and DOD is responsible for consideration of potential military operational applications. The agency roles and responsibilities are identified in more detail in the descriptions of the five principal portfolio elements that follow.

Advanced Materials, Portfolio Element 2.10, focuses on identifying, testing, and scaling up production of low-cost, high-performance scalable materials for DAC, including sorbents, solvents, membranes, contactors, and other materials. The effort includes proposals to a new DOE Energy Frontier Research Center (EFRC) and an NSF Engineering Research Center (ERC) as large-scale hubs for fundamental research in DAC materials. This will be complemented by grants and cooperative agreements for fundamental research in associated areas, managed by DOE/Basic Energy Sciences (BES) and NSF/ Directorate for Mathematical and Physical Sciences (MPS). NIST is proposed to lead research on standard test procedures and calibration for DAC-related materials.

Engineering Development, Portfolio Element 2.20, focuses on applied technology development of DAC components and small-scale integrated systems. Focus areas include air contactor design, manufacturing scale-up, low-carbon heat provision, and advanced/unconventional components and systems, including cryogenic or other non-sorbent-based methods, passive contactors, and moisture-swing approaches. This effort is proposed to be led by FE/NETL, which already supports a small portfolio of DAC technology development projects, with engagement from DOE/Advanced Manufacturing Office (AMO). The proposed portfolio also would include National Laboratory research and grants and collaborative agreements with industry and universities.

Pilot Plants, Test Facilities, and Demonstrations, Portfolio Element 2.30, is proposed to support four major sub-elements. All four are proposed to be led by DOE/FE:

- **Scale-Up Studies and Pilot Plants, Portfolio Element 2.31,** supports proof-of-concept, engineering scale-up, semi works, and pilot-scale (1,000 to 10,000 tCO_2 per year) applications of DAC technology advancements, and provides public data to support full-scale demonstrations and commercial deployment.
- **Operational Data Collection, Portfolio Element 2.32,** is proposed to acquire operational performance data from DAC facilities that have already been commercially deployed. These data sets will enable DOE to conduct a more comprehensive techno-economic assessment of DAC technology that, in turn, will guide future RD&D plans and priorities. The funding support to existing DAC prototype facilities also will enable them to undertake more robust testing programs. The DOE Bioenergy Technologies Office (BETO) recently issued a request for proposal for a similar effort to collect and publish existing underused or economically stranded bioenergy datasets.[66] FE/NETL has a cooperative agreement in place with Carbon Engineering that could form a model for the proposed larger effort to encompass all DAC technologies. Current DOE authority to enter into Technology Investment Agreements (TIAs) would provide needed

flexibility to tailor agreements in a manner that protects existing intellectual property.

- **DAC Engineering Design Support, Portfolio Element 2.33,** is proposed to support up to three cost-shared front-end engineering and design (FEED) studies that eventually could qualify for large-scale demonstration funding. This will be led by FE with industry cost-sharing and also could include participation from states, municipalities, and other businesses.
- **Regional and National Test Facilities, Portfolio Element 2.34,** is proposed to support several (perhaps as many as five) regional test centers to provide facilities to test the performance and aging of DAC equipment prototypes in different climate and atmospheric conditions. The centers should be located at existing DOE, federal, or nonfederal research facilities to take advantage of infrastructure support; nonfederal locations could provide various forms of in-kind support and assistance.

Environmental and Techno-Economic Assessments, Portfolio Element 2.40, will support techno-economic analysis (TEA), lifecycle analysis (LCA), and assessments of environmental impacts from DAC manufacture, installation, and operation. TEA work will be led by FE, drawing on its existing (albeit small) portfolio of DAC technology development projects, coordinated with EPA, with the use of third-party independent analysis as necessary. The LCA and environment assessments will be led jointly by DOE/FE and the EPA's Office of Research and Development (ORD). It is proposed that EPA exercise its technology research and development (R&D) authorities under Section 103 of the CAA to coordinate with DOE/FE in this joint work.

Military Operational Energy Air/Water-to-Fuels Development, Portfolio Element 2.50, will support applied development of two categories of CO_2 removal and utilization technology for military liquid fuel production. Small-scale air-to-diesel systems appropriated for use at forward operating bases (FOBs) will be developed, led by the Army Research Laboratory (ARL) within DOD. Shipboard seawater-to-fuels systems will be developed, led by the Naval Research Laboratory (NRL) within DOD.

Support for At-Scale DAC Demonstration Projects

Table 2-3 does not include budget planning estimates for large-scale demonstrations of advanced DAC technologies. The pilot testing and demonstration of DAC plants, as well as the systems assessments of cost, lifecycle emissions, and environmental impacts, will be used to examine various DAC systems for feasibility and value of full-scale demonstrations. These would be conducted as part of the large-scale demonstration projects component of the overall RD&D initiative [**Portfolio element 8.10**], and as such would be assessed relative to all other CDR pathways that have reached the demonstration stage. DAC technologies that appear promising and also have a demonstrated need for publicly supported large-scale testing could therefore potentially qualify for funding under this component.

Table 2-3
Direct Air Capture RD&D Portfolio ($millions)

Portfolio Element	Funding Agency	Funding Office or Organization	Year 1	5-Year Total	10-Year Total
2.10 Advanced Materials					
2.11 DOE Energy Frontier Research Center	DOE	SC (BES)	$0	$24	$32
2.12 Grants and cooperative agreements	DOE	SC (BES)	$5	$50	$89
2.13 NSF Engineering Research Center	NSF	MPS	$0	$20	$25
2.14 Grants and cooperative agreements	NSF	MPS	$3	$44	$89
2.15 Materials testing and standards	DOC	NIST	$2	$16	$21
2.10 Subtotal, Advanced Materials			$10	$154	$256
2.20 Engineering Development					
2.21 Contactor design	DOE	FE	$3	$23	$33
	DOE	EERE (AMO)	$0	$17	$22
2.22 Manufacturing improvement	DOE	EERE (AMO)	$2	$37	$67
2.23 Low-carbon heat provision	DOE	FE	$4	$39	$69
2.24 Advanced systems and components	DOE	FE	$0	$25	$92
2.20 Subtotal, Engineering Development			$9	$141	$283
2.30 Pilot Plants, Test Facilities, and Demonstrations					
2.31 Scale-up studies and pilot plants	DOE	FE	$0	$90	$300
2.32 Operational data collection	DOE	FE	$0	$20	$25
2.33 Engineering design support	DOE	FE	$0	$30	$50
2.34 Regional and national test facilities	DOE	FE	$0	$100	$290
2.35 DAC demonstrations & National Air Capture Test Center	N/A	N/A	$0	$0	$0
2.30 Subtotal, Pilot Plants, Test Facilities, and Demonstrations			$0	$240	$665
2.40 Environmental and Techno-Economic Assessments					
2.41 External techno-economic analysis	DOE	FE	$3	$23	$48
2.42 Lifecycle analysis	DOE	FE	$2	$20	$45
2.43 Environmental impacts	EPA	ORD	$12	$70	$145
2.40 Subtotal, Environmental and Techno-Economic Assessments			$17	$113	$238
2.50 Military Operational Energy Air/Water-to-Fuels Development					
2.51 Forward operating base air-to-fuel system development	DOD	ARL	$7	$51	$79
2.52 Seawater-to-fuels system development ("blue carbon removal")	DOD	NRL	$7	$51	$79
2.50 Subtotal, Military Operational Energy Air/Water-to-Fuels Development			$14	$102	$158
TOTAL, Direct Air Capture			$50	$750	$1,600

Source: EFI, 2019.

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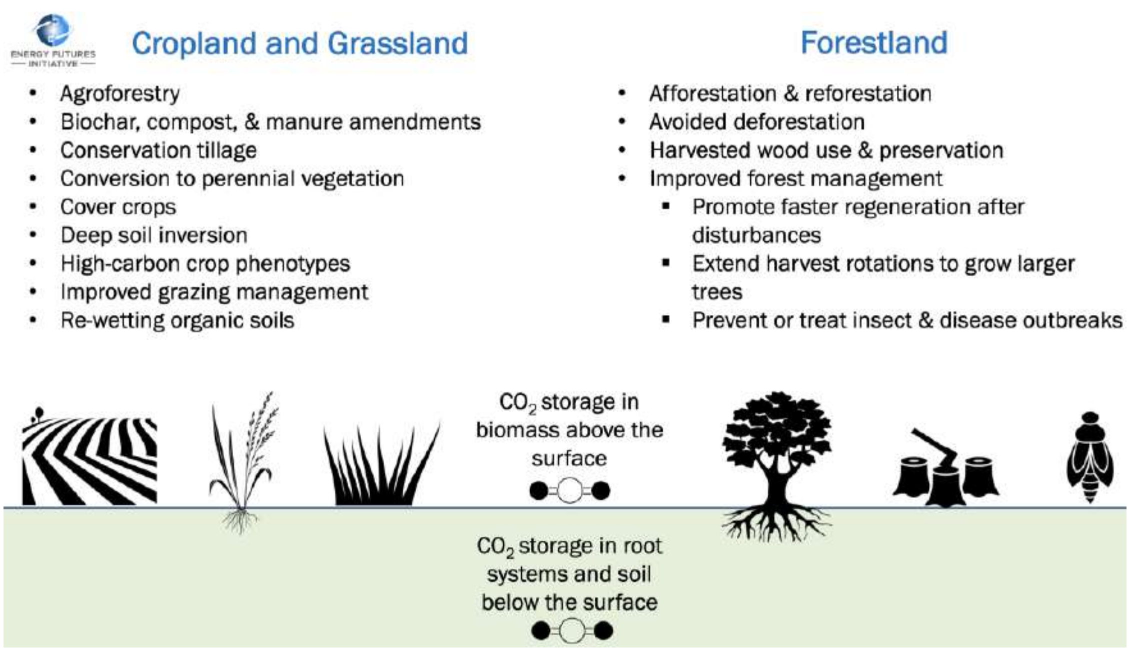
CHAPTER 3.
TERRESTRIAL AND BIOLOGICAL

All plants naturally remove CO_2 from the atmosphere as they grow through the process of photosynthesis. Some of this removed CO_2 is converted to biomass and soil organic carbon as a result of the balance between photosynthesis and respiration and several other biological factors. While the carbon in herbaceous biomass (e.g., leaves, grains) usually decomposes rapidly and is returned to the atmosphere on timescales of less than a year, carbon that is stored in some forms of living biomass or soils can remain for decades or longer.

Terrestrial CDR pathways (Figure 3-1)[1] focus on increasing the production of particular forms of living biomass and/or preserving it from decomposition (such as forest-related techniques) and increasing the creation of soil organic carbon and/or reducing its rate of loss (such as soil carbon storage).

Figure 3-1

Opportunities for Terrestrial and Biological CO_2 Capture



There are numerous strategies to enhance the uptake of CO_2 in terrestrial and biological ecosystems. Source: EFI, 2019. Compiled using data from National Academies of Sciences, Engineering, and Medicine. Graphics from Noun Project.

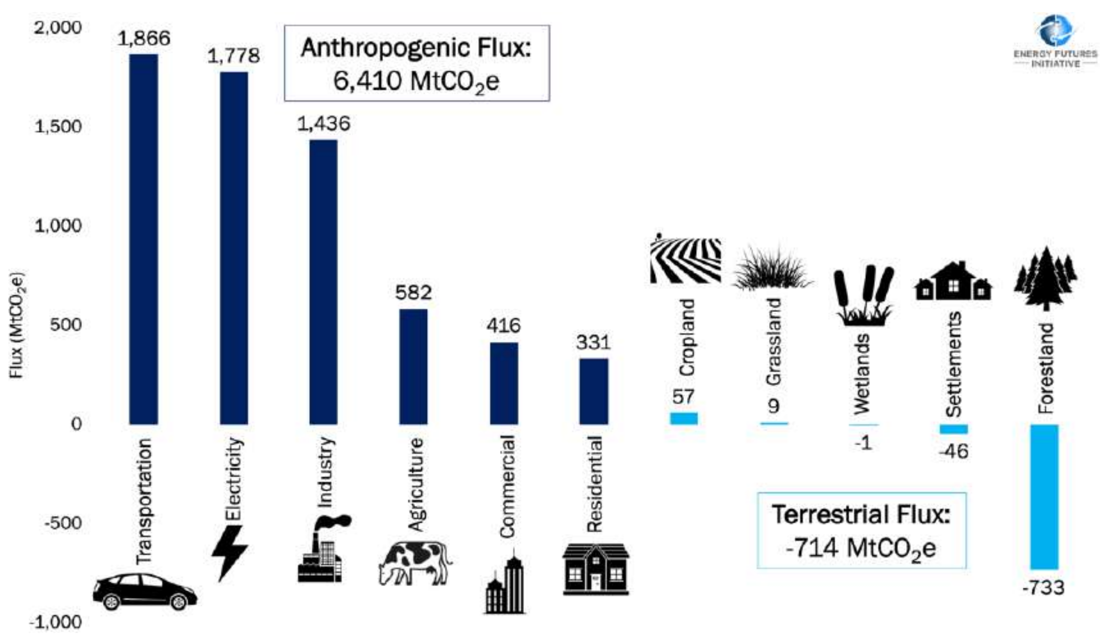
In addition to carbon removal, these pathways can have important co-benefits, including increased biodiversity, improved soil productivity, and reduced fertilizer use. Harvested wood also has a wide range of economically valuable applications, some of which are well-established (e.g., heating fuel), while others are relatively new or are reemerging as economically competitive with alternatives (e.g., building construction). Carbon that is fixed in biomass can also be used for energy production, such as generating electricity and manufacturing liquid fuels. Both herbaceous and woody biomass can be used in this way. In these cases, coupling biomass-based energy production with CCUS can result in reduced emissions and potentially net CO_2 removal (usually called BECCS). These pathways are of particular interest because their economic potential may lead to faster and more widespread deployment while also offsetting fossil fuel consumption.

As of 2017, the land use, land-use change, and forestry (LULUCF) sector in the United States was a carbon sink that accounted for a net carbon removal of 714 $MtCO_2e$, which was the equivalent of approximately 11 percent of total economywide emissions in that year (Figure 3-2).[2] Forestland is the major sink for net carbon removal in the U.S. LULUCF sector, which alone accounted for a sequestration rate of 733.1 $MtCO_2e$ in 2017.

Forestland in the United States has declined from an estimated 46 percent of total land area in 1630 to 33 percent in 2012, mostly due to conversion for agricultural activities.[3] Estimates suggest that forestland in the United States could be increased by 40 to 50 million acres in the coming decades as part of a deep decarbonization strategy; this would recovery one-third of lost forestland.[4]

Figure 3-2

Anthropogenic and Terrestrial CO_2 Fluxes in the United States, 2017



There is a substantial terrestrial CO_2 sink in the United States due largely to forests. However, this only offsets a relatively small portion of U.S. anthropogenic CO_2 emissions. Note: Numbers may not add exactly due to rounding. Source: EFI, 2019. Compiled using data from the Environmental Protection Agency.

Land Use Considerations for Bioenergy and Biological CDR

Despite the potential for carbon removal and other co-benefits, terrestrial and biological CDR pathways can also have limitations related to competing land uses such as food and fiber production. All of these CDR approaches rely on specific, and generally exclusive, uses of land. Forest-based approaches envision expanding the amount of land dedicated to tree growth, while BECCS envisions dedicating an increasing fraction of land to production of biomass for energy or harvesting an increasing fraction of residues. These various methods must be evaluated holistically to ensure that the "land budget" is not over-allocated when estimating the total carbon removal potential of a suite of terrestrial and biological CDR pathways. Moreover, approximately 70 percent of ice-free land surface globally is already impacted by humans, leaving little room for expanding the overall amount of land dedicated to specific purposes, including CDR.

A recent report from the IPCC noted that pursuing several terrestrial and biological CDR pathways at scale (e.g., afforestation, BECCS) can create greater demand for land conversion, and large-scale deployment of certain pathways could increase risks related to desertification, land degradation, and food security. Furthermore, some of these pathways may be vulnerable to reversal where the carbon that has been sequestered is released back into the atmosphere through various natural or human disturbances (e.g., forest fires, soil tillage).[5]

These concerns highlight the need for more comprehensive and inclusive system modeling, going beyond estimates that are based on extending each CDR pathway to "all available land" and instead emphasizing the significant constraints on land that can be used for these purposes (Chapter 8).[6]

Forest-Related CDR and Storage

Between 1850 and 2015, the clearing of forests to make way for agricultural land led to the loss of approximately 145 GtC (equivalent to 532 $GtCO_2$) from woody biomass and soils.[7] While it is widely recognized that avoiding deforestation has the most immediate impact on preserving carbon stocks in forestlands, this is considered a mitigation pathway and is therefore not addressed in this report. Instead, the forest-related CDR pathways considered here include actively afforesting lands that were not previously forested and/or reforesting previously cleared areas, modifying forest management practices to enhance carbon uptake and storage, and several emerging "frontier" pathways.

Afforestation and Reforestation

The practice of afforestation and reforestation is well understood, and there is deep expertise available to guide the selection of tree species and the optimal process for (re)planting. The rates at which afforestation and reforestation remove and store atmospheric carbon are estimated to be 0.7 to 6.4 MgC per hectare[a] per year (2.6 to 23 tCO_2 per hectare per year) over a period of 50 to 100 years in the United States.[8] The removal rate is thought to be fastest in the early stages of growth, saturating in later years

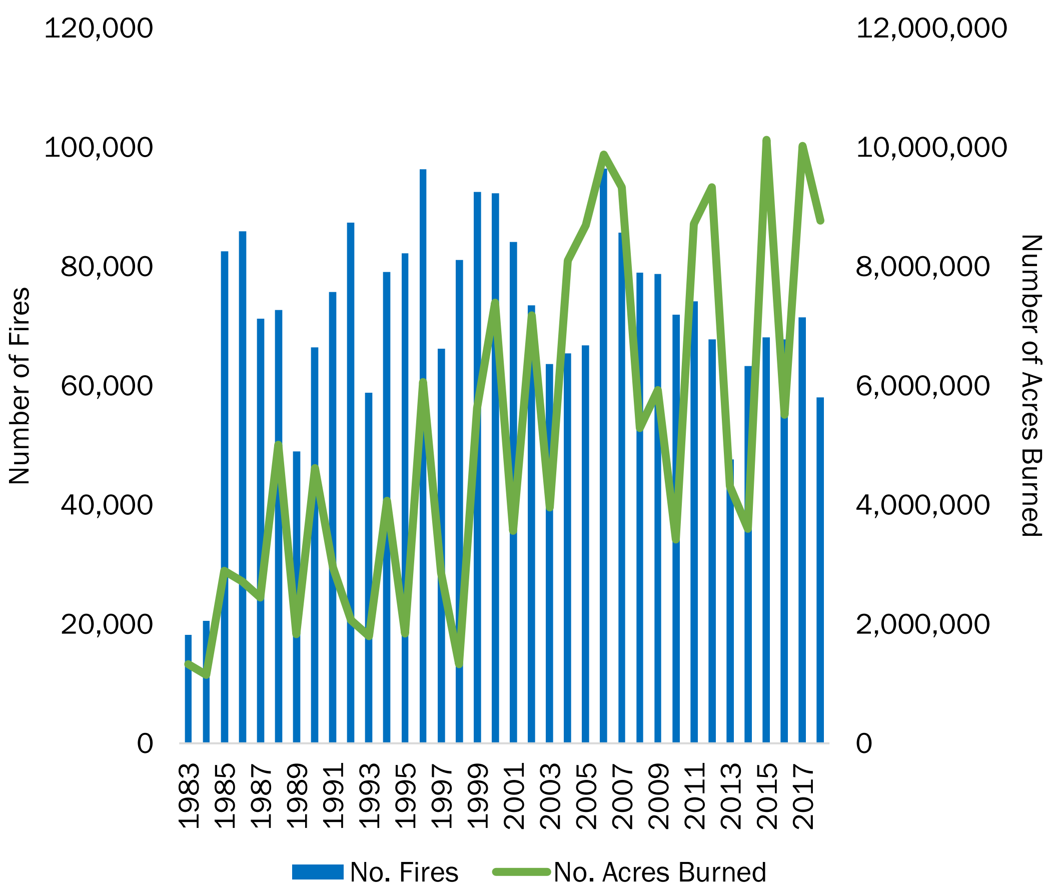
[a] 1 hectare is approximately 2.5 acres

as the forest reaches maturity, although the interactions among growth rate, lifespan, future climate scenarios, and carbon removal potential are still not entirely understood.[9]

Notably, if a forested area is disturbed through human activity or fires (Figure 3-3),[10] a substantial portion of its stored carbon can be released. For example, wildfires in California are estimated to have released 45.5 $MtCO_2$ in 2018, compared to total emissions of 424 $MtCO_2$ in 2017.[11,12] Globally, the expansion of agricultural land into previously unmanaged forested areas has led to a net decrease in CO_2 emissions from wildfires over the past 80 years.[13] However, it is unclear how this trend would be impacted by substantial amounts of afforestation and reforestation in the future.

Figure 3-3

Wildfire Activity in the United States, 1983-2017



The number of wildfires and acres burned has increased since 1983 in the United States. Source: EFI, 2019. Compiled using data from the National Interagency Fire Center.

Recommended RD&D Portfolio Elements

Forestry, Portfolio Element 3.10, addresses CDR RD&D for forestry. Since the forestry CDR pathways are relatively well established, their research needs are limited. The NASEM report recommended two specific research needs:

- **Enhanced Forest Stock Monitoring, Portfolio Element 3.11,** addresses the need to enhance the monitoring of forest carbon stock, as well as any "leakage" of timber harvest to other geographies in response to afforestation and reforestation efforts, in order to improve the understanding of the effectiveness of different approaches. The U.S. Forest Service (USFS) currently operates the Forest Inventory and Analysis (FIA) program,[14] which conducts an annual forest survey that covers all 50 states and includes data collection related to forest area and location, tree health and growth, and removals through harvest.[15] This program can be enhanced through improvements in the application of remote-sensing techniques.
- **IAMs and Forest Impacts Modeling, Portfolio Element 3.12,** addresses the need to update IAMs to include the technical, social, and economic impacts on land use from afforestation, reforestation, and forest management changes. Similar modeling should address the social and emissions impacts of reducing the use of biomass for heating and cooking. These studies would enable a better understanding of the implications for worldwide consumption of wood products, land-use change, and their associated lifecycle emissions. This work is proposed to be led by NSF/Directorate for Social, Behavioral, and Economic Sciences (SBE)[16] and USFS, in coordination with DOE and EPA.

Both of these research topics would improve the ability to estimate and validate CO_2 removal rates estimates and allow them to be better integrated into overall CDR modeling efforts.

Forest Management Pathways

Improved forest management practices such as extending timber harvest rotation, thinning and related silvicultural treatments to promote overall stand growth, and treating areas with insect or disease outbreaks are generally well understood. These practices are estimated to be able to remove and store atmospheric carbon at the rate of 0.2 to 2.5 MgC per hectare per year (0.7 to 9.2 tCO_2 per hectare per year) for several decades in the United States and globally (excluding the stock of harvested wood products).[17] The potential total removal rate of improved forest management practices is estimated to be 0.0 to 1.6 $GtCO_2$ per year in the United States and 1.1 to 9.2 $GtCO_2$ per year globally.[18]

- **Forest Carbon Management Demonstration, Portfolio Element 3.13,** addresses the primary research need for enhanced forest management techniques to be a set of large-scale field experiments of best practices for forest management that maximize carbon removal and storage. The demonstration projects will help confirm and better constrain these values and elucidate areas of remaining uncertainty and barriers to adoption. This effort is proposed to be led by USFS and EPA/ORD.

Frontier Pathways

A variety of pathways have been proposed for increasing the carbon removal and storage potential of forests. The most notable is advanced landfilling, in which wood waste from the processing of harvested timber and discarded wood products at the end of their lifecycle could be disposed in landfills optimized for minimizing decomposition (the opposite of most landfill designs), which would preserve their biomass in the stock of fixed carbon. These landfills could also potentially be used for green-tree burial, in which trees would be harvested and immediately buried/landfilled without further processing or utilization in order to enhance the stock of fixed/removed carbon. This would also allow further tree growth, and thus carbon removal, on the corresponding land. The pursuit of engineered wood products could also expand the opportunity for harvested wood to contribute carbon sequestration benefits, assuming sustainable forestry practices.[19]

Advanced landfilling with wood waste and end-of-life products is estimated to be able to create an additional sink of 0.1 to 0.3 $GtCO_2$ per hectare per year in the United States and 0.2 to 0.8 $GtCO_2$ per year globally. Preliminary analysis of the removal potential of green-tree burial suggests a rate of 1.0 to 3.0 $GtCO_2$ per year globally, requiring roughly double the current global wood harvest.[20]

- **Preservation of Harvested Wood, Portfolio Element 3.14,** supports work on the design and demonstration of landfills intended to minimize biological decomposition of wood. The concept of green-tree burial should also be analyzed through modeling and simulation and considered for demonstration if it appears promising. This work is proposed to be led by USFS and EPA/ORD.

Land Considerations and Costs

Accomplishing CDR through expansion of afforestation and reforestation would require significant land-use change. At the low end of the spectrum, a removal rate of 0.15 $GtCO_2$ per year would require converting approximately 3 million to 4 million hectares of non-forested land to never-to-be-harvested forestland, equivalent to approximately 1 percent of the total U.S. forestland area.[21] Achieving a higher removal rate of 0.4 $GtCO_2$ per year would require conversion of up to an estimated 20 million hectares of land.

The total removal potential of afforestation and reforestation is estimated to be 0 to 0.45 $GtCO_2$ per year in the United States and 2.7 to 17.9 $GtCO_2$ per year globally, with the higher end of this range applying to scenarios with carbon prices of up to \$100 per tCO_2.[22] These pathways therefore meet the target thresholds for removal potential and cost for investment in RD&D.

The proposed CDR RD&D portfolio does not address directly the issue of expansion of afforestation and reforestation. It focuses instead on the research to improve the tools, techniques, and monitoring that would make any deployment program of afforestation and reforestation more effective.

Enhanced Soil-Based CDR and Storage

Globally, soils down to 1 meter in depth contain approximately 1,500 to 2,400 GtC (equivalent to 8,067 $GtCO_2$) in the form of soil organic carbon (SOC).[23] This motivates the investigation of soil carbon storage techniques. However, most agricultural soils in the United States and globally are not actively managed with the explicit objective of promoting soil carbon accumulation and retention. The long history of agricultural and grazing patterns has been to reduce organic matter in soils; since agriculture was first practiced 12,000 years ago, an estimated 116 GtC (equivalent to 425 $GtCO_2$) have been lost from soils globally.[24] Pathways to remove CO_2 from the atmosphere and store it in soils include conventional management practices for cropland and grassland, biochar amendment, deep soil inversion, and the development of high carbon input crop varieties.

Cropland and Grassland Management

There are many well-understood agricultural practices that increase the amount of carbon stored in the soil. These include the expanded use of cover crops to replace winter bare fallow; an increased use of resource-conserving crop rotation, compost, and manure amendment; and the use of reduced- or no-till practices.[25] These techniques enhance carbon storage by increasing the fraction of time that soil is covered with vegetation, increasing the amount of plant residues left on the soil, increasing direct carbon inputs, and reducing soil disturbances that accelerate decomposition.[26]

There is also a range of techniques to grassland management that increase stored soil carbon. The most well-understood technique is reducing overgrazing, which allows plant productivity to recover. There is more uncertainty around the relative impacts on soil carbon storage of continuous grazing versus intensively managed, periodic grazing systems. Furthermore, organic soils (e.g., peats) have an extremely high fraction of carbon but lose carbon rapidly when drained and converted to agriculture. Rewetting these soils to convert them back to wetlands can lead to significant carbon removal and soil storage.[27]

The "practically achievable" rate of carbon removal and storage from these pathways is estimated to be 0.25 $GtCO_2$ per year in the United States and 3 $GtCO_2$ per year globally, according to NASEM.[28]

Recommended RD&D Portfolio Elements

The NASEM report identified a series of specific recommendations on research needs for soil carbon RD&D. Each is specifically addressed in the recommended RD&D portfolio.

- **Fundamental Research, Portfolio Element 3.21,** supports fundamental research on soil carbon chemistry. Funding is recommended to support research programs at USDA Agricultural Research Service (ARS), DOE Biological and Environmental Research (BER), and the NSF Directorate for Geosciences (GEO).
- **Enhanced Soil Monitoring, Portfolio Element 3.22,** is to expand the monitoring of soil carbon fluxes through a combination of in situ sensors and remote sensing. This is proposed to be led by the USDA Natural Resources Conservation Service

(NRCS) by expanding the National Resources Inventory (NRI) program and the National Aeronautics and Space Administration (NASA) Earth Sciences Division (ESD).

- **Cultivation System Optimization, Portfolio Element 3.24,** supports research projects to develop and test regionally specific best-practice approaches to cropland and grassland management for increased soil carbon sequestration. This is proposed to be led by USDA/ARS.
- **Modeling and Predictive Tool Development, Portfolio Element 3.27,** is to develop a data platform that integrates data from soil carbon flux monitoring with simulation tools to model and predict spatially resolved soil carbon sequestration. This should be led by USDA/ARS and the NSF/GEO.
- **Scaling Up Agricultural Sequestration, Portfolio Element 3.28,** involves research to identify barriers to adoption of the broad set of agricultural CDR pathways. This is proposed to be led by USDA/NRCS.

Biochar Amendment and Reactive Minerals

Biochar is an organic carbon material that results from pyrolysis (heating in the absence of oxygen) of plant matter. The pyrolysis process liberates oil and volatile compounds that are useful for bioenergy and biomaterials, leaving biochar as the residual material. When added to soil, biochar can be extremely resistant to decomposition and thus form a potential long-term storage opportunity for carbon. In some contexts, biochar also enhances soil productivity and reduces non-CO_2 GHG emissions. However, there are major uncertainties about the impacts of biochar prepared under different pyrolysis conditions, as applied to different soil types and climate conditions. The global potential sink capacity from large-scale deployment of biochar application is estimated in various studies to be 0.5 to 6.6 $GtCO_2$ per year.[29]

- **Biochar Impact Studies, Portfolio Element 3.25,** provides for a research program to support a set of carefully monitored field studies on the impact of biochar prepared under different conditions on soil carbon, crop productivity, water and nutrient retention, albedo, and soil residence time. This is proposed to be led by USDA/ARS.
- **Reactive Minerals in Agricultural Soils, Portfolio Element 3.26,** supports research on surficial carbon mineralization (discussed in more detail in Chapter 4). Surficial carbon mineralization involves spreading chemically reactive alkaline minerals on land, leading to reactions with and removal of atmospheric CO_2. The primary research need for this technique in the context of agriculture is better understanding the impact of the application of these materials to agricultural soils. This effort is proposed to be led by USDA/ARS.

Deep Soil Inversion

Since microbial decomposition of soil organic matter decreases significantly with depth, as does carbon content, researchers have investigated the impact of a one-time “deep tillage” that buries surface soil at depths of 50 centimeters or more, exposing lower-carbon-content soil on the surface.[30] This can help increase long-term soil carbon retention and increase the rate of soil carbon uptake. Initial experiments in Germany have shown that this practice can lead to carbon removal rates of 3.6 tCO_2 per hectare per year over a time period of 40 years.[31] No estimates of global potential are currently available.

- **Fundamental Research, Portfolio Element 3.21,** discussed earlier, will support fundamental research projects to develop and test methods for deep inversion, accompanied by the monitoring of impacts on soil carbon uptake, crop productivity, water and nutrient retention, albedo, and soil residence time. This is proposed to be led by USDA/ARS in coordination with the DOE/BER program and NSF/GEO.

High Carbon Input Crop Phenotypes

Most soil organic carbon comes from plant roots, either as transfer to soil microorganisms or from root death. The size, shape, and depth of plant roots are usually genetic traits; it should be possible to breed crop varieties that grow deeper, larger roots and thereby add more carbon to the soil. Similar approaches could lead to varieties that produce more root mass in the form of biopolymers such as suberin that are highly resistant to decomposition. Adoption of these varieties is estimated to be able to lead to carbon removal rates of 0.5 to 0.8 $GtCO_2$ per year over several decades in the United States.[32]

A related strategy is to develop perennial varieties of the most widespread annual grains (e.g., wheat, maize, rice) and oilseeds (e.g., soybeans, sunflowers). Perennial analogs for these crops would grow larger roots and transfer more carbon to the soil, thereby increasing carbon removal and storage rates, although estimates of the scale are not currently available.

Current research programs provide a strong foundation for advancing the state of the science in this area. This includes the DOE Advanced Research Projects Agency-Energy (ARPA-E) Rhizosphere Observations Optimizing Terrestrial Sequestration (ROOTS) program (Box 3-1) and private sector efforts such as the Salk Institute.

Box 3-1

DOE ARPA-E ROOTS Program

The ARPA-E ROOTS program is focused on developing “root-focused” cultivars of crops that can increase soil carbon sequestration by 50 percent, while also increasing water productivity by 25 percent and decreasing N_2O emissions by 50 percent. Launched in 2016, ROOTS awarded $35 million to 10 projects that are developing tools to improve the ability to characterize the root size and structure of growing crops in a nondestructive manner. These sensor platforms will also collect data on soil properties near root systems, including water and nitrogen levels. Information about root architecture and soil properties will inform breeding and cultivar development projects for wheat, corn, sorghum, and other crops.[33]

- **High-carbon Input Crop Phenotypes, Portfolio Element 3.23,** supports an expanded research program to screen and develop crop varieties with improved soil sequestration and equivalent or improved above-ground productivity. The program would primarily use conventional breeding and selection methods but may also explore genetic modification to engineer desired traits. Investigating perennial analogs of grain and oilseed crops should be a secondary priority for this research area. This is proposed to be led by USDA/ARS. This portfolio element could be funded from a mix of new funding and refocusing of existing research programs that currently support efforts to develop crop phenotypes focused more narrowly on other research objectives such as improved productivity and reduced nutrient intake. DOE/BER and NSF/SBE programs also could provide important contributions to this portfolio element.

Box 3-2

The Salk Institute's Harnessing Plants Initiative

The Salk Institute is an independent nonprofit research institution for biological sciences located in San Diego, California. Founded by Jonas Salk, the inventor of the polio vaccine, the institute is a global leader in biological research. It is supported by a combination of grants and donations, bringing in $136 million in revenue in fiscal year 2018.[34]

The Salk Institute is currently pursuing a CDR R&D project centered on the genetic modification of plants to increase their CDR potential. The Harnessing Plants Initiative aims to develop "Salk Ideal Plants," which will have:[35]

- Deeper and bigger root systems, to be able to store more carbon; and
- Roots that contain more suberin, a naturally occurring polymer (found in cork and cantaloupe rinds) that resists decomposition, slowing CO_2 release.

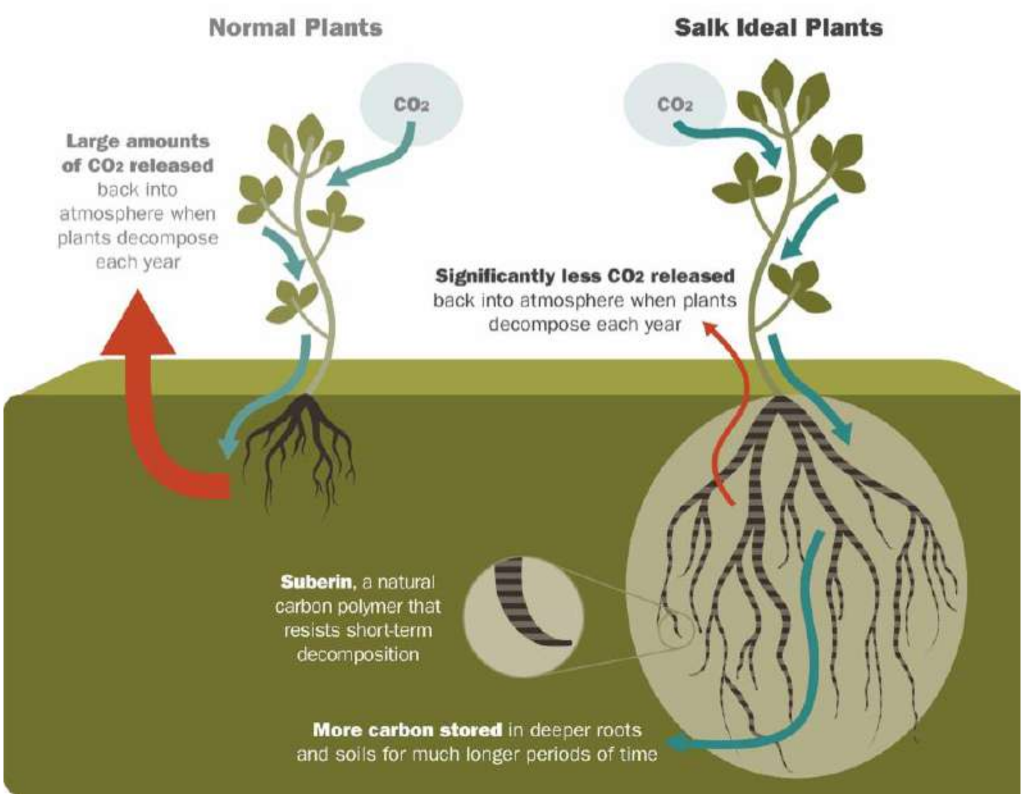
The institute is currently working on developing these modifications in model plants and later transferring the traits to major food crops (canola, cotton, soybean, rice, maize, and wheat) and cover crops (radish, crimson clover, and annual rye grass). The institute is also considering pathways to transfer these characteristics to aquatic plants in wetland systems in order to help restore ecosystems and boost coastal blue carbon uptake.[36] The Institute says that Salk Ideal Plants will provide ancillary benefits, including improved soil health; improved (or neutral impact on) crop yield; and increased tolerance to drought, heat, and flooding.

The Harnessing Plants Initiative is in its early stages. In 2019, the initiative received a gift of $35 million from a group of foundations and donors through The Audacious Project, an organization that directs philanthropic funding to projects that tackle large global challenges.[37] The initiative has convened a group of scientists to work on the project and is building out capacity. The current phase of the project involves basic research on genetic enhancement, gene stacking, etc., and later field testing with model plants. The eventual plan for commercialization involves engaging and licensing to commercial partners. The initiative has been and will continue to publish some of the results in journals in order to facilitate knowledge-sharing.

The Salk Institute's goals for this project are highly ambitious. The project claims that Salk Ideal Plants will be faster to implement at scale and more cost-effective than other CDR pathways.

They estimate a CDR cost of $8 per tCO_2, based on the assumption that Salk Ideal Plant seeds will cost double the seeds of current crops (at maximum).[38] The Institute estimates that when planted at scale, the Salk Ideal Plants can achieve at 20 percent to 46 percent reduction of annual excess CO_2 levels.[39]

Figure 3-4
Salk Ideal Plants Core Idea



Bioenergy with Carbon Capture and Sequestration

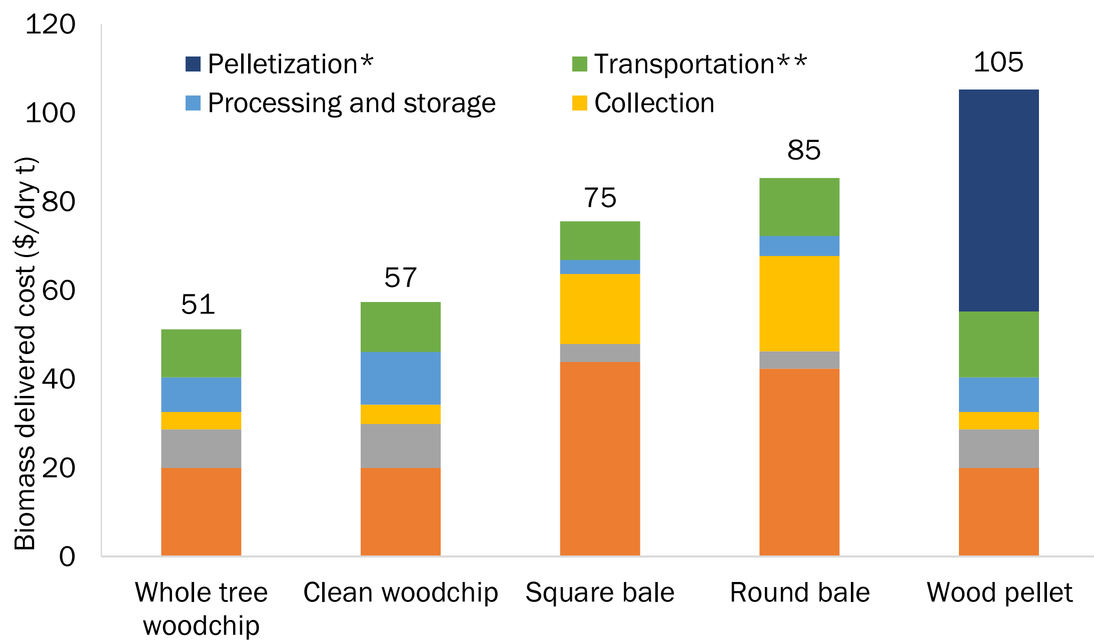
The concept of BECCS encompasses both *biopower* and *biofuels*. BECCS conventionally refers to firing biomass in boilers to generate steam for electricity production, accompanied by post-combustion capture of CO_2 from flue gas and subsequent storage (biopower with CCUS). It also includes the conversion of biomass to liquid fuel through fermentation, or to liquid fuel and volatiles through thermochemical routes, possibly accompanied by the production of biochar (biofuels with CCUS/biochar). Since plants capture and fix atmospheric carbon as they grow, converting biomass to various forms of energy and capturing CO_2 emissions can result in net carbon removal.

Biomass Productivity and Transportation

The potential carbon removal scale of all BECCS approaches is limited by the availability of biomass, and the cost of delivered biomass can vary considerably depending on the type of feedstock (Figure 3-5).[40] At a price of $60 per ton, an estimated 1 billion dry tons of biomass could be available in 2030 in the United States, rising to 1.2 billion in 2040, with contributions from forestry, agriculture, and waste.[41] Achieving high levels of biomass fuel could place pressure on the production of food and fiber due to competition for land. Improvements in biomass cultivation productivity could help lessen this pressure.

Figure 3-5

Breakdown of Delivered Biomass Cost



*Note: Assumed capacity of 2,600 dry tonnes per day; *source of energy for drying and pelletization: natural gas; ** using trucks.* Source: Herzog, 2019, courtesy of MIT Energy Initiative.

Biomass resources are also not evenly distributed and must be transported to processing locations. Transport by barge is significantly cheaper than all other modes, but it is not available in all locations. Truck transport is the next cheapest option for distances below 150 to 350 kilometers, at which point rail transport becomes preferable. Costs for these distances are estimated to be $10 to $20 per ton, representing a significant fraction of overall supply costs.[42]

Biomass from microalgae may also represent an important resource for BECCS if technological scaling challenges can be overcome.[43] For microalgal cultivation to be relevant to CDR, it will be necessary to improve strains, better understand the microbiome of operating production systems, and develop improved concepts for rapid delivery of CO_2 to cultivation ponds. Microalgal systems may be able to directly remove CO_2 from ambient air (avoiding the cost of concentrated CO_2 delivery) through the use of genetic modification techniques to enhance the production of the enzyme carbonic anhydrase or other approaches.

Biomass Conversion Options

Biomass energy encompasses a broad array of potential biomass feedstocks, conversion processes, and ultimate forms of energy and bioproducts. While there has been a robust foundation of R&D on various biomass energy permutations and combinations, not all are at the same degree of technological maturity. The breadth of options and range of technology maturation are illustrated in (Figure 3-6).[44] The principal biomass conversion alternatives that are most relevant for consideration as CDR pathways include the following:

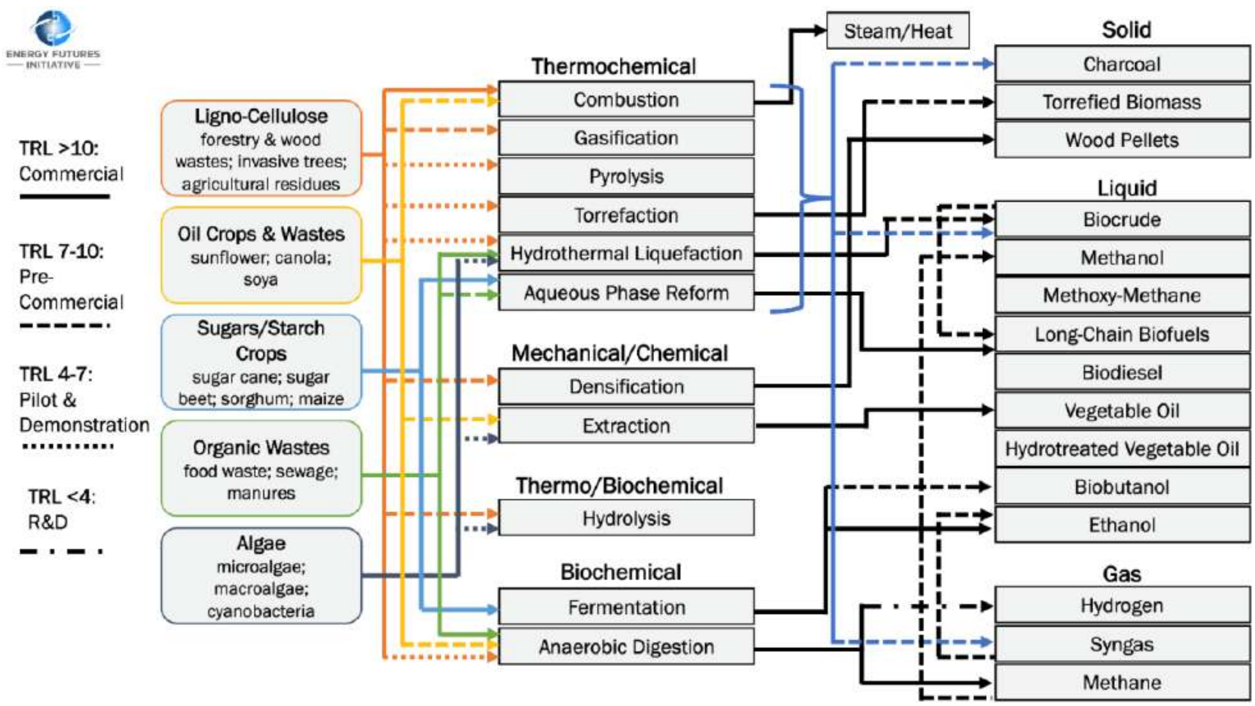
Biopower. Biomass can be combusted to produce steam for power generation, accompanied by flue-gas CCUS (biopower with CCUS). The combustion process is relatively well understood, but biomass power plants often have lower efficiency than coal plants.[45] Biomass is less energy-dense than coal, with a higher moisture content and a higher hydrogen-to-carbon ratio. It is also more heterogeneous, increasing the need to characterize arriving fuel shipments and potentially requiring blending. It is also prone to degradation from handling and weather, increasing costs for transportation and storage.

The pretreatment of biomass can help improve combustion efficiency, including methods such as torrefaction (mild pyrolysis) and densification (briquetting and pelleting), although these incur additional costs and emissions. Because of their flexibility, fluidized bed boilers (either circulating or bubbling) are the best-suited for biomass combustion but are relatively rare in the U.S. coal fleet, limiting deployment potential. Retrofit of existing coal-fired power plants to burn biomass represents a potentially large opportunity for biopower with CCUS deployment. However, almost all of this capacity utilizes pulverized coal boiler technology, representing a more challenging application for coal-to-biomass conversion. Differences in fuel handling (in the pulverization stage), combustion temperatures (biomass more closely matches subbituminous coals), and ash composition and volume are perhaps the most difficult challenges. Most U.S. applications of coal-to-biomass in power plants rely on co-firing, i.e., using coal in combination with biomass as the fuel and thus reducing the operating challenges.

The Drax project (Box 3-3) is the most prominent deployment of a pulverized coal boiler with 100 percent biomass fuel and CCUS. In February 2019, the Drax Power Station in England initiated operation of a BECCS pilot that captures 1 tCO_2 per day and became the first project in the world to capture CO_2 from the combustion of a 100 percent biomass feedstock.[46] Biomass contains lower levels of sulfur and nitrogen than coal;

consequently, coal-to-biomass conversions also provide benefits in terms of reduced NOx and SO_2 emissions.[47]

Figure 3-6
Biomass Conversion Pathways



There are multiple biomass conversion pathways. Source: National Academies of Sciences, Engineering, and Medicine.

Box 3-3
Drax Power Station

Drax Power Station in Selby, England, is the United Kingdom's largest power station.[48] Constructed as a coal-fired station by the government-owned Central Electricity Generating Board in the 1970s, it is now owned by Drax Group, which also owns a number of other power stations and electricity supply chain businesses. The 4-gigawatt (GW) power station,[49] which generates 5 percent of the UK's electricity,[50] consists of six generating units, plus a 75-megawatt (MW) backup gas plant.

Four of the generating units (each of which has its own boiler and turbine assemblage) have been converted from coal to biomass and now are fueled by wood pellets.[51] These units' configuration was mostly unchanged in the conversion: The pulverizers and boilers were modified to accept the pellets, but the turbines and generators remain the same.[52] More expensive upgrades were required for the biomass's storage, transportation, and supply chain. The wood is largely imported from outside the UK; U.S. wood pellet exports to the UK grew from

637 kilotons in 2012 to 4,177 kilotons in 2017, largely because of Drax.[53] Drax has announced plans to convert the remaining two units to natural gas and to connect them to battery storage.[54] These units currently co-fire limited quantities of biomass alongside coal.[55]

Drax had previously explored CCUS with the now-canceled White Rose project, which would have constructed a new coal plant with carbon capture. It is now pursuing BECCS technology through a partnership with C-Capture, a spinoff company from the University of Leeds. A pilot plant has been constructed and has been capturing carbon since February 2019.[56] The pilot plant uses flue gas from the biomass units at Drax and C-Capture's solvent to capture one tCO_2 per day. The pilot is scheduled to run for six months. Captured CO_2 is currently stored on site,[57] but Drax is exploring utilization options, such as fuels and beverages.[58] C-Capture and Drax have also done a lab-scale study of the feasibility of converting the flue gas desulphurization absorbers at Drax for CCUS, which are now defunct on the biomass-burning units.

Drax has invested £400,000 (around $500,000[b]) into the pilot project;[59] it has also been subsidized by the UK government, largely through different programs of the Department for Business, Energy, and Industrial Strategy (BEIS). C-Capture has received £2.2 million ($2.7 million) in funding from BEIS's Energy Entrepreneurs Fund and £3.5 million ($4.4 million) in equity funding from Drax and others.[60] In June 2019, Drax and C-Capture secured a grant of £5 million ($6.2 million) through BEIS's carbon capture, utilization, and sequestration (CCUS) innovation program for work over two years that includes an extension of the pilot facilities, optimization trials, and a chemistry validation and testing program (with SINTEF and the CO_2 Technology Centre in Norway), and made movement toward commercial-scale deployment—which could include repurposing existing Drax infrastructure for BECCS.[61] Drax has received an additional grant of £500,000 ($620,000) from BEIS's Carbon Capture, Usage, and Demonstration program to study the feasibility of additional CCUS with a different technology—molten carbonate fuel cells from the U.S.-based FuelCell Energy.[62] These grants are in addition to the renewable generation subsidy that Drax already receives on one of its units under the Contracts for Difference program (also through BEIS) and the Renewables Obligation Certificates (analogous to Renewable Energy Certificates in the United States) that it generates.[63]

Because of higher feedstock costs, lower efficiency, and higher capital costs, biopower is more expensive than natural gas-fired generation, with levelized costs before adding CCUS of approximately $100 per MWh compared with $41 to $74 per MWh for natural gas power generation.[64,65]

The higher costs for biopower compared with natural gas-fired generation, combined with the challenges of retrofitting coal-fired power plants to biomass, suggest it is unlikely that biopower with CCUS could ever compete in electricity markets alone. Therefore, a price on carbon would be needed to make BECCS economically viable (similar to many other CDR technologies), but the revenue from power sales may offset the level of needed carbon price relative to the carbon price required for other CDR approaches. The appropriate focus for an RD&D agenda on biopower with CCUS is therefore to reduce the overall cost of CO_2 removal, not power generation *per se*.

[b] All USD conversions in this box use the average July 2019 exchange rate from OFX

Biofuels. Biomass can also be fermented to produce liquid fuel (ethanol), accompanied by CCUS. Since fermentation produces nearly pure CO_2, the costs for separation and capture are much lower than in the case of combustion. It is estimated that approximately 60 percent of the CO_2 currently emitted by U.S. ethanol plants (45 $MtCO_2$ per year) could be captured and compressed at a cost of under $25 per tCO_2.[66]

Bioproducts. Biomass can also be treated thermochemically to produce oils, synthesis gas, biogas, hydrogen, and biochar. Although these processes produce CO_2, they can potentially incorporate conventional CCUS technology to operate as a negative emissions strategy. Carbon in the form of solid biochar can also be buried as a form of storage; in agricultural soils, this may have beneficial effects for productivity. While current thermochemical conversion methods that produce biochar are not optimized, if they were modified, the cost of carbon removal could be in the range of $37 to $132 per tCO_2, neglecting any revenues from the sale of biochar.[67]

Hybrid Systems

Recently, Segues et al. have proposed a hybrid BECCS-DAC system, in which biomass is used as the energy source for direct air capture (DAC). They find this type of system could increase net CO_2 removal by 109-119 percent at lower costs than stand-alone DAC, with a potential capacity in the US of 1.5 $GtCO_2$ per year in 2030. Hybrid systems of this kind have not previously been examined in detail, and merit further research.[68]

Recommended RD&D Portfolio Elements

- **Algal Biomass Capture, Portfolio Element 3.31,** supports research on algal biomass systems to explore the feasibility of optimizing algal systems as a means of CO_2 air capture. Current federally funded research on algal systems focuses on overall energy yield and not CO_2 capture. This concept was not addressed in the NASEM CDR pathways report but is explored in more detail in a separate white paper to be released in parallel with this report. This effort is proposed to be led by DOE, acting through the BER and BETO program offices.
- **Biomass Supply, Logistics, and Pretreatment, Portfolio Element 3.32,** supports expanded research on biomass supply, logistics, and pretreatment. All BECCS pathways could benefit from research on biomass supply and transportation logistics. Research is needed on improving the understanding of optimal logistics for biomass transport, including the trade-off between densification and pretreatment at distributed versus centralized facilities through modeling and simulation. A related need is the development of improved methods of biomass pretreatment, both as a drop-in replacement for coal (biopower) and pretreatment to better enable biomass fermentation and thermochemical conversion to liquid fuels and/or biochar. This research could be implemented with a test facility to develop, scale up, and validate both categories of pretreatment technologies, taking advantage of technology synergies. This effort should be led by DOE/BETO and the USDA National Institute of Food and Agriculture (NIFA), under the existing Biomass Research and Development Initiative (BRDI),[69] whose mandate was expanded to explicitly include CDR in the 2018 Farm Bill.

- **Biomass Conversion to Fuels with Biochar, Portfolio Element 3.33,** supports research related to biochar production and utilization. Research is needed on improving thermochemical biomass conversion pathways, particularly fast pyrolysis. Identifying optimal conditions for producing bio-oil and biochar would enhance the utility of this conversion pathway in providing drop-in biofuels with associated carbon removal.[70] It may also enable distributed biomass processing that would reduce logistics challenges. Research in this area should be accompanied by analysis of the potential scale of carbon removal from biomass-derived fuel with biochar. This effort should be led by DOE/BETO and USDA/NIFA under the existing BRDI.
- **Advanced Biomass-to-Power Conversion, Portfolio Element 3.34,** supports research on the development of advanced boiler technology for biomass firing for power generation, particularly in existing coal-fired power plants. This work should be accompanied by a careful analysis of the lifecycle impacts of biomass firing with CCUS, including the associated emissions from transportation and the impact on forests and land-use change. This work is proposed to be led by DOE/FE.

Disruptive Research/Novel Concepts, Portfolio Element 3.40, provides a separate budget planning estimate line item to support research on disruptive concepts. Because of the well-established science and technology base for the terrestrial and biological CDR pathway, the RD&D recommendations in the proposed portfolio largely support incremental improvements to current technologies and methods. A separately funded program of disruptive research will enable new ideas to seek funding support and not be crowded out by conventional thinking in this CDR pathway. The new authorized Agriculture Advanced Research and Development Authority (AGARDA) program (Box 3-4) may be the appropriate vehicle to lead this effort, since its charter includes an explicit mandate for research on innovative approaches to terrestrial and biological CDR.

- **AGARDA, Portfolio Element 3.41,** includes funding for AGARDA to implement a program of innovative approaches to terrestrial and biological CDR. Other USDA programs and the DOE BER and BETO programs also may set aside a small portion of overall funding to ensure that innovative and potentially disruptive concepts receive appropriate attention within their research portfolios.

Box 3-4

Agriculture Advanced Research and Development Authority

The Agriculture Improvement Act of 2018 (P.L. 115-334, the "2018 Farm Act") established a five-year pilot program at USDA known as the Agriculture Advanced Research and Development Authority (AGARDA). This program, which has similarities to the Defense Advanced Research Projects Agency (DARPA), Advanced Research Projects Agency–Energy (ARPA-E), and other advanced research agencies, is intended to support the development and deployment of advanced agricultural technology, with a focus on export competitiveness, environmental sustainability, resilience to extreme weather, and economic opportunities for farmers, ranchers, and rural communities.

The director of AGARDA will be appointed by, and will report to, the USDA chief scientist (who also serves as the Under Secretary for Research, Education, and Economics). The AGARDA authority is extremely broad and enables USDA to support RD&D on a wide range of innovative technologies related to agriculture and natural lands. It is not restricted to conventional forms of financial support or a limited set of funding recipients, as is the case for many other USDA RD&D programs.

The legislation authorizes AGARDA $50 million per year for fiscal years 2019 through 2023, although no funds have yet been appropriated. USDA has until December 2019 to develop a strategic plan for AGARDA (no date is specified for naming a director). Because of its mission focus and operational flexibility, the AGARDA program, if fully funded and established, could be an important source of support for RD&D on terrestrial and biological CDR and biological conversion of CO_2 for utilization.[71]

Program Coordination Within USDA

As discussed above, a number of CDR research areas should be pursued by various offices within USDA (Table 3-1). It will be necessary to carefully coordinate this work across the agency to ensure close cooperation among different USDA offices and appropriate leveraging of funding resources to avoid duplication. The Under Secretary for Research, Education, and Economics (REE), who also serves as the USDA chief scientist, should be designated as the lead for coordinating all USDA activities related to CDR and should also serve as the lead for interagency coordination as necessary. USDA should also seek to leverage its existing network of climate hubs for CDR RD&D, particularly for topics that are regionally specific. USDA's focus on technology transfer—including more than 300 invention disclosures, 100 granted patents, and 200 active Cooperative Research and Development Agreements (CRADAs) in fiscal year 2018—highlights the importance of coordination with relevant intellectual property (IP) organizations within USDA, particularly the ARS Office of Technology Transfer, as an avenue to help accelerate the rapid and widespread commercial adoption of CDR technology.[72] (See Chapter 9 for further discussion of how USDA's RD&D infrastructure should implement efforts related to CDR.)

The overarching RD&D objective for terrestrial and biological CDR is to develop new approaches for enhanced carbon uptake in trees, plants, and soils in a manner consistent with advancing traditional food and fiber mission objectives.

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Table 3-1

Terrestrial and Biological RD&D Portfolio ($millions)

Portfolio Element	Funding Agency	Funding Office or Organization	Year 1	5-Year Total	10-Year Total
3.10 Forestry					
3.11 Enhanced forest stock monitoring	USDA	USFS	$5	$25	$35
3.12 IAMs and forest impacts modeling	NSF	SBE	$3	$15	$30
	USDA	USFS	$3	$15	$30
3.13 Forest carbon management demonstration	USDA	USFS	$3	$9	$9
	EPA	ORD	$2	$6	$6
3.14 Preservation of harvested wood	USDA	USFS	$1	$3	$3
	EPA	ORD	$1	$3	$3
3.15 Extension and outreach	USDA	USFS	$0	$0	$0
3.10 Subtotal, Forestry			$18	$76	$116
3.20 Soil Carbon Storage					
3.21 Fundamental research	USDA	ARS	$10	$50	$100
	DOE	SC (BER)	$5	$25	$50
	NSF	GEO	$5	$25	$50
3.22 Enhanced soil monitoring	USDA	NRCS	$3	$15	$30
	NASA	ESD	$2	$10	$20
3.23 High-carbon input crop phenotypes	USDA	ARS	$5	$145	$395
	USDA	*ARS (redirected)*	*$0*	*-$65*	*-$190*
3.24 Cultivation system optimization	USDA	ARS	$5	$27	$62
3.25 Biochar impact studies	USDA	ARS	$3	$15	$30
3.26 Reactive minerals in agricultural soils	USDA	ARS	$3	$15	$30
3.27 Modeling and predictive tool development	USDA	ARS	$5	$25	$25
	NSF	GEO	$5	$25	$25
3.28 Scaling up agricultural sequestration	USDA	NRCS	$0	$4	$4
3.20 Subtotal, Soil Carbon Storage			$51	$316	$631
3.30 Bioenergy with Carbon Capture and Sequestration					
3.31 Algal biomass capture	DOE	SC (BER)	$2	$28	$63
	DOE	EERE (BETO)	$2	$28	$63
3.32 Biomass supply, logistics, and pretreatment	USDA	NIFA	$2	$37	$80
	DOE	EERE (BETO)	$2	$37	$80
	DOE	EERE (BETO)	$4	$69	$144

3.33 Biomass conversion to fuels with biochar	USDA	NIFA	$4	$69	$144
3.34 Advanced biomass-to-power conversion	DOE	FE	$5	$50	$154
3.35 Biomass to fuel with CCUS	DOE	EERE (BETO)	$0	$0	$0
3.30 Subtotal, Bioenergy with Carbon Capture and Sequestration			$21	$318	$728
3.40 Disruptive Research/Novel Concepts					
3.41 AGARDA	USDA	AGARDA	$0	$40	$100
3.40 Subtotal, Disruptive Research/Novel Concepts			$0	$40	$100
TOTAL, Terrestrial and Biological			$90	$750	$1,575
Source: EFI, 2019.					

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72 FY2018 Annual Report on Technology Transfer, USDA (2019).

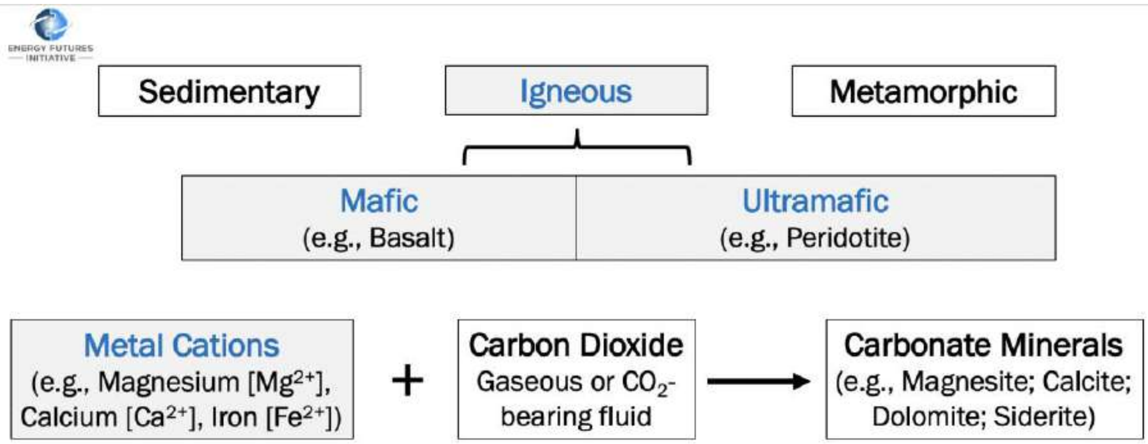
CHAPTER 4. CARBON MINERALIZATION

Carbon mineralization is a naturally occurring process[1] where certain types of rocks and minerals react with CO_2 to form solid carbonate minerals. Unlike other forms of CO_2 conversion that can be energy intensive, mineralization is an exothermic reaction, i.e., the conversion process releases energy.[2] The mineralization process has the potential to store carbon permanently.[3,4,5] The mineralization process can take place either at ground surface (ex situ mineralization) or in underground rock formations (in situ mineralization).[6] Ex situ typically occurs as a passive process—i.e., reactive materials are placed on the surface near the CO_2 source—but research also has been conducted on active ex situ mineralization, i.e., reacting materials and CO_2 in reaction vessels at elevated temperatures and pressures. NASEM identified carbon mineralization as one of two NETs that has a particularly large capacity for CDR—possibly greater than the total need for removal—including ample opportunities in the United States. However, there remains a considerable amount of fundamental scientific, technical, economic, and environmental uncertainty associated with this CDR pathway.[7]

Carbon Mineralization Process

The process of carbon mineralization occurs through exothermic carbonation reactions whereby reactive rocks and minerals, particularly those with abundant divalent metal cations such as calcium, magnesium, and iron, form chemical bonds with CO_2 to yield stable carbonate minerals (Figure 4-1).[8,9]

Figure 4-1
Carbon Mineralization Process



Igneous rocks are the most suited rock type for carbon mineralization. Sedimentary and metamorphic rocks also have the potential for carbon mineralization. Source: EFI, 2019. Compiled using data from Blondes et al., 2019.

The Earth consists of three major types of rocks, classified according to their chemical and mineral composition. Igneous rock types (formed when hot molten rock solidifies)[10] are especially suitable candidates for the purposes of carbon mineralization due in part to their relative abundance of divalent metal cations.[11,12] Metamorphic and sedimentary rocks also have some capacity for carbon mineralization.

Igneous rock includes mafic (e.g., basalt) and ultramafic (e.g., peridotite and serpentinite) rock that have strong potential as a source material for mineralization given their high level of availability and relatively fast carbonation kinetics.[13]

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.[14] Peridotite, which is particularly rich in magnesium, is also highly reactive but is less common compared to basalt.[15,16] Peridotite is typically found beneath the Earth's crust at more than 6 kilometers below the ocean floor and 40 kilometers below the continental surface.[17] The properties of these two rock types are summarized in Table 4-1.

Table 4-1
Comparison of Major Reactive Feedstocks for Carbon Mineralization

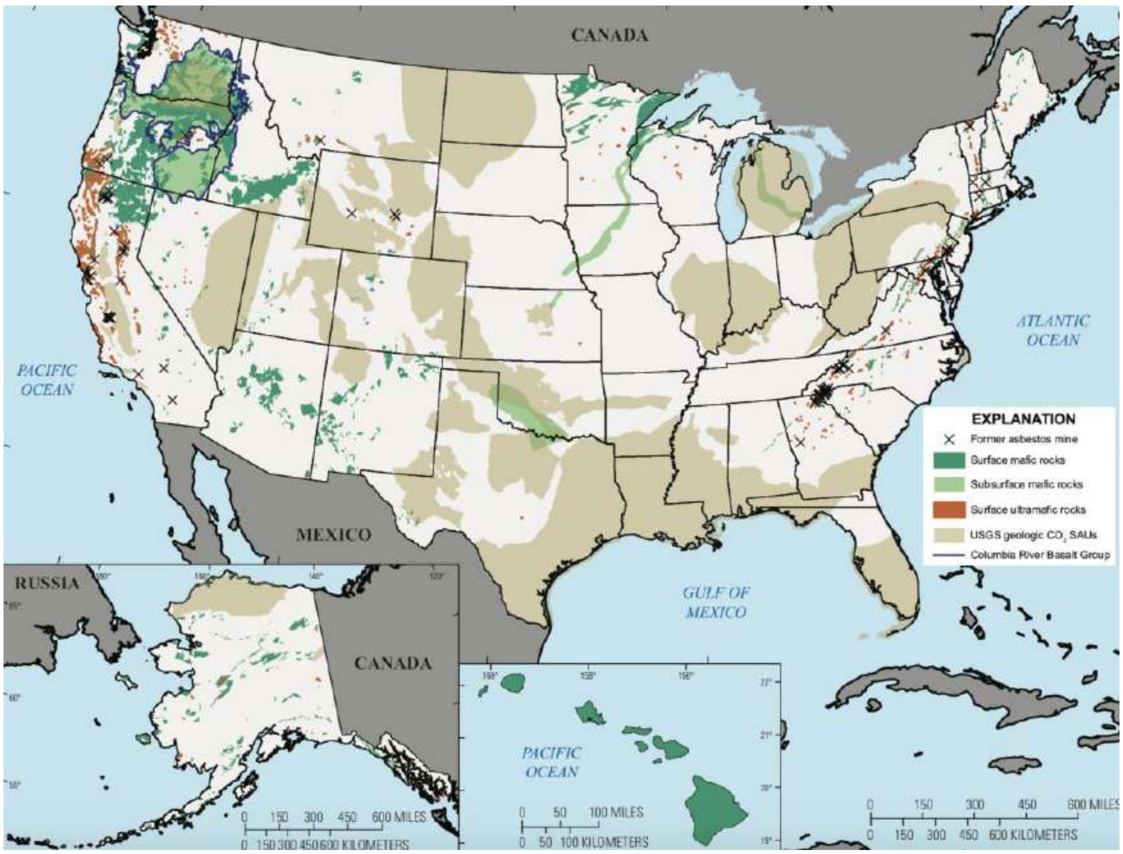
Metric	Basalt	Peridotite
Feedstock Availability in Earth's Crust	More common	Less common
Reaction Time	Slow	Fast
Porosity	High	Low
Permanence	High	High
Permeability	High	Low

Source: EFI, 2019. Compiled using data from the National Academies of Sciences, Engineering, and Medicine.

The United States has a host of suitable reactive rocks for carbon mineralization that include both mafic and ultramafic rock types. A 2019 report by the U.S. Geological Survey (USGS) identified potentially suitable locations for carbon mineralization in igneous and metamorphic rocks, which are prime candidates for mineralizing CO_2 compared to sedimentary reservoirs. (Figure 4-2).[18] The report found that opportunities for carbon mineralization are geographically dispersed across the United States, providing near-term opportunities to explore local potential. The locations with considerable potential include the Pacific Northwest and Hawaii.[19] For the Pacific Northwest, basalts found in the Columbia River basin were estimated to have a carbon mineralization potential of 10-100 $GtCO_2$, while offshore basalt formations along the Juan de Fuca Ridge had an estimated storage potential of 134-668 $GtCO_2$.[20]

Figure 4-2

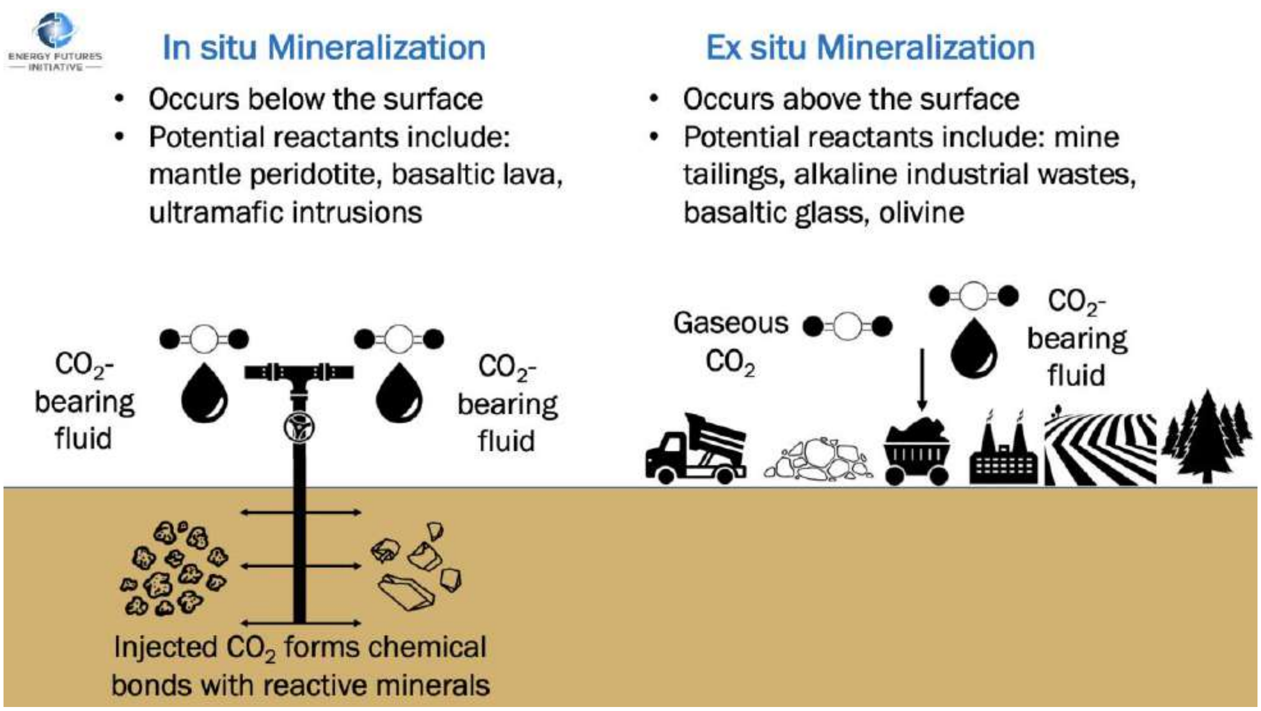
Opportunities for In Situ and Ex Situ Carbon Mineralization in the United States



The United States has a sizable potential for in situ and ex situ mineralization across surface and subsurface mafic rocks, surface ultramafic rocks, and asbestos mine tailings. Source: Blondes et al., 2019.

Carbonate formation is dependent upon cation availability in the feedstocks for these reactions and is a major determinant for the amount of CO_2 that can be trapped through the process of carbon mineralization.[21] The CO_2 used for these chemical reactions can be captured directly from the atmosphere or from concentrated point sources (e.g., power plants, industrial facilities) and either injected into the subsurface as a CO_2-bearing fluid (in situ) or exposed to reactive rocks and alkaline industrial wastes on the surface (passively or actively) as a gas or CO_2-bearing fluid (ex situ). The two methods are shown in (Figure 4-3).[22,23,24]

Figure 4-3
In Situ and Ex Situ Processes for Carbon Mineralization



Source: EFI, 2019. Compiled using data from the National Academies of Sciences, Engineering, and Medicine. Graphics from Noun Project.

In Situ Mineralization for Subsurface Terrestrial Storage

In situ mineralization involves natural and human-induced carbon mineralization in the subsurface. The human-induced method is facilitated by injecting a CO_2-bearing fluid into reactive rock formations below the surface along fractures and pores to form solid carbonate minerals,[25,26,27] of which the CO_2-bearing fluid can be in the form of water with a high concentration of dissolved CO_2 or water that bears supercritical CO_2 (fluid state with properties of a gas and liquid).[28,29] Minerals can become naturally carbonated within mafic and ultramafic rocks through carbon mineralization over time, which renders them less reactive and diminishes their potential for subsequent mineralization reactions due to mineral coating.[30] The in situ mineralization process differs from other forms of geological sequestration in the choice of underground media; geologic sequestration of CO_2 typically utilizes underground saline aquifers as the storage media, while CO_2 for enhanced oil recovery involves injection into petroleum- and natural gas-bearing sedimentary rock formations.

A major benefit of in situ mineralization is that it provides a much larger potential opportunity for carbon mineralization compared to ex situ methods, given the disproportionate amount of reactive minerals that are found below the surface.[31] Another major benefit is the long-term stability that is accomplished through the formation of solid carbonate minerals in the subsurface, which is considered one of the best trapping mechanisms for geologic sequestration.[32] However, target reservoirs for the purposes of in situ mineralization remain largely unexplored. In addition, there is a need for a better understanding of the carbon mineralization process including injectivity and permeability,[33] reaction limits, volume of rock contacted, and natural fracture distribution.

Cost estimates for in situ mineralization are driven by drilling, pumping, and transport costs. Previously reported cost estimates for in situ mineralization are highly variable and have included \$17 per tCO_2,[34] \$30 per tCO_2 (basalt formations),[35] and \$50 to \$100 per tCO_2.[36] Comparative analysis indicates, however, that this method has the potential to be less costly than ex situ mineralization[37] and could be competitive with geologic sequestration using supercritical CO_2 in ultramafic formations on the basis of both cost and capacity for removal.[38]

Ex Situ Mineralization for Surface Terrestrial Storage

Ex situ mineralization involves exposing reactive rock and minerals, alkaline industrial wastes, or mineral wastes from mining operations (tailings) to CO_2 above the Earth's surface.[39] This process can be facilitated by crushing and grinding reactive feedstocks to fine grain sizes and either spreading it across a surface or transporting it to pressure vessels where it can react with CO_2.[40] Several byproducts of industrial processes that provide opportunities for carbon mineralization include cement kiln dust, waste concrete, fly ash, mine tailings, alkaline waste from paper mills, red mud, and iron and steel slag.[41,42] Early estimates of alkaline industrial wastes found that these sources of reactive materials were limited in supply and best suited for specific applications (e.g., hazardous waste remediation through carbonation).[43] More recent estimates suggest that there are more than 7 billion tons of alkaline industrial products and byproducts produced each year globally, which could have an annual sequestration potential of 2.3-3.3 $GtCO_2$ by 2050 and 2.9-8.5 $GtCO_2$ by 2100 (Table 4-2).[44] Industrial subsectors that produce especially large feedstocks include cement, iron, and steel.[45] Mine tailings provide a further opportunity for carbon mineralization and include abandoned asbestos mines in the United States that contain large amounts of ultramafic rocks[46] in addition to tailings from chromite, diamond, nickel, platinum group elements, talc, and brine mining operations.[47]

Table 4-2
Sequestration Potential of Various Alkaline Materials

Type	Carbonation Potential (kg CO_2/t)	Enhanced Weathering Potential (kg CO_2/t)
Lime	777 ± 13	1,165 ± 19
Ordinary Portland cement	510	773
Blast furnace slag	413 ± 13	620 ± 19
Basic oxygen furnace slag	402 ± 17	602 ± 25
Electric arc furnace slag	368 ± 10	552 ± 15
Cement kiln dust	330 ± 12	530 ± 21
Biomass (average)	186 ± 126	461 ± 260
Lignite ash	146 ± 28	246 ± 52
Construction and demolition waste	77 to 110	110 to 190
Animal biomass ash	56 to 376	145 to 724
Red mud	47 ± 8	128 ± 18
Ultrabasic mine tailings	40 to 250	60 to 377
Hard coal ash	36 ± 6	73 ± 10
Marine algae biomass ash	31	348
Wood/woody biomass ash	-89 to 815	-118 to 1,766
Herbaceous and agricultural biomass ash	-239 to 520	-323 to 1,505

Source: Renforth, 2019.

There are several attributes of ex situ mineralization that make it an attractive pathway for CDR. One major benefit of ex situ mineralization, compared to in situ methods, is the ability to maximize the surface area of the reactive feedstock exposed to CO_2 through the use of crushed or pulverized rock, which can accelerate the time requirement for the mineralization process. Another benefit of ex situ mineralization is the avoidance of subsurface injection and attendant risk of CO_2 migration and pressure buildup in the target reservoir, which can lead to seismic risk.[48] A third benefit of ex situ mineralization involves flexible project siting, where projects can be co-located with emissions from power plants or industrial facilities and thereby avoid the need for transporting large amounts of feedstock.[49]

Key hurdles for ex situ mineralization are potential practical limitations on scale (e.g., land requirements) and the energy requirements and costs for processing the raw materials suitable for mineralization. Some early work on ex situ mineralization indicated that the process could be infeasible given the scale of mining operations and costs required to prepare an adequate feedstock of reactive rocks and minerals. For example, it has been estimated that 55,000 tons of silicate mineral feedstock would be required per day to mineralize the daily emissions from a coal-fired power plant (capacity of 1 GW), of which the processing of the feedstock can constitute up to 75 percent of the total energy cost.[50]

Cost estimates for ex situ mineralization are driven by feedstock production, processing, and transport. Ex situ mineralization techniques have been demonstrated on larger scales relative to in situ methods but tend to have substantially higher estimated costs by as much as 10 times that of CO_2 injection into the subsurface.[51,52,53] (The costs for producing and processing reactive feedstocks through mining and grinding could be roughly equivalent to the costs of direct air capture (DAC) systems,[54] in addition to potentially large transport costs.)[55] Previous cost estimates for ex situ mineralization have included \$8 per tCO_2 (which can be substantially higher if mining and transport of the rocks is required),[56] \$10 per tCO_2 (crushed peridotite),[57] and \$50 to \$300 per tCO_2.[58] Grinding and processing of rock could cost between \$20 and \$60 per tCO_2, while the cost per ton of CO_2 removed could range between \$40 and \$125 per tCO_2.[59]

Hybrid Systems

Recently, McQueen et al. have proposed a hybrid carbon mineralization-direct air capture (DAC) system, in which a surficial weathering cycle is used to repeatedly capture high-purity CO_2 from the atmosphere.[60] The costs of this system appear to be comparable to or less than existing DAC technologies. Additionally, Kelemen et al. have proposed a related system, which combines DAC configured for producing low end-purity CO_2 with in situ mineralization for storage. The costs of this system appear to fall below \$200 per tCO_2 depending on rock permeability.[61] Hybrid systems of this kind have not previously been examined in detail, and merit further research.

Enhanced Weathering for Ocean Alkalinity Storage

Enhanced weathering (EW) is a form of ex situ mineralization that is focused on ultimate storage of the mineralized CO_2 in the ocean as a means to enhance ocean alkalinity. EW involves artificially accelerating the natural decomposition (weathering) of rocks by crushing and grinding a reactive feedstock into powder form and spreading it across a surface (e.g., cropland, forestland), where it dissolves in the presence of water and CO_2 and can be transported to the oceans via rivers and ultimately stored as bicarbonate. The primary distinction between EW and ex situ mineralization is that the weathering focuses on ocean alkalinity storage of CO_2 as its ultimate objective, whereas ex situ mineralization focuses on carbonate storage in terrestrial settings. EW also can provide an important co-benefit if the carbonate material product is allowed to remain on land, improving soil quality by ameliorating phosphorus deficiencies and soil acidification.[62,63,64]

It is estimated that EW currently mineralizes 1.1 $GtCO_2$ per year, most of which is stored as bicarbonate in the oceans.[65] Estimates suggest that EW in practice removes 1.5-1.8 times more CO_2 than carbon mineralization.[66] The feedstock requirements for meaningful CDR through EW can be sizeable; estimates suggest that 3 Gt of basalt per year would be required to sequester 1 $GtCO_2$ per year. By comparison, global upstream coal production was more than 8 Gt in 2014.[67] Alternative feedstocks such as alkaline industrial wastes can also be used for EW and could lessen some of the energy and cost requirements to produce and process large volumes of reactive minerals.

The chemical reactions in the EW process are water- and temperature-dependent and occur considerably faster under higher temperatures in warm to temperate and humid regions.[68] Tropical climates are thus especially suitable locations for EW. However, tropical land areas can be more difficult to access and therefore may lead to higher costs for EW projects compared to cropland.[69] One study indicated that if silicate rock were broadcast over roughly one-third of tropical land area through EW, it could potentially lower atmospheric CO_2 composition by 30-300 ppm by 2100 and help mitigate ocean acidification.[70]

The sustainable global potential for CDR through EW has been estimated at 2-4 $GtCO_2$ per year by 2050 at a cost of \$50 to \$200 per tCO_2.[71] EW on croplands has the potential to remove 95 $GtCO_2$ per year globally for dunite and 4.9 $GtCO_2$ per year for basalt, with the most favorable locations being warm and humid areas (including the southeastern United States).[72] Estimated carbon storage through EW of alkaline industrial materials could be 2.6-3.8 $GtCO_2$ per year by 2050 and 4.3-8.5 $GtCO_2$ per year by 2100 globally.[73]

Costs for EW are driven by two major factors, including the source of the feedstock (e.g., mining and processing requirements) and transport requirements to a suitable project site. For transport, the cheapest cost for large quantities is via maritime shipping (\$0.0016 per tCO_2 per kilometer), while road transport via trucking is the most expensive option (\$0.07936 per tCO_2 per kilometer).[74] Although cost estimates in the literature for EW are variable, estimates suggest that they could be \$60 per tCO_2 for dunite and \$200 per tCO_2 for basalt.[75]

Status of Carbon Mineralization in the Research Process

Federally funded research on carbon mineralization has been very limited, with the DOE having played the most significant role. 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.[76] Carbon mineralization currently has been identified by DOE as one of the four research efforts for CO_2 utilization pathways.[77] In view of the limited progress in some historical research on carbon mineralization, numerous RD&D needs and priorities remain across in situ and ex situ methods that stem from considerably less data and practical experience with storage via carbon mineralization compared to geologic sequestration in sedimentary formations.[78]

There have been several significant field experiments that have established important baseline information to guide further RD&D efforts. These projects are described in the Box 4-1.

Box 4-1

Selected Current and Former Carbon Mineralization Research Projects

CarbFix and SulFix. CarbFix and SulFix are in situ carbon mineralization pilot projects conducted at the Hellisheidi geothermal power plant in Iceland. Both projects use a mixture of either water with CO_2 or water with CO_2 and hydrogen sulfide (H_2S) for injection into the subsurface; CarbFix mixes the water and gases in the subsurface (post-injection), while SulFix mixes the water and gases at the surface (pre-injection).[79] CarbFix pilot injections began in 2012 and currently captures and injects 12,000 tCO_2 per year from the Hellisheidi plant for the purposes of carbon mineralization at a cost of approximately $30 per tCO_2, of which more than 95 percent of the injected CO_2 was mineralized after two years.[80,81] CarbFix has reported an overall carbon storage efficiency of 72 percent through the mineralization of CO_2 into calcite[82] at a cost of approximately $25 million across the lifetime of the project since it began in 2007.[83]

De Beers Project Minera. In May 2017, De Beers, a diamond mining and trading company, announced it would lead a carbon mineralization research project with the intent of making several of its mines carbon neutral in five years. The goal of the project is to use ultramafic kimberlite mine tailings from the diamond extraction process to mineralize CO_2 at mine sites in South Africa (Venetia) and Canada (Gahcho Kué). The research team has considered several methods to help facilitate the carbon mineralization process including: more frequent rotations of the deposition points (where mine tailings are collected and exposed to CO_2 under ambient conditions) to allow greater time for tailings to interact with CO_2; the use of process additives to enhance carbonation; CO_2 injection into tailings using onsite generators; and the use of microbes to increase the dissolution rate of the tailings and catalyze carbonation reactions.[84,85]

Oman Drilling Project. Approximately two-thirds of the Earth's surface consists of oceanic crust, which plays a key role in the carbon cycle. In some locations, the oceanic lithosphere is exposed at the Earth's surface due to tectonic activity, which provides unique opportunities for geologic research.[86] For example, the Oman Drilling Project is a collaborative effort among 150 international scientists to conduct geologic research (including carbon mineralization) in the Samail Ophiolite in Oman, which is the largest exposure of oceanic crust and upper mantle in the world (similar exposures are found in Northern California, Papua New Guinea, and Albania).[87,88] The aim of the Oman Drilling Project is to help advance future prospects for geologic CO_2 capture and sequestration, where it has been reported that in situ mineralization of peridotite has the potential to sequester more than 1 $GtCO_2$ per year.[89]

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 $ktCO_2$ into continental basalt formations, which led to the successful mineralization of CO_2 over a two-year period. The project was reportedly the first to provide field evidence of in situ mineralization using free phase supercritical CO_2 in a flood basalt reservoir.[90,91,92]

Cascadia Basin. The Carbon Storage Assurance Facility Enterprise (CarbonSAFE) Initiative, the DOE/NETL carbon sequestration research program, is currently funding a pre-feasibility study for offshore carbon mineralization in the Cascadia Basin near Washington and British Columbia.[93] This project is seeking to capture and sequester 50 $MtCO_2$ from concentrated point sources over a 20-year period and inject the CO_2 into offshore basalt reservoirs 200 miles off the Pacific Coast, where it would mineralize into calcium carbonate.[94] Project goals include technical (e.g., site characterization and monitoring) and nontechnical (e.g., regulatory and liability frameworks) assessments of the proposed injection site,[95] with future plans of launching a pilot project.[96]

Carbon Mineralization RD&D Portfolio

The overarching RD&D objective for carbon mineralization is to enhance the understanding of the feasibility and potential for carbon mineralization as a CDR technology pathway. This will include efforts such as expanding support for fundamental research on mineral dissolution and precipitation kinetics, assessing the feasibility of alternative sources of alkaline materials (natural and anthropogenic), implementing in situ and ex situ field experiments with various locations and materials, and conducting in-depth assessments of environmental impacts, costs, and scalability. The proposed funding level for this capture technology pathway is $700 million over 10 years, with RD&D roles and responsibilities divided among four federal agencies: DOE, Department of the Interior (DOI), EPA, and NSF (Table 4-4).

The overarching RD&D objective for carbon mineralization is to enhance the understanding of the feasibility and potential for carbon mineralization as a CDR technology pathway.

Challenges and Uncertainties

A major uncertainty associated with carbon mineralization involves the kinetics of CO_2 mineralization and management of mine tailings for optimal CO_2 uptake.[97] Despite some prior research, slow mineralization kinetics for both in situ and ex situ methods remains a major challenge[98] and warrants further research to increase the speed of chemical reactions.[99] Other major challenges for carbon mineralization include high financial and energy requirements (Table 4-3)[100] for mining, grinding, and transporting feedstocks; reduced permeability when cracks in the geologic subsurface become filled with carbonate;[101,102] diminished reactivity due to mineral grain coating; and the potential environmental impacts of carbon mineralization and associated mining operations. Potential environmental risks associated with carbon mineralization include large water requirements, water contamination from mining operations, local air pollution, induced seismicity from subsurface fluid injection, management of waste rock, and heavy metal pollution in soils.[103,104,105,106] Research needs for carbon mineralization and EW using alkaline industrial materials include data collection for materials production and feedstock availability, framework for assessing sequestration potential, and valuation mechanism for CO_2 captured in waste material.[107]

Table 4-3 **Primary Energy Requirements for Carbon Mineralization**	
In Situ	**Ex Situ**
Drilling	Crushing and grinding feedstock
Hydraulic fracturing	Feedstock transport
Fluid pumping	Feedstock heat treatment
Fluid preheating and CO_2 dissolution	Achievement of elevated temperature and pressure in reaction vessel
CO_2 purification	Energy requirements of chemical additives
CO_2 capture and transport	
Source: EFI, 2019. Compiled using data from Keleman & Matter, 2008.	

Recommended RD&D Portfolio Elements

Research and Assessments, Portfolio Element 4.10, involves research and assessments and is composed of two budget planning estimate line items that seek to advance fundamental research on mineralization kinetics and assess feedstock availability.

- **Fundamental Research, Portfolio Element 4.11,** involves fundamental research on dissolution and precipitation kinetics, geomechanics, rock physics, and utilization-oriented carbonation. This effort is proposed to be jointly managed by NSF/GEO and DOE/BES.
- **Resource Assessments, Portfolio Element 4.12,** involves mapping and assessing geological resources, mine tailings, and other alkaline industrial wastes for mineralization, development of supply cost curves, and a public database to disseminate the results. This effort is proposed to be jointly managed by DOI/USGS and DOE/FE. Particular focus should be placed on the minerals and mineral classes with extremely high reactivity and fast kinetics (e.g., brucite) but limited commercial value and, as such, have not been mapped or assessed at all.

Field Experiments, Portfolio Element 4.20, involves field experiments and is composed of three budget planning estimate line items that seek to conduct pilot studies for ex situ and in situ mineralization, including the use of mine tailings and industrial waste. Field experiments are needed to overcome uncertainties related to carbon mineralization, as previous research has mostly been limited to laboratory and modeling studies.[108] These experiments need to be carefully defined to take into account a range of variables including location and amount of reactive rocks; rock mineralogy and chemistry; mineral dissolution and precipitation kinetics; extent and timing of carbonation reactions; temperature; pressure; catalyst addition(s); and reactive surface area of the feedstock, which is dependent upon rock porosity and permeability (in situ) or grain size (ex situ).[109]

- **Pilot Studies of Ex Situ Mineralization, Portfolio Element 4.21,** involves field experiments of ex situ approaches. Although relatively extensive laboratory-scale research has been conducted on ex situ carbon mineralization, inconsistent methodologies have made the results difficult to compare,[110] which could underscore the need for greater multidisciplinary cooperation (e.g., in the geochemistry and chemical engineering fields) for carbon mineralization RD&D. A major research need for ex situ mineralization involves decreasing the energy requirements and costs to produce and process the feedstock. This portfolio element also includes the broadcast of reactive minerals on soils, beaches, and shallow ocean, in addition to desalination brine treatment. This effort is proposed to be jointly managed by DOE/FE and EPA/ORD.
- **Pilot Studies of In Situ Mineralization, Portfolio Element 4.22,** involves field experiments of in situ approaches. In situ mineralization using mafic and ultramafic rocks is an active area of basic and applied research.[111] However, there is a need for more large-scale field projects due to the difficulty of simulating those processes (particularly at scale) in a laboratory setting.[112] Although there have been pilot experiments performed in basalt formations, there have not been field-scale in situ pilot projects in ultramafic rocks.[113] The proposed research portfolio element includes drilling and injection in reactive formations, including mantle peridotite and basalt. This effort is proposed to be jointly managed by DOE/FE and NSF/GEO.
- **Tailings and Waste Mineralization, Portfolio Element 4.23,** involves field experiments using mine tailings and industrial wastes such as slags. Alternative feedstocks such as mine tailings, asbestos wastes, and alkaline industrial wastes could provide lower-cost options for ex situ mineralization. Mine tailings may provide a low-cost option for carbon mineralization but are feedstock-limited (less than 10 Gt of existing ultramafic tailings) relative to the needed scale of CDR.[114,115] Pursuing carbon mineralization using alkaline industrial wastes could be another low-cost method for CDR, as most of the produced materials are either byproducts or low-value products that are already of small grain size, which could negate the cost of feedstock processing.[116] This effort is proposed to be jointly managed by the DOI/USGS and EPA/ORD.

Environmental Studies, Portfolio Element 4.30, involves environmental impacts and is composed of two budget planning estimate line items that seek to better understand the environmental and social impacts of mineralization products and associated mining activities.

- **Environmental Impacts of Mineralization Products, Portfolio Element 4.31,** involves studying the environmental impacts of broadcasting materials and disturbing piles of mine tailings. This effort is proposed to be jointly managed by EPA/ORD and DOI/USGS.
- **Environmental and Social Impacts of Expanded Mining for Mineralization, Portfolio Element 4.32,** involves studying the environmental and social impacts of an expanded mining industry for the purpose of carbon mineralization. This effort is proposed to be jointly managed by NSF/GEO and DOI/USGS.

Table 4-4
Carbon Mineralization RD&D Portfolio ($millions)

Portfolio Element	Funding Agency	Funding Office or Organization	Year 1	5-Year Total	10-Year Total
4.10 Research and Assessments					
4.11 Fundamental research	NSF	GEO	$2	$46	$121
	DOE	SC (BES)	$2	$36	$86
4.12 Resource assessments	DOI	USGS	$2	$22	$47
	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 mineralization products	EPA	ORD	$1	$19	$44
	DOI	USGS	$1	$19	$44
4.32 Environmental and social impacts of expanded mining for mineralization	NSF	GEO	$2	$18	$38
	DOI	USGS	$1	$5	$10
4.30 Subtotal, Environmental Studies			$5	$61	$136
TOTAL, Carbon Mineralization			$20	$325	$700

Source: EFI, 2019.

1 https://www.nap.edu/read/25210/chapter/1#4
2 https://www.nap.edu/read/25259/chapter/8
3 https://www.nap.edu/resource/25259/Negative%20Emissions%20Technologies.pdf
4 https://blogs.ei.columbia.edu/2018/11/27/carbon-dioxide-removal-climate-change/
5 https://pubs.usgs.gov/sir/2018/5079/sir20185079.pdf
6 https://blogs.ei.columbia.edu/2018/11/27/carbon-dioxide-removal-climate-change/
7 https://www.nap.edu/resource/25259/Negative%20Emissions%20Technologies.pdf
8 https://www.osti.gov/servlets/purl/1187926
9 https://pubs.usgs.gov/sir/2018/5079/sir20185079.pdf
10 https://www.usgs.gov/faqs/what-are-igneous-rocks?qt-news_science_products=0#qt-news_science_products
11 http://www.columbia.edu/~vjd1/igneous.htm
12 https://www.nap.edu/read/25259/chapter/8#273
13 https://www.nap.edu/read/25259/chapter/8#269
14 https://science.sciencemag.org/content/352/6291/1312
15 https://www.technologyreview.com/s/411129/carbon-capturing-rock/
16 https://www.nap.edu/read/25210/chapter/1
17 https://www.pnas.org/content/105/45/17295
18 https://pubs.usgs.gov/sir/2018/5079/sir20185079.pdf
19 https://www.usgs.gov/news/making-minerals-how-growing-rocks-can-help-reduce-carbon-emissions
20 https://pubs.usgs.gov/sir/2018/5079/sir20185079.pdf
21 https://www.osti.gov/servlets/purl/1187926
22 https://pubs.usgs.gov/sir/2018/5079/sir20185079.pdf
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CHAPTER 5.
COASTAL AND OCEANS

The impacts of climate change on the oceans are profound. More than 90 percent of the warming that has occurred on Earth over the past 50 years has been absorbed by the oceans.[1] The average temperature of the ocean surface has risen almost 1°C above the 1971-2000 average.[2] The Arctic sea ice minimum has been shrinking at a rate of 12.8 percent per decade since 1979,[3] and thermal expansion of seawater combined with the melting of ice sheets and glaciers has led to a global sea level rise of 9 centimeters since 1993.[4] U.S. coastal flooding rates were at record highs in 2017 and 2018,[5] and seawater warming is driving mass fish migration poleward.[6]

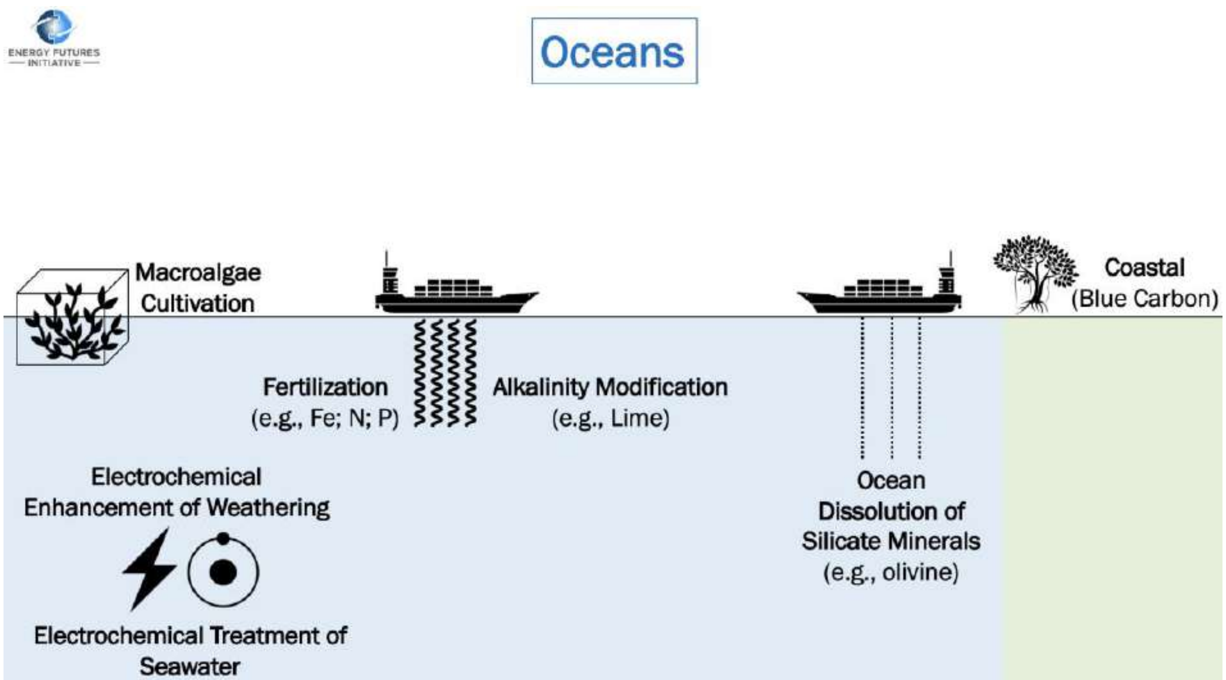
Currently, the oceans contain about 50 times as much carbon as the atmosphere,[7] and they have absorbed about 40 percent of all anthropogenic CO_2 emitted since the Industrial Revolution.[8] The interaction of CO_2 with the oceans and the resultant impacts on ocean ecosystems are complex and multifaceted.

- The oceans currently absorb approximately a quarter of anthropogenic CO_2 emissions.[9] As CO_2 dissolves in the ocean, it reacts with water to form bicarbonate ions (HCO_3^-) and hydrogen ions (H^+). Most of the hydrogen reacts with existing carbonate ions $(CO3)^{2-}$ to form additional bicarbonate, but some remains, acidifying seawater.
- The excess H^+ causes increased acidity. The pH of ocean surface waters has been reduced by 0.1 units, equivalent to a 30 percent increase in acidity, since the beginning of the industrial era, faster than any change in ocean acidity over the past 20 million years.[10]
- Increased acidity has put enormous pressure on marine life and ecosystems.[11] The reaction between hydrogen and carbonate ions depletes the amount of carbonate that is available for marine organisms such as shellfish and coral to form calcium carbonate ($CaCO_3$) for shells and skeletons (see Figure 5-2 in Box 5-1 for further discussion).[12] This problem is compounded by the fact that if acidification trends continue, seawater will become corrosive to these shells by the end of the century. Increased acidification also threatens corals, and bleaching events are becoming more common.[13] Increased ocean acidification will also have major impacts on phytoplankton, the foundation of the entire marine food web.[14]
- Absorption of CO_2 in the oceans is a two-way phenomenon governed by thermodynamic relationships. So if atmospheric CO_2 levels ultimately can be reduced, the rate of atmospheric decrease will be slowed by release of dissolved CO_2 from ocean waters. CDR pathways for ocean waters thus need to be considered in concert with atmospheric capture and not as an either/or alternative.

Oceans also offer potential opportunities for CDR, including removing and storing atmospheric CO_2 as well as opportunities to convert and isolate CO_2 already dissolved in ocean waters (Figure 5-1).[15] Because of the complex relationships between CO_2 and the ocean ecosystem, each of the potential CDR approaches must be considered within a comprehensive environmental framework.

Figure 5-1

CDR Opportunities in Coastal and Ocean Environments



Several opportunities exist to pursue CDR in coastal and deep oceans environments. Source: EFI, 2019. Compiled using data from the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection. Graphics from Noun Project.

The chemistry of CO_2 in ocean waters points to a key CDR approach for the conversion of dissolved CO_2 to the bicarbonate chemical form that can be safely stored in deep ocean waters (see Box 5-1). Another key approach is to enhance the ocean photosynthesis process. Just as on land, plants in the ocean perform photosynthesis, combining sunlight, water, nutrients, and CO_2 to form biomass. In the ocean, the vast majority of these plants are phytoplankton, which float in the upper region of the ocean and consume approximately 180 $GtCO_2$ per year, roughly equal to terrestrial plants.[16] As phytoplankton die, their biomass is mostly recycled in the upper ocean, but a small fraction (1 to 2 percent) sink to the deep ocean, where they remain stored for hundreds or thousands of years. This process is known as the "biological pump" because its net result is to move atmospheric CO_2, via dissolution in seawater and phytoplankton photosynthesis, into deep ocean storage.

Box 5-1

Ocean Acidification

The oceans currently absorb approximately a quarter of anthropogenic CO_2 emissions.[17] As CO_2 dissolves in the ocean, it reacts with water to form bicarbonate ions (HCO_3^-) and hydrogen ions (H^+). Most of the hydrogen reacts with existing carbonate ions ($(CO3)^{2-}$) to form additional bicarbonate, but some remains, acidifying seawater. This has led to a 30 percent increase in ocean acidity since the beginning of the industrial era, faster than any acidity change in the oceans over the last 20 million years.[18]

The reaction between hydrogen and carbonate ions depletes the amount of carbonate that is available for marine organisms such as shellfish and coral to form calcium carbonate ($CaCO_3$) for shells and skeletons (Figure 5-2).[19,20] This problem is compounded by the fact that if acidification trends continue, seawater will become corrosive to these shells by the end of the century. Increased acidification also threatens corals, and bleaching events are becoming more common.[21] Increased ocean acidification will also have major impacts on phytoplankton, the foundation of the entire marine food web.[22]

The relationship between CO_2 and ocean acidification may make it seem counterintuitive to actively store CO_2 in the oceans as a CDR technique. However, proposed CDR techniques such as ocean alkalinity modification (OAM) focus on storing carbon in the form of bicarbonate, chemically balanced by sources of alkalinity such as lime (CaO). These approaches would leave the pH of seawater unchanged or act to counter increasing acidification on a local basis. This can be an important co-benefit of these pathways in addition to their climate impact.

Figure 5-2

Impacts of Ocean Acidification on Marine Organisms

Marine organisms in some parts of the ocean are already experiencing corrosion of their shells due to increased ocean acidity from anthropogenic CO_2. At left: a healthy shell. At right: a shell affected by increased ocean acidity at pH and carbonate levels projected for the year 2100. Source: National Oceanic and Atmospheric Administration.

Carbon in the Ocean

Atmospheric CO_2 dissolves in ocean water in a chemical equilibrium. Increased atmospheric CO_2 increases the level of dissolution in ocean waters as well. The dissolved CO_2 can take several forms, including dissolved gaseous CO_2, carbonic acid (H_2CO_3), bicarbonate ions, and carbonate ions. These are collectively known as dissolved inorganic carbon (DIC), and the relative amount of each one is determined by pH.[23] At normal seawater pH values, most DIC is in the form of bicarbonate ions.[24] Since this carbon is out of contact with the atmosphere, it is sequestered for the purposes of climate, and it can remain in this form for millennia.

An important feature of DIC is that it is larger in the deep oceans than on the surface because of several "pumps," including upwelling/circulation (the "solubility pump"), phytoplankton photosynthesis (the "soft-tissue pump"), and the formation of hard shells (the "carbonate pump"). These pumps export carbon to the deep ocean and ocean sediments, separating it from the atmosphere for thousands of years or longer. They also keep the concentration of CO_2 in ocean surface waters lower than it otherwise would be, leading to continued removal of CO_2 from the atmosphere.

International Context for Ocean-Related CDR RD&D

Any proposal for CDR that involves the oceans must take into account the total ecological effects on the marine environment. This issue is particularly complex because most of the oceans are international waters, outside of the jurisdiction of any one nation. A variety of international agreements have been created to govern activities that impact the oceans, such as the United Nations Convention on the Law of the Sea (UNCLOS), the London Convention (LC), the London Protocol (LP), and the UN Convention on Biological Diversity (CBD).[a] There also are regional agreements, including the OSPAR Convention in the EU. Ecological and legal factors associated with oceans CDR methods must be considered carefully within the context of the requirements established in these international agreements.

UNCLOS applies to the seabed and sub-seabed. It establishes that nations have full sovereignty over their "territorial sea," which extends 12 nautical miles from the shoreline. States have some sovereign rights over the exclusive economic zone (EEZ), which extends 200 nautical miles beyond the territorial sea. Beyond this are the "high seas." No nation has jurisdiction in these areas, although the International Seabed Authority has some level of authority.

Storing CO_2 in geological formations under the seafloor is permitted under UNCLOS, the LC and the LP, and it has been in commercial practice for more than a decade at several sites, including two in Norway (Sleipner and Snohvit).[25] CO_2 pipelines on the seafloor would similarly be permitted within the EEZ and potentially beyond. EOR in seafloor hydrocarbon formations is allowed.[26]

[a] The U.S. is a party to the London Convention. The U.S. has signed but not ratified the London Protocol, the UN Convention on Biological Diversity, and UNCLOS. The U.S. scientific community generally follows the requirements of these agreements.

Ocean fertilization has a more complex history. In 2008, the LC and the LP adopted a resolution declaring that ocean fertilization other than for legitimate scientific research was “contrary to the aims” of the convention. In 2010, they established an assessment framework for evaluating proposals for scientific research on ocean fertilization, and in 2013, the LP was amended to regulate ocean fertilization activities.[27] This also envisioned that the LP could regulate other “marine geoengineering” activities in the future.[28] Direct injection of CO_2 into the oceans (as opposed to sub-seafloor geological formations) is illegal under the LP. Its status is unclear under the LC.[29]

Box 5-2

Legislative Proposals to Address Ocean Acidification

Several bills focused on ocean acidification have been under active consideration by the 116th Congress. These authorize additional research, monitoring, and assessment activities, including socioeconomic assessments. However, they do not address research activities specifically focused on oceans-related CDR. The principal bills include:

The Coastal and Ocean Acidification Stressors and Threats (COAST) Research Act (H.R. 1237) was introduced by Reps. Suzanne Bonamici, Don Young, Chellie Pingree, and Bill Posey in February 2019 and would amend the Federal Ocean Acidification Research and Monitoring Act of 2009 to reauthorize ocean acidification R&D at the National Oceanic and Atmospheric Administration (NOAA) and NSF, expand the mandate of the Interagency Working Group on Ocean Acidification to include socioeconomic effects, designate NOAA as the lead federal agency on ocean acidification, and improve ocean acidification data standardization and sharing.[30]

The Coastal Communities Ocean Acidification Act (H.R. 1716 and S. 778) was introduced by Reps. Pingree, Francis Rooney, Jared Huffman, Bonamici, Peter King, Young, and Mike Thompson and Sens. Lisa Murkowski, Sheldon Whitehouse, Gary Peters, and Susan Collins in March 2019 and would direct NOAA to study the socioeconomic impacts of ocean acidification on coastal communities.[31,32]

The Ocean Acidification Innovation Act (H.R. 1921) was introduced by Reps. Derek Kilmer, Jaime Herrera Beutler, Bonamici, and Young in March 2019 and would enable federal agencies to sponsor innovation prizes related to ocean acidification, using existing authority under the Stevenson-Wydler Act.[33]

Coastal Systems (“Blue Carbon”)

The pathway of coastal “blue carbon” refers to the growth of plants in coastal environments such as salt marshes, mangroves, and seagrass meadows and the subsequent natural burial of their biomass in coastal soil. This bears many similarities to terrestrial CDR pathways but requires separate attention because of the unique characteristics of these ecosystems. It is estimated that coastal carbon sequestration in soil occurs naturally at a rate of 0.84 $GtCO_2$ per year,[34] and additional sequestration occurs in the form of woody biomass in mangroves.

Coastal CDR rates could be substantially increased through wetlands preservation and restoration efforts. By contrast, sea-level rise and wetland damage from human activities could reduce this rate. Wetlands also face “coastal squeeze” between rising sea levels and upland areas that are often developed, constraining the ability of plants to migrate.

Pathways for enhancing coastal CDR include active management of wetlands (such as controlling shoreline erosion and coastal nitrogen runoff), restoring lost or degraded wetlands (approximately 1.3 million hectares of former wetlands are potentially available for restoration),[35] converting hardened shorelines to instead use natural features, and managing wetland transgression into uplands. Additionally, adding more carbon to wetland soils through burying wood or biochar, or breeding or genetically engineering wetland plant species to produce more decomposition-resistant biomass (lignin or suberin) would lead to increased carbon storage.

Many of these pathways would also produce important co-benefits, including natural hazard mitigation (attenuating waves), restoring fisheries, and enhancing biodiversity. The costs of most of the pathways considered here are almost entirely based on increased monitoring of carbon fluxes and are estimated by NASEM at $0.75 to $4 per t$CO_2$. Techniques involving adding carbon are estimated at $1 to $30 per t$CO_2$.

Recommended RD&D Portfolio Elements

Based on the cost and scale estimates, it is clear that blue carbon techniques meet the target thresholds for removal potential and cost to justify federal RD&D investment. While some of these techniques are mature, there are significant areas where RD&D is needed. NASEM recommended four areas of research needs. These needs can be addressed by incorporating CDR objectives into the mission and programmatic objectives of current NOAA research and monitoring programs, supported by additional funding as delineated below.

- **Fundamental Research, Portfolio Element 5.11,** provides additional funding for the NOAA Office of Oceanic and Atmospheric Research (OAR) and NSF Division of Ocean Sciences (OCE) to support fundamental research focused on better understanding CO_2 removal and sequestration in coastal ecosystems.
- **Coastal Resource Assessments, Portfolio Element 5.12,** provides additional funding to expand the scope of the NOAA Office for Coastal Management (OCM) and the NASA Earth Science Data Systems (ESDS) programs to carry out mapping and evaluation of coastal resources for carbon removal.
- **Regional Coastal Blue Carbon Field Experiments, Portfolio Element 5.13,** provides additional funding for the NOAA Coastal Resilience Grants Program to support an expanded scope that incorporates CDR research objectives in monitored field trials of coastal wetlands restoration. This is assumed to be conducted in coordination with the U.S. Army Corps of Engineers (USACE) Ecosystem Management and Restoration Research Program (EMRRP).
- **Coastal Data Management, Portfolio Element 5.14,** provides additional funding for the NOAA OCM to establish a National Coastal Wetland Data Center to

integrate and manage data on coastal CDR research. This should be conducted in coordination with the USACE EMRRP.

Marine Biomass Capture and Storage

Growing and harvesting macroalgae (seaweed) in the ocean offers a potential route to CDR that is not constrained by land-use limitations. Macroalgae exist in large stands as kelp forests, and this pathway is sometimes referred to as ocean afforestation. Variants include restoring and expanding kelp forests and moving macroalgae aquaculture—which is currently practiced in coastal areas particularly in Asia—farther offshore to expand the available area.

Because macroalgae attach to rocky surfaces, they do not sequester carbon in the soil through roots. Instead, their biomass becomes detritus in the ocean, and there is substantial uncertainty about what fraction of this is exported to the deep ocean for permanent storage. CDR techniques would include harvesting and sinking macroalgae biomass in the deep ocean or using the biomass for "aquatic BECCS."[36,37,38] The estimated potential for some forms of macroalgae CDR is approximately 630 $MtCO_2$ per year, although cost estimates are not available. Reliable potential and cost estimates for other forms are not available; however, it appears that at least some of these pathways could meet the target thresholds for removal potential and cost. The ARPA-E Macroalgae Research Inspiring Novel Energy Resources (MARINER) program is currently funding advanced research on macroalgae cultivation techniques, which provides a foundation for further RD&D.

Recommended RD&D Portfolio Elements

Research needs in this area fall into two categories: improvements in macroalgae cultivation and biomass conversion processes. There is little-to-no current RD&D focused on macroalgae as a CDR pathway, but both DOE and NOAA have ongoing research programs that can be readily expanded to support research in this area.

- **Aquatic Macroalgae Cultivation, Portfolio Element 5.21,** provides funding for applied research on best practices in macroalgae cultivation and phenotype selection, including at-sea pilots. The recommendation assumes that NOAA/OAR and DOE/BETO would collaborate in leading this effort.
- **Aquatic Biomass Conversion, Portfolio Element 5.22,** provides funding for applied research on optimizing aquatic biomass conversion pathways for biopower, biofuels, or other uses. The recommendation assumes that DOE/BETO will lead this effort in coordination with NOAA/OAR.

Ocean Alkalinity Modification

The pathway of removing atmospheric CO_2 through OAM was first proposed in 1995.[39] The basic concept is to artificially add sources of alkalinity, such as calcium oxide (CaO; lime) or magnesium oxide (MgO), to the surface layer of the ocean. This raises pH and converts dissolved CO_2 into bicarbonate, a chemical form that provides for the isolation of carbon from the atmosphere in ocean waters. The reduction of CO_2 dissolved in ocean waters in turn will lead to more uptake of CO_2 by the oceans until chemical equilibrium between atmospheric CO_2 and dissolved CO_2 in oceans waters is restored. It also helps counter the effects of ocean acidification and increases the availability of calcium carbonate.[40]

OAM represents a technologically enhanced form of the natural process of weathering, in which silicate and carbonate minerals react with water and CO_2 to remove and store atmospheric CO_2 on geologic timescales. There are a large number of possible approaches to OAM.

One of the earliest versions of OAM is ocean liming, which envisions using lime as the source of alkalinity. Obtaining lime requires calcining limestone ($CaCO_3$)—an energy-intensive process that releases CO_2 (which must be captured and sequestered)—as well as crushing, transporting, and sinking the resulting lime powder. The estimated cost of this process is $72 to $159 per tCO_2.[41,42]

An alternative is to react seawater with power plant flue gas and carbonate minerals (e.g., $CaCO_3$). This approach, known as accelerated weathering of limestone, also converts dissolved CO_2 into bicarbonate in solution, which would be released back into the ocean.[43,44] It requires moving large amounts of minerals and seawater but could potentially be implemented in power plant cooling water outflows. A variant of this pathway uses the enzyme carbonic anhydrase to catalyze the dissolution of calcites and further accelerate the process.[45]

Producing hydrogen from seawater via electrolysis provides another possible approach to ocean CDR known as electrochemical enhancement of weathering. When electrolyzing seawater, mineral hydroxides are produced (in addition to hydrogen), which react strongly with atmospheric CO_2, forming bicarbonates. This process requires electrical energy; it cannot achieve negative emissions when powered by fossil fuel, but it can be net negative when it uses carbon-free electricity and the generated hydrogen (in fuel cells) and has a large potential capacity.[46]

Another pathway is brine thermal decomposition, which envisions heating reject brine from seawater desalination plants to produce magnesium oxide. When this is added to seawater, it consumes CO_2 and results in dissolved bicarbonate. This is basically a variant of ocean liming, using desalination waste rather than lime from calcination of limestone. The temperatures required are less than 600°C, which is achievable through solar concentrators. This approach has the logistical advantage of involving source material (desalination brine) that is already sited on the coast.[47]

Another proposed approach is open ocean dissolution of olivine (a silicate material), which envisions grinding it into small particles and adding them to the ocean surface. This would be similar to accelerated weathering, causing reactions with CO_2 that lead to dissolved bicarbonate and carbonate ions. However, in order to dissolve rapidly enough, the particles would need to be less than 1 micron in size, implying large energy requirements for crushing and grinding. A variation of this is coastal spreading of olivine, in which olivine particles of larger size would be placed on the coast (possibly as part of dredging or landreclamation projects), and wave action would provide some acceleration of grinding and dissolution.[48,49]

Weathering of mine waste envisions agitating or spreading carbonate and silicate mine waste (tailings), which is already crushed to small particle size. This would react with atmospheric CO_2 and form dissolved bicarbonate and carbonate ions in runoff water. In certain locations, this runoff would reach the ocean with this elevated alkalinity. Energy requirements would be lower than similar concepts using rock because of the small particle size, but little is known about trace contaminants in mine tailings that might be released.[50]

Electrochemical treatment of seawater modifies seawater chemistry using electric current. One pathway employs membrane electrodialysis to produce an acid (HCl) and base (NaOH) solution from seawater; the acid solution is then added to additional volumes of seawater to convert bicarbonate to dissolved CO_2, which is vacuum-stripped and compressed for pipeline transport or utilization. The base solution is returned to the treated seawater, restoring the original pH.[51] A complementary process can be used to precipitate $CaCO_3$ from seawater, followed by storage or utilization of the resulting solid. Costs are estimated to be \$373 to \$604 per tCO_2 produced, although costs for a partial system that would integrate with ocean alkalinity enhancement are \$100 to \$300 per tCO_2 sequestered as bicarbonate.[52] A similar pathway using electrolytic cation exchange can produce CO_2 from seawater by acidification, although relevant cost estimates are not available for this process.[53]

Recommended RD&D Portfolio Elements

Because of the enormous scale of this natural process—and the fact that the Earth's crust is largely composed of alkaline minerals—OAM is considered to have "no known physical limit."[54] The key questions center on engineering and economic feasibility and environmental impact. The costs of various sources of alkaline materials, and the emissions and costs associated with obtaining, transforming, and transporting them, have large uncertainties.

There nonetheless is sufficient potential to justify federal RD&D investments in OAM. Resolving the outstanding research questions and refining the scale and cost estimates will require techno-economic analysis, laboratory-scale experiments, and at-sea pilot projects. There are enough sufficient similarities across the proposed pathways that they should be addressed within the same broad program.

- **Fundamental Research, Portfolio Element 5.31,** supports fundamental research focused on the biogeochemical interactions due to alkaline materials added to the oceans and ecological impacts from alkalinity modification. To implement this research, the mission objectives of the NOAA Ocean Acidification Program (OAP) should be expanded to address CDR research in addition to the current mandates for monitoring and assessments. This element also includes additional funding for fundamental research in NSF/OCE.
- **Ocean Alkalinity Experiments, Portfolio Element 5.32,** provides funding for applied research on OAM options, including carefully designed and monitored at-sea pilot

experiments. The applied research objectives also should be incorporated into the mission objectives of the NOAA OAP. NOAA and NSF should work collaboratively with DOE/AMO to address research questions related to industrial availability of alkaline materials relevant to OAM.

Ocean Fertilization

Three large ocean regions—the Southern Ocean, the subarctic North Pacific, and the Eastern Equatorial Pacific—have large amounts of macronutrients (phosphorous and nitrogen) but very low photosynthetic activity. These areas are known as High-Nutrient Low-Chlorophyll (HNLC), and they are caused by a lack of iron, which is necessary for photosynthesis. Only a trace amount (less than parts per billion) is needed. Artificial ocean iron fertilization (OIF) envisions adding relatively small amounts of iron to these regions to stimulate a large phytoplankton bloom. This, in turn, may lead to CO_2 removal and storage, as organic matter resulting from the bloom sinks to the deep ocean.[55]

Thirteen medium-scale OIF experiments have been performed to date. Many of the experiments were not carefully controlled or fully analyzed, so the results are inconclusive and not scientifically robust. All of the experiments demonstrated that the addition of iron in HNLC regions does lead to phytoplankton blooms (Table 5-1).[56] However, there was substantial variation in the size of the phytoplankton bloom relative to the amount of iron added. Moreover, there was also a wide range in the amount of carbon from enhanced phytoplankton photosynthesis that ultimately sank to the deep ocean and was thus sequestered, ranging from 8 percent to 50 percent. Understanding this variation remains a key area for research.[57]

Table 5-1
Summary of Artificial Ocean Iron Fertilization Experiments

Name	Year	Ocean	Outcomes
IronEx-1	1993	EP	Small response in primary productivity
IronEx-2	1995	EP	Large biogeochemical response; diatom shift
SOIREE	1999	SO	Diatom-dominated bloom; no measurable carbon export
EisenEx	2000	SO	Diatom-dominated bloom; no carbon flux difference
SOFeX-N	2002	SO	Diatom biomass increase; large export flux event
SOFeX-S	2002	SO	Enhanced export flux similar to natural blooms
EIFEX	2004	SO	Full phytoplankton bloom; significant carbon export
SAGE	2004	SO	No diatom shift; no induced export
LOHAFEX	2009	SO	Phytoplankton bloom; no diatom shift or induced export
SEEDS-1	2001	NP	Large biogeochemical response; no carbon export
SERIES	2002	NP	Full phytoplankton bloom; no carbon export
SEEDS-2	2004	NP	Full phytoplankton bloom; no diatom shift or export
FeeP	2004	NA	Increased picophytoplankton abundance

EP = Equatorial Pacific; SO = Southern Ocean; NP = Subarctic North Pacific; NA = Subtropical North Atlantic. Source: Yoon, 2018.

In addition to CO_2 removal effectiveness, a crucial question is what ecological impacts may occur. There is some evidence for the growth of toxic diatoms following iron fertilization and possibly larger concentrations of methane and nitrous oxide. Better understanding these impacts is another key area for research.

A related pathway is nitrogen and phosphorous ocean fertilization. This would be used in areas of the ocean where photosynthesis is limited by a lack of these nutrients. There is very little experimental evidence about its effectiveness. Since these nutrients are required in more than just trace amounts (unlike iron), there does not appear to be the same potential for highly amplified phytoplankton blooms from a small addition of material. This suggests the cost of this pathway is likely to be considerably higher than OIF.

Reliable estimates of the costs and potential scale of OIF or fertilization with nitrogen and phosphorous are not available. A 2010 NOAA report to Congress on OIF highlighted a variety of important considerations for potential ecological impacts, as well as scale and feasibility.[58] In the decade since, several small- to medium-scale OIF experiments have been conducted, and one is currently planned for the near future by Korean researchers.[59]

OIF experiments have raised public concerns regarding potential adverse ecological impacts. One reason for this involves concerns about nations or individuals implementing large-scale OIF without authorization or international consultation, an example of which occurred in 2012 when a private company dumped 100 tons of iron sulfate in waters off British Columbia to stimulate a phytoplankton bloom and ultimately drive a restoration of the salmon population. Evidence shows that the region experienced a phytoplankton bloom and a short-term increase in salmon populations, but there are no published reports that documented a clear causal linkage, other environmental impacts, or net carbon reduction. This example also highlights the need to carefully consider the interplay between ocean fertilization for CDR purposes and for fisheries restoration/enhancement purposes.[60]

Concerns about ecological impacts have led to the establishment of the LC/LP Ocean Fertilization Assessment Framework, which establishes procedures for member nations to evaluate proposals for OIF experiments.

Recommended RD&D Portfolio Elements

Given the potential for large-scale, low-cost carbon removal and storage represented by OIF, and to a lesser degree nitrogen and phosphorous fertilization, further research is justified but should be carefully planned and coordinated within the guidelines of the LC/LP Ocean Fertilization Assessment Framework.

- **Fundamental Research, Portfolio Element 5.41,** supports fundamental research and modeling on the impacts and effectiveness of OIF and nitrogen and phosphorous fertilization research. The research is proposed for NOAA/OAR and the NSF/OCE. This work would not include field trials or demonstrations.
- **Ocean Iron Fertilization Experiments, Portfolio Element 5.42,** supports funding to conduct well-defined and carefully monitored small- to medium-scale field (at-sea)

experiments on artificial OIF. This work would be carried out in full alignment with the LC/LP Ocean Fertilization Assessment Framework. Any such at-sea experiments should be carefully planned and coordinated with appropriate international scientists. The proposed budget planning estimate assumes that a two-year preparation process will be needed, with no field work conducted earlier than Year Three of the initiative. This effort is proposed to be led by NOAA/OAR and NSF/OCE.

- **Ocean Macronutrient Experiments, Portfolio Element 5.43,** provides funding to conduct small- to medium-scale field (at-sea) experiments on artificial ocean macronutrient fertilization (with nitrogen and phosphorous). This work would be carried out in full alignment with the LC/LP Ocean Fertilization Assessment Framework. No field work would be conducted earlier than Year 3 of the initiative. This effort is proposed to be led by NOAA/OAR and NSF/OCE.

Ocean Environmental Assessments and Modeling

The ecology of the oceans is highly complex, involving a range of biogeochemical interactions, intricate food webs, interaction with the atmosphere, and other factors. The full scope of these interactions is not completely understood, and the ways in which ocean systems may respond, or are already responding, to human disturbances related or analogous to CDR are not well known.[61,62] A robust and well-funded effort to measure, model, and predict the full range of ocean systems potentially affected by CDR is needed, with an emphasis on the impacts of anthropogenic changes to seawater chemistry and primary productivity. This should also be accompanied by an expanded campaign to monitor ocean ecosystems.

Recommended RD&D Portfolio Element

- **Comprehensive Environmental Assessments, Portfolio Element 5.51,** provides funding for a comprehensive ecological research program to better understand the impact and fate of CO_2 in the oceans. The program is proposed for implementation by NOAA/OAR and DOE/BER.

Innovative Approaches and Other Techniques

Various other pathways related to the removal and storage of atmospheric CO_2 in the oceans have been proposed, including artificial upwelling/downwelling, direct CO_2 injection in seawater or on the seafloor, depositing harvested terrestrial biomass in the deep ocean, and genetically engineering phytoplankton to produce recalcitrant biomass.[63,64] In some cases, these pathways have not been reviewed by credible scientific organizations; in other cases, scientific review has shown that these pathways face a range of challenges that make them inappropriate for further RD&D at this time, including high costs, low potential scale, or significant ecological challenges. No specific funding is recommended for these activities at this time. Promising research experiments can be funded as part of the fundamental research programs at NOAA, NSF, and DOE. It is recommended that the research agencies set aside a small portion of funding to address well-formulated unsolicited proposals for research on innovative research concepts that might have significant potential.

It is also worth noting that storage of CO_2 in sub-seafloor basalt and peridotite formations has been proposed. The CarbonSAFE Cascadia project is currently conducting pre-feasibility studies of this technique for a site offshore from Washington State and British Columbia.[65] This and related RD&D are already being conducted by DOE and are further addressed in Chapter 4.

The overarching RD&D objective for coastal and oceans CDR is to develop a better understanding of the effectiveness and ecosystem impacts of carbon removal processes in coastal areas and deep ocean waters to provide the basis for determining feasibility of future CDR implementation measures.

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Table 5-2
Coastal and Oceans RD&D Portfolio ($millions)

Portfolio Element	Funding Agency	Funding Office or Organization	Year 1	5-Year Total	10-Year Total
5.10 Coastal Systems (Blue Carbon)					
5.11 Fundamental research	DOC	NOAA (OAR)	$3	$15	$30
	NSF	GEO	$2	$14	$29
5.12 Resource assessment	DOC	NOAA (OAR)	$1	$5	$10
	NASA	ESD	$1	$5	$10
5.13 Regional field trials	DOC	NOAA (Fisheries)	$10	$185	$435
	DOD	USACE	$10	$110	$235
5.14 National Coastal Wetland Data Center	DOC	NOAA (OAR)	$2	$10	$20
5.15 Coastal blue carbon project deployment	N/A	N/A	$0	$0	$0
5.10 Subtotal, Coastal Systems (Blue Carbon)			$29	$344	$769
5.20 Marine Biomass Capture and Storage					
5.21 Aquatic biomass cultivation	DOC	NOAA (OAR)	$1	$19	$40
	DOE	EERE (BETO)	$1	$19	$38
5.22 Aquatic biomass energy conversion	DOE	EERE (BETO)	$2	$47	$107
5.20 Subtotal, Marine Biomass Capture and Storage			$4	$85	$185
5.30 Alkalinity Modification					
5.31 Fundamental research	NSF	GEO	$2	$31	$71
	DOE	SC (BER)	$2	$28	$63
5.32 Applied alkalinity modification techniques	DOC	NOAA (OAR)	$0	$65	$175
	NSF	GEO	$0	$25	$65
5.30 Subtotal, Alkalinity Modification			$4	$149	$374
5.40 Ocean Fertilization					

5.41 Fundamental research	NSF	GEO	$2	$32	$72
	DOC	NOAA (OAR)	$2	$14	$34
	DOE	SC (BER)	$0	$12	$27
5.42 Artificial ocean iron fertilization	DOC	NOAA (OAR)	$0	$25	$75
	NSF	GEO	$0	$15	$40
5.43 Artificial ocean macronutrient fertilization	DOC	NOAA (OAR)	$0	$15	$40
	NSF	GEO	$0	$15	$40
5.40 Subtotal, Ocean Fertilization			$4	$128	$328
5.50 Ocean Environmental Assessments					
5.51 CO_2 impacts and fate in the oceans	DOC	NOAA (OAR)	$2	$22	$47
	DOE	SC (BER)	$2	$22	$47
5.50 Subtotal, Ocean Environmental Assessments			$4	$44	$94
TOTAL, Coastal and Oceans			$45	$750	$1,750
Source: EFI, 2019.					

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CHAPTER 6. GEOLOGIC SEQUESTRATION

Geologic sequestration provides a disposition pathway to store CO_2 captured from concentrated point sources (e.g., power plants, industrial facilities), CDR via DAC, and BECCS. The process involves the subsurface injection of CO_2 into various onshore and offshore geologic formations for the purposes of dedicated sequestration or enhanced resource recovery (e.g., oil), both of which can lead to the permanent storage of CO_2 (defined on a timescale of more than 1,000 years).[1] Many suitable geologic formations have naturally stored CO_2 for thousands of years, while oil and gas reservoirs have successfully contained energy resources for millions of years.[2] Estimates of the total potential storage capacity for geologic sequestration are on the scale of trillions of tons of CO_2 (at both the U.S and global levels). However, further scientific, technical, and environmental risk management RD&D is needed to fully maximize the opportunity for geologic sequestration.

Geologic Sequestration Process

Prior to injection, CO_2 is compressed into a fluid state.[3] CO_2 becomes supercritical when it is injected underground and subjected to high temperature and pressure where it adopts the density of a liquid (similar to oil). At sufficient depths of greater than 800 meters, the CO_2 remains in this dense (supercritical) phase.[4,5] The CO_2 that is injected into a geologic formation becomes trapped through several different mechanisms including mineral trapping (carbon mineralization), residual trapping (CO_2 trapped in pore spaces), solubility trapping (CO_2 dissolved into saline water), and structural trapping (trapped beneath an impermeable rock layer).[6,7] Geologic attributes that help define viable sequestration opportunities include ample pore space availability, high permeability to allow CO_2 to move between pore spaces, and an impermeable layer above the injection location (caprock) to seal the CO_2 in its intended storage reservoir.[8]

Sequestration Locations

There are several types of onshore and offshore locations that could be suitable for geologic sequestration, including saline formations, oil and gas reservoirs, unmineable coal seams, and shale basins.[9] (Note: In situ mineralization of CO_2 involves underground injection into subsurface rock formations, such as basalt, where the CO_2 is converted to carbonate; this process is discussed in Chapter 4.)

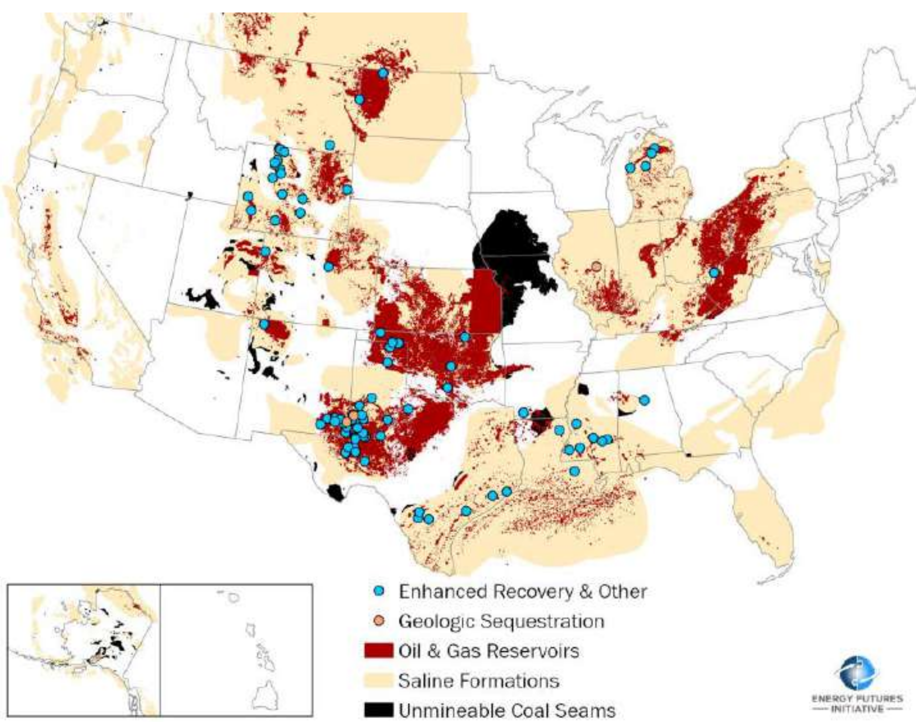
Saline Formations. Saline formations are a viable storage medium for CO_2 that contain varying levels of saline (salty) water, also known as brine, that can range from low salinity to non-potable.[10] This storage medium has a relatively high potential for geologic sequestration (including in the United States) due in part to its large geographic distribution,[11] and it is common in both onshore and offshore sedimentary basins in North America.[12]

Oil and Gas Reservoirs. Oil and gas production typically takes place in sedimentary formations, where the same geologic characteristics that made them suitable reservoirs for oil and gas over the span of thousands to millions of years can also make them viable repositories for injected CO_2.[13] Producing oil and gas reservoirs provide the benefit of known attributes that are important for geologic sequestration, including injectivity, capacity, and a viable caprock for structural trapping.[14] Depleted oil and gas reservoirs that are devoid of economic opportunities for resource recovery typically have geologic trapping mechanisms that make them suitable candidates for sequestration.[15] Geologic sequestration in depleted gas reservoirs requires minimal pressure management, since the injected CO_2 would replace methane in the reservoir.[16]

Unmineable Coal Seams. Coal seams can be considered unmineable due to geologic or economic factors. These formations could provide a viable opportunity for geologic sequestration, since coal selectively adsorbs CO_2 at a rate of 2-13 times higher than methane through the process of adsorption trapping.[17] This process can also enable enhanced coal-bed methane recovery, which involves CO_2 injection into coal beds to exchange CO_2 with CH_4.[18]

Figure 6-1

Subsurface Geologic Sequestration Resources and Reported CO_2 Injection Sites



In 2017, there were 98 covered entities that reported CO_2 injection activities through the EPA GHGRP. Source: EFI, 2019. Compiled using data from the Environmental Protection Agency and National Energy Technology Laboratory.

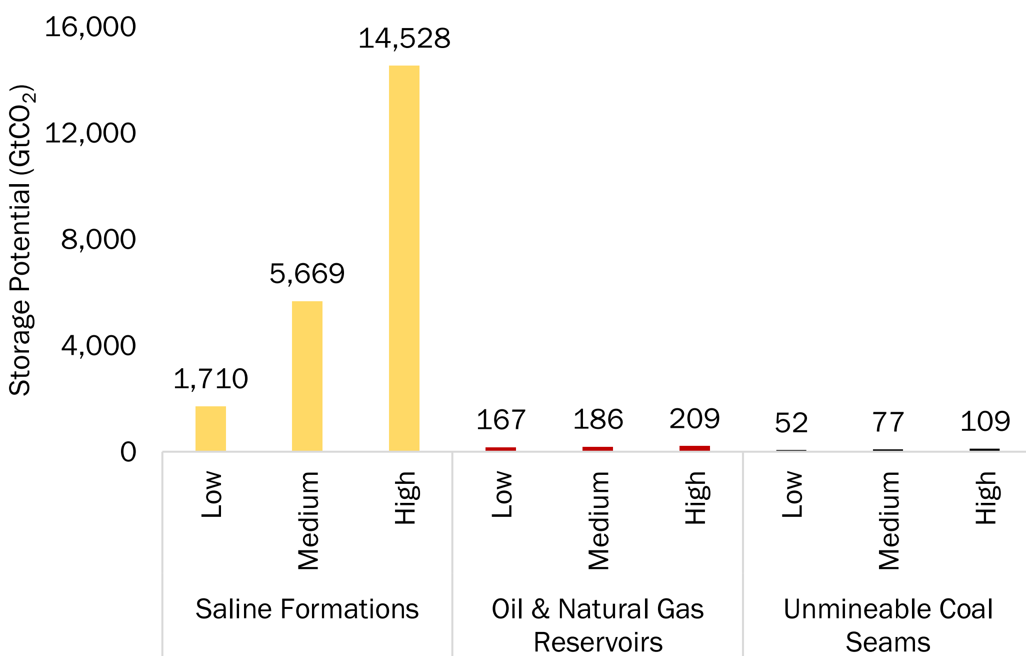
Shale Basins. Shale basins are composed of silicate minerals that are often used as a caprock or confinement area for injected CO_2. However, recent evidence suggests that these formations also have the potential for dedicated geologic sequestration projects.[19]

Figure 6-1[20,21] illustrates the distribution of subsurface geological sequestration resources with an overlay of the locations where actual CO_2 injection activities were reported to the EPA Greenhouse Gas Reporting Program (GHGRP) in 2017 for the purposes of dedicated geologic sequestration and enhanced resource recovery.

Estimated Potential for Geologic Sequestration

DOE has estimated the potential for geologic sequestration in the United States, defined as the fraction of pore volume of porous and permeable reservoirs available for CO_2 injection, across three different storage types. The results yielded a total U.S. sequestration potential of 1,929 to 14,846 $GtCO_2$ across saline formations, oil and gas reservoirs, and unmineable coal seams (Figure 6-2).[22] Globally there are four large-scale dedicated geologic sequestration projects in operation, including an additional project that is under construction.[23]

Figure 6-2
Estimated Geologic Sequestration Potential in the United States



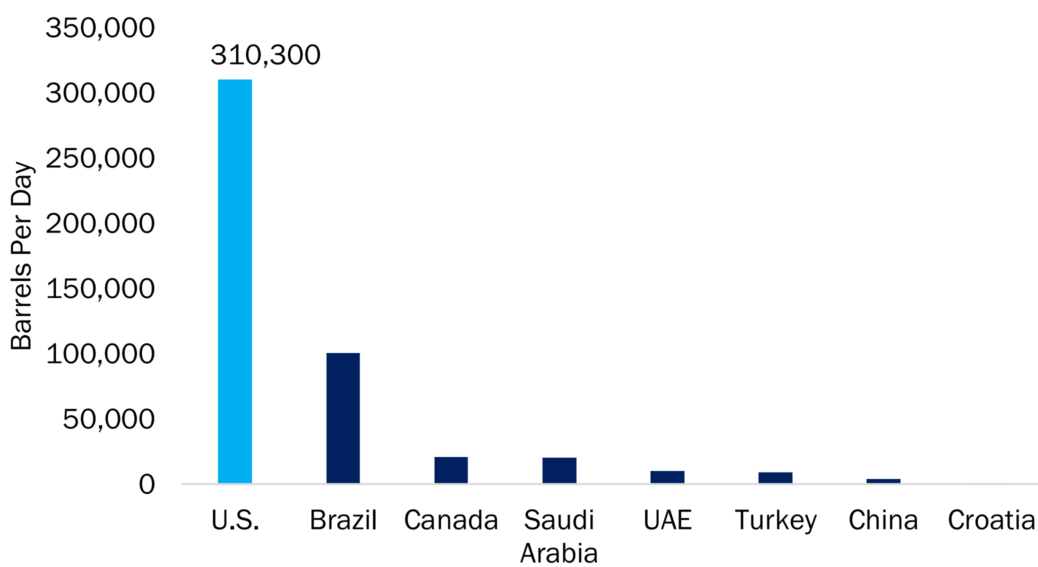
The United States has an estimated total geologic sequestration potential of 1.9 trillion to 14.8 trillion tons of CO_2 across saline formations, oil and gas reservoirs, and unmineable coal seams. Source: EFI, 2019. Compiled using data from the National Energy Technology Laboratory, 2015.

DOI has also helped to advance the knowledge base for geologic sequestration. The Energy Independence and Security Act of 2007 required DOI to undertake national assessments of subsurface carbon sequestration potential.[24] In 2013, DOI released its first national assessment of geologic sequestration with an estimated total storage potential of 3,000 GtCO_2 (probabilistic range of 2,400 to 3,700 GtCO_2) across 36 sedimentary basins in the United States, 65 percent of which were located in the Coastal Plains region.[25,26]

Enhanced Oil and Gas Resource Recovery

Enhanced resource recovery involves the use of different subsurface injection methods to increase the production of oil—it can also be used for natural gas—from reservoirs after initial production methods have been conducted. Primary oil production, based on pressure gradients, typically accounts for 10 percent to 15 percent of resource recovery, while secondary production (mostly water injection) can produce 15 percent to 25 percent of the oil in place, which can leave roughly two-thirds of the resource available for tertiary recovery.[27,28] EOR is a tertiary production method that has reportedly led to resource recovery rates in excess of 60 percent.[29] EOR can utilize a broad range of injectants, including CO_2, steam, chemicals, microbes, in situ combustion, and other gases (e.g., natural gas, nitrogen).[30]

Figure 6-3
Daily Oil Production through CO_2-EOR by Country, 2017



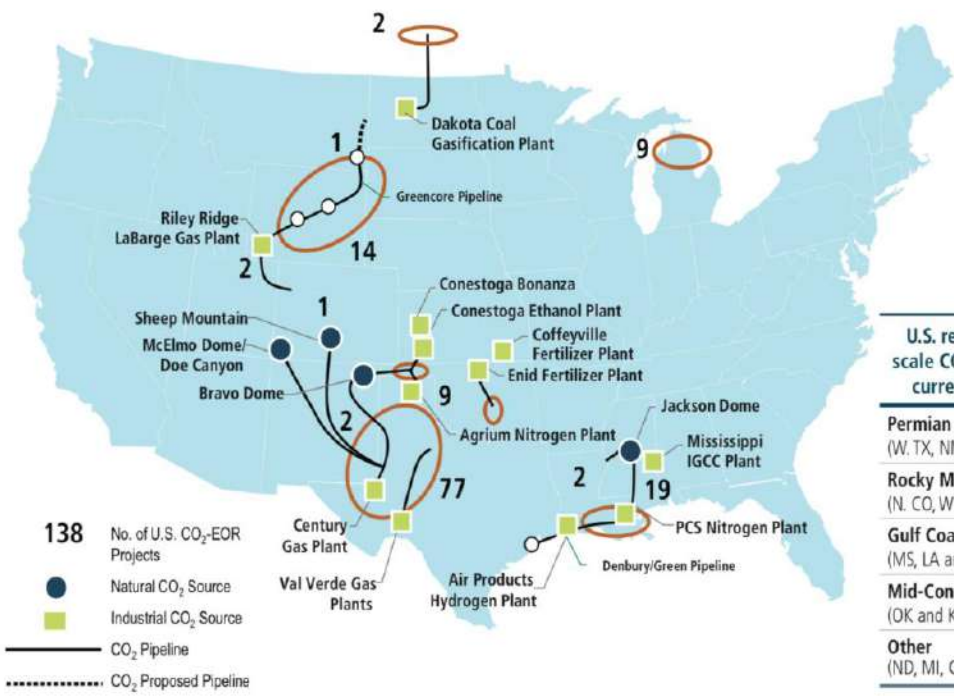
Approximately 474,000 barrels per day were produced through CO_2-EOR in 2017, most of which was in the United States. The United States produces more oil using CO_2-EOR than any other country. Source: EFI, 2019. Compiled using data from the International Energy Agency, 2019.

The CO_2-EOR process involves subsurface injection of CO_2 to stimulate production by increasing reservoir pressure and mixing it with oil in the target reservoir to facilitate its geomechanical movement to the surface.[31] During this process, a portion of the injected CO_2 is produced along with the oil and reinjected for further resource recovery and CO_2 storage. The portion of CO_2 that is stored via CO_2-EOR has been estimated at 33 percent to 50 percent for the initial injection, while the remainder that is produced with the oil is captured and reinjected until it has been sequestered.[32] Almost all of the CO_2 used for CO_2-EOR is sequestered over the lifetime of a project.[33]

CO_2-EOR began in the 1970s, and the United States is by far the global leader in EOR production (Figure 6-3).[34,35] In 2017, the U.S. produced 310,300 barrels per day on average through CO_2-EOR,[36,37] approximately 3.3 percent of the average daily oil production of 9.3 million barrels per day in that year.[38] The U.S. EOR industry is supported by a series of regional CO_2 pipelines that connect CO_2 sources (both natural and anthropogenic) with EOR project locations (Figure 6-4).[39,40]

Figure 6-4

Existing and Proposed CO_2 Pipeline Infrastructure in the United States



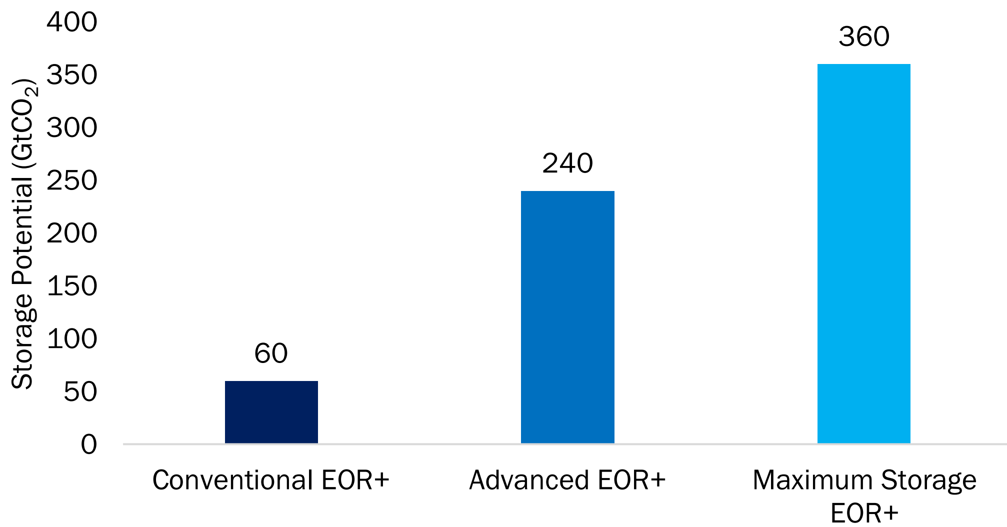
U.S. regions with large-scale CO_2 pipeline systems currently in operation	Miles of Pipeline
Permian Basin (W. TX, NM, and S. CO)	2,320
Rocky Mountains (N. CO, WY and MT)	810
Gulf Coast (MS, LA and E. TX)	740
Mid-Continent (OK and KS)	480
Other (ND, MI, Canada)	215

There are more than 5,200 miles of CO_2 pipelines operating in the United States. Note: Operation of the Mississippi IGCC Plant has been terminated. Source: Department of Energy.

Sequestration Potential through CO_2-Intensive EOR

A potential opportunity to expand the prospects for geologic sequestration and the global CO_2 market involves CO_2-intensive EOR. Whereas traditional CO_2-EOR operations seek to minimize CO_2 use and maximize resource recovery due to the cost incurred for purchasing CO_2 on the commercial market,[41] CO_2-intensive EOR could seek to maximize CO_2 injection for the purposes of geologic sequestration. This requires a different EOR technique, namely a gravity CO_2-flood concept that utilizes a larger amount of CO_2 to create a layer of CO_2 at the top of the oil reservoir. The pressure of the top layer gradually forces the oil out of the reservoir, resulting in a slower EOR production rate without reducing ultimate oil yield. IEA estimates the potential to store up to 360 $GtCO_2$ in oil reservoirs globally by 2050 through CO_2-intensive EOR (Figure 6-5).[42,43]

Figure 6-5
Estimated Global Sequestration Potential for Various CO_2-EOR Scenarios



Estimates suggest that 60 to 360 $GtCO_2$ could be sequestered globally through various EOR methods. Conventional EOR+ maximizes production and minimizes CO_2 used for injection. Advanced EOR+ has greater resource recovery and more CO_2 injected than Conventional EOR+. Maximum Storage EOR+ achieves the same resource recovery as Advanced EOR+ but maximizes CO_2 storage. Source: International Energy Agency.

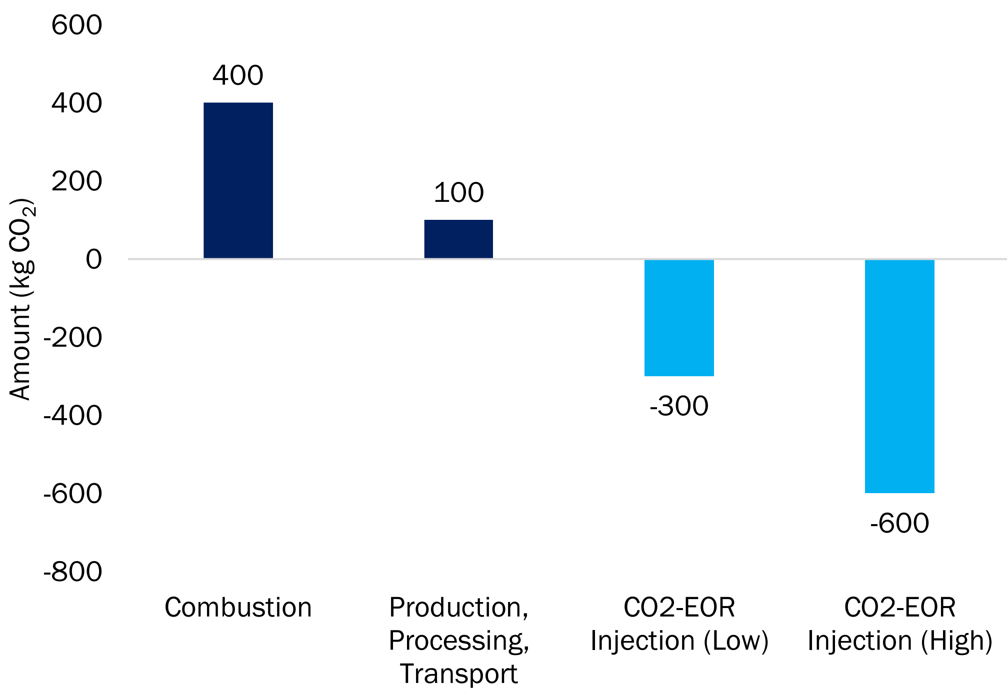
Lifecycle Carbon Impact of CO_2-Intensive EOR

CO_2-intensive EOR has the potential to reduce the lifecycle footprint of EOR to potentially carbon-neutral or even carbon-negative. The two keys are the source of CO_2 and the rate of intensive CO_2 injection.

The use of anthropogenic rather than naturally occurring CO_2 is a key determinant for the climate benefit of geologic sequestration achieved through CO_2-EOR. On a global level, total demand for CO_2 is estimated to be around 80 MtCO_2 per year,[44] of which 65 MtCO_2 are used for EOR; the resulting EOR production accounts for approximately 2 percent of the global oil supply.[45] Of this total, only one-third of the CO_2 is from anthropogenic sources;[46,47] in the United States, less than 30 percent of the CO_2 feedstock used for CO_2-EOR is from natural sources.[48]

CO_2-EOR operations have the potential to be carbon-neutral or carbon-negative depending upon the source of the CO_2 and the intensity of the CO_2 injection rate relative to the EOR production levels. In the United States, an estimated 300 to 600 kilograms of CO_2 are injected for each barrel of oil produced through CO_2-EOR, while emissions spanning from oil production and consumption include approximately 100 kilograms of CO_2 per barrel from production, processing, and transport and 400 kilograms of CO_2 per barrel from combustion. Therefore, CO_2-intensive EOR that uses an anthropogenic CO_2 supply of at least 500 kilograms of CO_2 per barrel of oil produced has the potential to yield carbon-neutral oil on a full lifecycle basis; if the CO_2 feedstock came from a BECCS refinery or DAC plant, it could yield carbon-negative oil (Figure 6-6).[49]

Figure 6-6
Lifecycle Emissions for CO_2-EOR in the United States



CO_2-EOR has the potential to be carbon-neutral or carbon-negative in the United States.
Source: EFI, 2019. Compiled using data from the International Energy Agency.

Box 6-1

U.S. Large-Scale CCUS Projects from Concentrated (Point) Sources

As of 2019, there were 41 current and former CCUS projects in the United States across 18 states;[50] there are 11 large-scale CCUS facilities currently operating or in advanced development with an estimated capture capacity of 28 $MtCO_2$ per year.[51]

Table 6-1

Large-Scale CCUS Facilities in the United States, 2019

Name	State	Status	Operational Year	Industry	Capture Capacity ($MtCO_2$/yr.)	Primary Storage Type
Air Products Steam Methane Reformer	TX	Operating	2013	Hydrogen Production	1.0	EOR
Century Plant	TX	Operating	2010	Natural Gas Processing	8.4	EOR
Coffeyville Gasification Plant	KS	Operating	2013	Fertilizer Production	1.0	EOR
Enid Fertilizer	OK	Operating	1982	Fertilizer Production	0.7	EOR
Great Plains Synfuels Plant	ND	Operating	1984	Synthetic Natural Gas	1.8	EOR
Illinois Industrial Carbon Capture and Storage	IL	Operating	2017	Ethanol Production	1.0	Dedicated Geologic Storage
Lake Charles Methanol	LA	Advanced Development	2022 (est.)	Chemical Production	4.2	EOR
Lost Cabin Gas Plant	WY	Operating	2013	Natural Gas Processing	0.9	EOR
Petra Nova Carbon Capture	TX	Operating	2017	Power Generation	1.4	EOR
Shute Creek Gas Processing Plant	WY	Operating	1986	Natural Gas Processing	7.0	EOR
Terrell Natural Gas Processing Plant	TX	Operating	1972	Natural Gas Processing	0.4 to 0.5	EOR

As of 2019, the United States had a total installed CCUS capture capacity of approximately 28 $MtCO_2$ per year. Note: Large-scale is defined as those facilities that capture and store at least 800 $ktCO_2$ per year for coal plants or 400 $ktCO_2$ per year for all other facilities. Source: EFI, 2019. Compiled using data from the Global CCS Institute and Dakota Gasification Company.

DOE Geologic Sequestration Research Programs

DOE has played an instrumental role in helping to advance RD&D related to geologic sequestration, with Congressional appropriations support that totaled more than $4 billion for CCUS-related activities from fiscal year 2012 through fiscal year 2018. Of that total, carbon storage received more than $727 million at an average funding level of nearly $104 million per year.[52] The Carbon Storage Program at DOE began in 1997 through FE's Clean Coal and Carbon Management sub-office and has helped advance the knowledge base for geologic sequestration through a collaborative research network of national labs, academia, and the private sector.

Regional Carbon Sequestration Partnerships Initiative

The Regional Carbon Sequestration Partnerships (RCSP) Initiative was an effort led by DOE and NETL to promote the development of CCUS projects in the United States. The RCSP Initiative was funded through FE's Carbon Storage Program, which received an average annual funding level of approximately $109 million from fiscal year 2011 to fiscal year 2016.[53] To help facilitate the mission of the RCSP Initiative, the United States was divided into seven geographic regions that each consisted of a lead organization and network of participating entities[54] and comprised 43 states, four Canadian provinces, and more than 400 diverse entities (Table 6-2). The geographical coverage of the seven regions is shown in Figure 6-7).[55,56,57,58]

Table 6-2
RCSP Initiative Geographic Regions

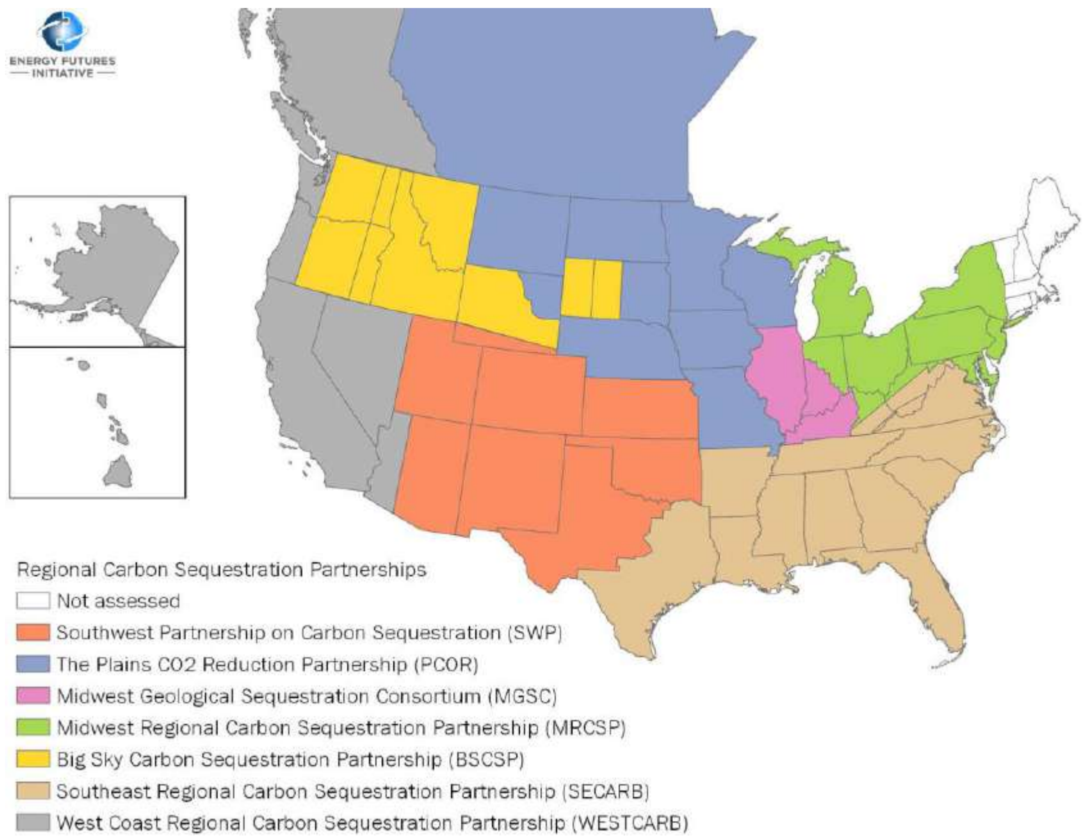
RCSP Region	Lead Entity	Participating Entities
Big Sky Carbon Sequestration Partnership (BSCSP)	Montana State University-Bozeman	➢ 6 states (ID, MT, OR, SD, WA, WY) ➢ 60+ entities from academia; national laboratories; private sector companies; state agencies; Native American tribes; international collaborators
Midwest Geological Sequestration Consortium (MGSC)	Illinois State Geological Survey	➢ 3 states (IL, IN, KY) ➢ Entities from state agencies; private sector companies; business associations; academia; Interstate Oil and Gas Compact Commission
Midwest Regional Carbon Sequestration Partnership (MRCSP)	Battelle Memorial Institute	➢ 9 states (IN, KY, MD, MI, NJ, NY, OH, PA, WV) ➢ 40 entities from academia; state agencies; nongovernmental organizations; private sector companies
The Plains CO_2 Reduction Partnership (PCOR)	University of North Dakota Energy and Environmental Research Center	➢ 9 states (IA, MN, MO, MT, ND, NE, SD, WI, WY) ➢ 3 provinces (Alberta, Saskatchewan, Manitoba) ➢ 100 entities from public and private sectors
Southeast Regional Carbon Sequestration Partnership (SECARB)	Southern States Energy Board	➢ 13 states (AL, AR, FL, GA, KY, LA, MS, NC, SC, TN, TX, VA, WV) ➢ 100+ entities from federal and state government; industry; academia; nongovernmental organizations

Southwest Regional Partnership on Carbon Sequestration (SWP)	New Mexico Institute of Mining and Technology	➢ 9 states (AZ, CO, OK, NM, UT, KS, NV, TX, WY) ➢ 50 entities from state and federal agencies; academia; nongovernmental organizations; oil, gas, and coal companies; electric utilities; Navajo Nation
West Coast Regional Carbon Sequestration Partnership (WESTCARB)	California Energy Commission	➢ 7 states (AK, AZ, CA, HI, OR, NV, WA) ➢ 1 province (British Columbia) ➢ 90+ entities from state and provincial agencies; National Laboratories and research institutions; academia; nongovernmental organizations; oil, gas, and pipeline companies; electric utilities; trade associations; vendors and service firms; consultants

The RCSP Initiative consisted of seven geographic regions and a large network of participating entities across the U.S. and Canada. Source: EFI, 2019. Compiled using data from the National Energy Technology Laboratory.

The RCSP Initiative was conducted in three phases that corresponded to an increasing level of project maturation: characterization, validation, and development. The characterization phase began in 2003 and involved an assessment of geologic sequestration potential in various formations. In 2005, the validation phase began with a series of small-scale field projects that led to the successful completion of 19 projects, of which eight projects were conducted in oil and gas reservoirs, five projects in unmineable coal seams, five projects in saline formations, and one project in a basalt formation. The development phase, which commenced in 2008 and was slated to last through 2018 (or later), involved large-scale field projects in oil and gas reservoirs and saline formations with the aim of sequestering a minimum of 1 $MtCO_2$ per project.[59,60]

Figure 6-7
RCSP Initiative Geographic Regions



Seven RCSP regions were created to characterize potential CO_2 storage opportunities and support the development of CCUS infrastructure. Source: EFI, 2019. Compiled using data from the National Carbon Sequestration Database and Geographic Information System Viewer 2.0.

Small- and large-scale field projects for geologic sequestration were conducted with support through the RCSP Initiative and the American Recovery and Reinvestment Act (ARRA),[61] with nine site characterization projects specifically funded through ARRA.[62,63] The 19 small-scale field projects led to the sequestration of 1 $MtCO_2$, along with an additional 10 $MtCO_2$ that were sequestered from six large-scale projects conducted in Alabama, Illinois, Michigan, Mississippi, Montana, and Texas (as of September 2016).[64,65] The aim of the large-scale field projects was to develop processes and procedures that could lead to future geologic sequestration projects at the scale of 50 $MtCO_2$ or more per project[66] and support the overarching goal of enabling the widespread commercial deployment of geologic sequestration projects by 2025-2035.[67] As of January 2018, DOE reported that its Clean Coal Research, Development, and Demonstration Programs had injected more than 16 $MtCO_2$, with active CO_2 injection activities occurring in five of the RCSP regions.[68]

To promote knowledge-sharing for agency-sponsored CCUS R&D projects, DOE's Carbon Storage Program published a series of best practice manuals (BPMs) that included lessons learned from the RCSP Initiative. The first edition of the BPMs were completed in 2011 based on the characterization and validation phases of the RCSP Initiative. In 2017, DOE published updated versions for five BPMs that included lessons learned in the development phase of the RCSP Initiative (Table 6-3). These five BPMs are intended to serve as a comprehensive guide to geologic sequestration projects that range in scope from ideation to project completion.[69,70] Data from the RCSP Initiative are available in the fifth edition of NETL's Carbon Storage Atlas, which was published in 2015 and reported a total geologic sequestration potential in the United States of 1.9 trillion to 14.8 trillion tons of CO_2 across saline formations, oil and natural gas reservoirs, and unmineable coal seams.[71] Data on estimated geologic sequestration resources and storage potential in the United States is also available through the National Carbon Sequestration Database and Geographic Information System (NATCARB), which is hosted on NETL's Energy Data eXchange.[72,73]

Table 6-3
Carbon Storage Program Best Practice Manuals for Geologic Sequestration

BPM Title	Description
Site Screening, Site Selection, and Site Characterization for Geologic Storage Projects	Guidelines that span from basin-scale regional exploration to the point at which individual sites become qualified for commercial storage projects
Risk Management and Simulation for Geologic Storage Projects	Evaluation of potential impacts to public health, safety, and the natural environment, including risk analyses to mitigate and remediate CO_2 migration events
Monitoring, Verification, and Accounting (MVA) for Geologic Storage Projects	MVA techniques and lessons learned through the RCSP Initiative and some international field projects, including monitoring tools and compliance with regulatory requirements
Operations for Geologic Storage Projects	Information on all facets of project management, from initial development to post-injection site care and monitoring
Public Outreach and Education for Geologic Storage Projects	Information dissemination to public audiences that covers issues related to how geologic sequestration works and analogous sequestration methods in nature

There are five DOE best practice manuals for geologic sequestration projects. Source: National Energy Technology Laboratory.

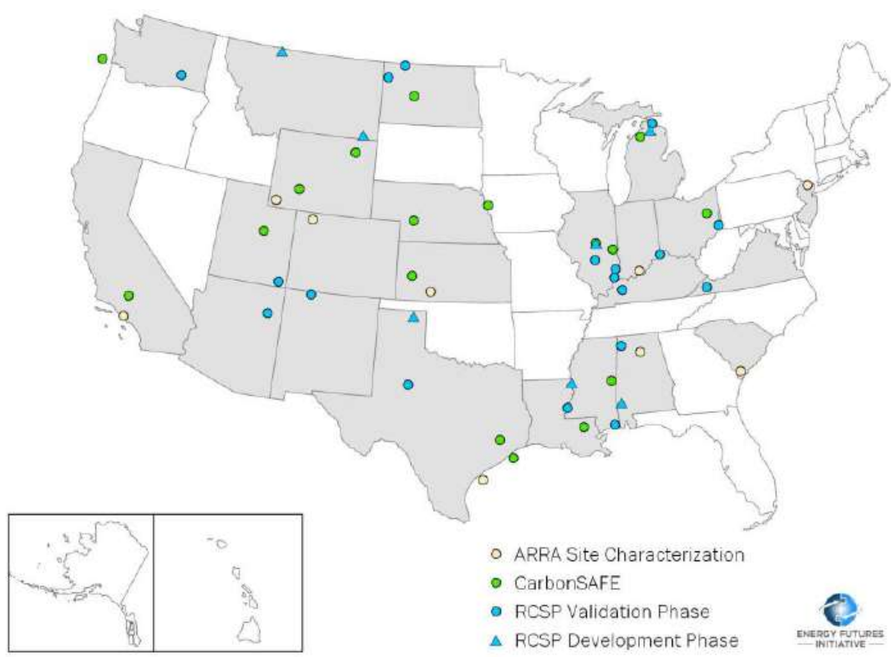
Carbon Storage Assurance Facility Enterprise Initiative

The CarbonSAFE Initiative is a project led by DOE and NETL to develop integrated CCUS projects that include emissions sources (e.g., power plant, industrial facility) and potential geologic sequestration sites. A major focus of the program is to improve the understanding of CCUS projects across the value chain, from screening and site selection to post-injection monitoring, with the aim of operational projects by 2026 (projects that begin construction by January 1, 2024, would be eligible for the 45Q tax credit). CarbonSAFE requires that potential projects will operate for at least 25 years and demonstrate the ability to capture and store a minimum of 50 $MtCO_2$ over the project lifetime.[74]

The CarbonSAFE program is designed in four phases: Phase 1 (pre-feasibility); Phase 2 (feasibility assessments); Phase 3 (site characterizations); Phase 4 (permitting and construction). There are currently 19 CarbonSAFE projects under development, of which 13 are in the pre-feasibility stage (Phase 1) and six are in the feasibility stage (Phase 2). Pre-feasibility assessments include the formation of project teams and scoping plans, while feasibility assessments develop detailed project information, including subsurface characterization, regulatory requirements, and public outreach.[75] The future remaining phases of CarbonSAFE will include site characterization (Phase 3) and permitting and construction (Phase 4).[76] Congress appropriated $30 million in fiscal year 2019 to continue CarbonSAFE, although no timeline has been specified for awarding funds.[77]

Figure 6-8[78,79,80,81,82] displays geologic sequestration projects that have been funded through ARRA, CarbonSAFE, and the RCSP program.

Figure 6-8
Geologic Sequestration Projects in the United States



Numerous projects related to geologic sequestration have been conducted in the United States, including nine ARRA-funded site characterizations, 16 CarbonSAFE projects, 19 small-scale RCSP validation phase projects, and seven large-scale RCSP development phase projects. Not shown: Zama Acid Gas EOR, CO_2 Storage, and the Monitoring RCSP Validation Phase project in Alberta, Canada. Source: EFI, 2019. Compiled using data from the National Energy Technology Laboratory, Rodosta et al., 2017, and the Department of Energy.

There have been several large-scale geologic sequestration projects that have established important baseline information to guide further RD&D efforts. These projects are described in the Box 6-2.

Box 6-2

Selected Current Large-Scale Geologic Sequestration Projects

Quest. The Quest CCUS project in Alberta, which became operational in 2015,[83] captures CO_2 emissions from the production of hydrogen for the conversion of oil sands bitumen into synthetic crude.[84] Since the project began, it has stored more CO_2 through dedicated geologic sequestration than any other onshore capture facility in the world.[85]

Sleipner. The Sleipner project off the coast of Norway was the first commercial demonstration of geologic sequestration of CO_2, and has stored more than 17 $MtCO_2$ in an offshore gas reservoir in the North Sea since it began injection in September 1996. A major RD&D contribution from this project, which was operated by Equinor, has been the development of monitoring techniques for the verification of CO_2 containment and environmental impacts in marine environments. Data collection from site monitoring since injections began in 1996 have not detected any CO_2 leakage events from the subsurface injections,[86,87] indicating that this project has been safely performing offshore geologic sequestration for more than 20 years.[88]

Snohvit. In April 2008, Equinor began injecting CO_2 into an offshore storage formation located off the coast of Norway in the Barents Sea.[89] Since 2008, this project has stored more than 4 $MtCO_2$. A major RD&D contribution from this project has been the regulation and mitigation of pressure buildup in the target reservoir.[90]

Geologic Sequestration RD&D Portfolio

The overarching RD&D objective for geologic sequestration is to demonstrate the potential for large-scale (at or near Gt-scale) geologic sequestration as a permanent storage option for captured carbon. This will include RD&D efforts such as enhancing and accelerating current DOE CarbonSAFE site characterizations, initiating 6-8 regional geologic sequestration demonstrations based on CarbonSAFE results, conducting one or more experiments at CO_2-EOR sites to co-optimize CO_2 sequestration with oil recovery, and supporting research on advanced subsurface monitoring technologies. The proposed funding level for this CO_2 disposition pathway is $1,600 million over 10 years, with RD&D roles and management exclusive to FE (Table 6-5).

The overarching RD&D objective for geologic sequestration is to demonstrate the potential for large-scale (at or near Gt-scale) geologic sequestration as a permanent storage option for captured carbon.

Challenges and Uncertainties

Unlike the CDR capture technology pathways, RD&D on geologic sequestration has been underway for many years, and a large information base has been developed. Therefore, identifying future RD&D priorities will need to take this into account. The key challenge is one of scalability, i.e., can the existing state of knowledge, including the experience with small-scale regional field experiments on the order of metric tons per year or smaller, be scaled to support large-scale sequestration projects operating at hundreds of metric tons per year? Answering this question will require further experiments at larger-scale facilities over longer periods of time to establish technical, economic, and environmental feasibility. Fortunately, the current DOE FE sequestration research program is poised to address this issue. The key issue is the degree to which current research plans can be expanded and accelerated.

Recommended RD&D Portfolio Elements

Advanced Storage R&D, Portfolio Element 6.10, involves advanced storage R&D and is composed of eight budget planning estimate line items that seek to assess and reduce risks associated with CO_2 injection, develop and improve site monitoring systems, improve CO_2 trapping mechanisms, and promote public engagement and acceptance. The eight sub-elements, drawn from the NASEM report recommendations, are summarized as follows:

- **Reduction of Seismic Risk, Portfolio Element 6.11,** involves experiments, modeling, and lab research to reduce risks of induced seismicity from CO_2 injection in saline aquifers.
- **Injection Site Research and Monitoring, Portfolio Element 6.12,** establishes a formal research and monitoring program to accompany commercial injection at CarbonSAFE sites.
- **Improved Long-Term Monitoring Systems, Portfolio Element 6.13,** involves technology development and field demonstrations of low-cost, long-term monitoring systems for large-scale injection sites.
- **Secondary Trapping, Portfolio Element 6.14,** involves modeling and improvements to secondary trapping mechanisms.
- **Simulation for Fate and Transport, Portfolio Element 6.15,** involves improving subsurface fate and transport simulation models.
- **Assessing Risk in Compromised Storage, Portfolio Element 6.16,** involves assessing leakage risk on the vadose zone (between the surface and location of groundwater) and groundwater reservoirs.
- **Public Engagement, Portfolio Element 6.17,** involves social science research on public engagement for geologic sequestration.
- **Cross-Cutting Storage R&D Topics, Portfolio Element 6.18,** involves a compilation of the research needs mentioned above and a summation of the funding totals.

These eight sub-elements closely crosswalk to the current DOE FE sequestration R&D program. The current DOE sequestration research program organizes these sub-elements into three broad technology areas to help execute its research portfolio (Table 6-4).[91,92]

Table 6-4
Carbon Storage Program Technology Areas

Technology Area	Components	Research Focus
Advanced Storage R&D	Wellbore Integrity and Mitigation	Improved wellbore construction materials; long-term CO_2 containment; leakage risk mitigation
	Storage Complex Efficiency and Security	Tools and methods for safe and effective injection operations
	Monitoring, Verification, Accounting (MVA) and Assessment	Atmospheric, near-surface, and subsurface monitoring
Storage Infrastructure	Regional Carbon Sequestration Partnerships Initiative	Characterizations for regional geologic sequestration potential
	Characterization Field Projects (Onshore and Offshore)	Field projects focused on storage complex characterizations (includes CarbonSAFE)
	Fit-for-Purpose Projects	Subsurface engineering approaches including reservoir modeling and risk assessment for seismicity and leakage
Risk and Integration Tools	Energy Data eXchange	Public dissemination of data and tools
	CO_2-SCREEN	Screening tool for assessing storage opportunities in saline formations
	National Risk Assessment Partnership	Risk assessments for long-term storage

Source: EFI, 2019. Compiled using data from the National Energy Technology Laboratory.

The proposed RD&D portfolio provides estimated planning funding for the total of these activities at the 6.10 portfolio element level. It is assumed that this program will continue to be managed by DOE/FE.

Regional Demonstrations, Portfolio Element 6.20, involves regional demonstrations and is composed of two budget planning estimate line items that seek to advance large-scale geologic sequestration demonstration projects.

- **CarbonSAFE Augmentation, Portfolio Element 6.21,** proposes to accelerate the pace of the current DOE CarbonSAFE program to encourage more of the current 19 sites to successfully complete the first three phases of the program and enter into Phase 4 (permitting and site construction). The budget planning estimates assume some further downselect of sites. The revised schedule and number of sites would be determined by DOE.
- **Regional Large-Scale Sequestration Demonstrations, Portfolio Element 6.22,** provides funding to further advance sites that have successfully entered into Phase 4 of the CarbonSAFE program to large-scale demonstration sites that could eventually serve as regional carbon sequestration hubs. A robust large-scale demonstration program might eventually involve 6-8 sequestration facilities across various regions of the United States. Large-scale demonstration of geologic sequestration will enable scientific study and data collection on a scale to validate experimental projects and reduce technical uncertainties.

CO_2-Intensive EOR, Portfolio Element 6.30, involves CO_2-intensive EOR and contains one budget planning estimate line item that seeks to advance methods to advance the amount of CO_2 that could be permanently sequestered through EOR operations.

- **Co-Optimizing CO_2 Storage and Oil Recovery, Portfolio Element 6.31,** involves modeling and experiments to develop improved methods for CO_2-intensive EOR including in residual oil zones (ROZ) and shale reservoirs, of which ROZ have the potential to sequester more CO_2 than would be emitted from the produced oil.[93] This portfolio element assumes a 50 percent industry cost-sharing arrangement.

Table 6-5
Geologic Sequestration RD&D Portfolio ($millions)

Portfolio Element	Funding Agency	Funding Office or Organization	Year 1	5-Year Total	10-Year Total
6.10 Advanced Storage R&D					
6.11 Reduction of seismic risk	DOE	FE	$0	$0	$0
6.12 Injection site research and monitoring	DOE	FE	$0	$0	$0
6.13 Improved long-term monitoring systems	DOE	FE	$0	$0	$0
6.14 Secondary trapping	DOE	FE	$0	$0	$0
6.15 Simulation for fate and transport	DOE	FE	$0	$0	$0
6.16 Assessing risk in compromised storage	DOE	FE	$0	$0	$0
6.17 Public engagement	DOE	FE	$0	$0	$0
6.18 Cross-cutting storage R&D topics	DOE	FE	$20	$220	$470
6.10 Subtotal, Advanced Storage R&D			$20	$220	$470
6.20 Regional Demonstrations					
6.21 CarbonSAFE augmentation	DOE	FE	$25	$250	$250
6.22 Regional large-scale sequestration demonstrations	DOE	FE	$0	$100	$700
6.20 Subtotal, Regional Demonstrations			$25	$350	$950
6.30 CO_2-Intensive EOR					
6.31 Co-optimizing CO_2 storage and oil recovery	DOE	FE	$5	$80	$180
6.30 Subtotal, CO_2-Intensive EOR			$5	$80	$180
TOTAL, Geologic Sequestration			$50	$650	$1,600

Source: EFI, 2019.

1 https://www.iea.org/topics/carbon-capture-and-storage/storage/
2 https://www.globalccsinstitute.com/why-ccs/what-is-ccs/storage/
3 https://www.globalccsinstitute.com/wp-content/uploads/2018/12/Global-CCS-Institute-Fact-Sheet_Geological-Storage-of-CO2.pdf
4 https://www.iea.org/topics/carbon-capture-and-storage/storage/
5 https://www.geo.arizona.edu/~reiners/geos195K/CO2Sequestration_Benson_ELEMENTS.pdf
6 https://www.netl.doe.gov/node/5964
7 https://www.globalccsinstitute.com/wp-content/uploads/2018/12/Global-CCS-Institute-Fact-Sheet_Geological-Storage-of-CO2.pdf
8 https://www.globalccsinstitute.com/wp-content/uploads/2018/12/Global-CCS-Institute-Fact-Sheet_Geological-Storage-of-CO2.pdf
9 https://www.netl.doe.gov/node/5964
10 https://www.globalccsinstitute.com/why-ccs/what-is-ccs/storage/

11 https://www.globalccsinstitute.com/wp-content/uploads/2018/12/Global-CCS-Institute-Fact-Sheet_Geological-Storage-of-CO2.pdf
12 https://www.netl.doe.gov/node/5964
13 https://www.globalccsinstitute.com/wp-content/uploads/2018/12/Global-CCS-Institute-Fact-Sheet_Geological-Storage-of-CO2.pdf
14 https://www.iea.org/topics/carbon-capture-and-storage/storage/
15 https://www.globalccsinstitute.com/wp-content/uploads/2018/12/Global-CCS-Institute-Fact-Sheet_Geological-Storage-of-CO2.pdf
16 https://www.nap.edu/read/25210/chapter/1#8
17 https://www.netl.doe.gov/node/5964
18 https://www.globalccsinstitute.com/why-ccs/what-is-ccs/storage/
19 https://www.netl.doe.gov/node/5964
20 https://www.epa.gov/ghgreporting/ghg-reporting-program-data-sets
21 https://edx.netl.doe.gov/dataset/natcarb-alldata-v1502
22 https://www.netl.doe.gov/coal/carbon-storage/strategic-program-support/natcarb-atlas
23 https://www.iea.org/topics/carbon-capture-and-storage/storage/
24 https://www.doi.gov/climate/carbonsequestration
25 https://www.doi.gov/news/pressreleases/interior-releases-first-ever-comprehensive-national-assessment-of-geologic-carbon-dioxide-storage-potential
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30 https://www.iea.org/newsroom/news/2018/november/whatever-happened-to-enhanced-oil-recovery.html
31 https://www.iea.org/newsroom/news/2019/april/can-co2-eor-really-provide-carbon-negative-oil.html
32 https://www.catf.us/wp-content/uploads/2018/11/CATF_Factsheet_CO2_EOR_LifeCycleAnalysis.pdf
33 https://www.iea.org/topics/ccs/storagethroughco2-eor/
34 https://www.iea.org/topics/carbon-capture-and-storage/storage/
35 https://www.iea.org/newsroom/news/2018/november/whatever-happened-to-enhanced-oil-recovery.html
36 https://www.iea.org/topics/carbon-capture-and-storage/storage/
37 https://www.iea.org/newsroom/news/2018/november/whatever-happened-to-enhanced-oil-recovery.html
38 https://www.eia.gov/todayinenergy/detail.php?id=35632
39 https://www.energy.gov/sites/prod/files/2015/04/f22/QER%20Analysis%20-%20A%20Review%20of%20the%20CO2%20Pipeline%20Infrastructure%20in%20the%20U.S_0.pdf
40 https://www.energy.gov/sites/prod/files/2015/04/f22/QER-ALL%20FINAL_0.pdf
41 https://www.cell.com/joule/pdf/S2542-4351(18)30179-X.pdf
42 https://www.iea.org/topics/carbon-capture-and-storage/storage/
43 https://www.iea.org/publications/insights/insightpublications/Storing_CO2_through_Enhanced_Oil_Recovery.pdf
44 https://hub.globalccsinstitute.com/publications/accelerating-uptake-ccs-industrial-use-captured-carbon-dioxide/2-co2-market
45 https://www.iea.org/newsroom/news/2018/november/whatever-happened-to-enhanced-oil-recovery.html
46 https://www.cell.com/joule/pdf/S2542-4351(18)30337-4.pdf
47 https://www.iea.org/newsroom/news/2018/november/whatever-happened-to-enhanced-oil-recovery.html
48 https://www.iea.org/newsroom/news/2019/april/can-co2-eor-really-provide-carbon-negative-oil.html
49 https://www.iea.org/newsroom/news/2019/april/can-co2-eor-really-provide-carbon-negative-oil.html
50 https://co2re.co/FacilityData
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52 https://fas.org/sgp/crs/misc/IF10589.pdf
53 https://fas.org/sgp/crs/misc/R44472.pdf
54 https://www.netl.doe.gov/coal/carbon-storage/storage-infrastructure/regional-carbon-sequestration-partnerships-initiative
55 https://edx.netl.doe.gov/geocube/#natcarbviewer
56 https://www.netl.doe.gov/coal/carbon-storage/storage-infrastructure/regional-carbon-sequestration-partnerships-initiative
57 https://www.netl.doe.gov/coal/carbon-storage/strategic-program-support/natcarb-atlas
58 https://www.energy.gov/fe/16067208-metric-tons-co2-injected-january-3-2018
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60 https://fas.org/sgp/crs/misc/R44902.pdf
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62 https://www.netl.doe.gov/sites/default/files/2018-10/ATLAS-V-2015.pdf
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64 https://www.netl.doe.gov/coal/carbon-storage/storage-infrastructure/regional-carbon-sequestration-partnerships-initiative
65 https://www.sciencedirect.com/science/article/pii/S1876610217318994
66 https://www.netl.doe.gov/coal/carbon-storage/storage-infrastructure
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68 https://www.energy.gov/fe/16067208-metric-tons-co2-injected-january-3-2018
69 https://netl.doe.gov/coal/carbon-storage/strategic-program-support/best-practices-manuals
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71 https://www.netl.doe.gov/sites/default/files/2018-10/ATLAS-V-2015.pdf
72 https://www.netl.doe.gov/coal/carbon-storage/strategic-program-support/natcarb-atlas
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74 https://www.sciencedirect.com/science/article/abs/pii/S1750583618307849
75 https://www.netl.doe.gov/coal/carbon-storage/storage-infrastructure/carbonsafe
76 https://www.wyoleg.gov/InterimCommittee/2019/09-201905163-02QuillinanJointMinerals.pdf
77 https://docs.house.gov/billsthisweek/20180910/Joint%20Statement.pdf
78 https://www.netl.doe.gov/coal/carbon-storage/storage-infrastructure/regional-carbon-sequestration-partnerships-initiative
79 https://www.netl.doe.gov/node/5900
80 https://www.netl.doe.gov/coal/carbon-storage/storage-infrastructure/carbonsafe
81 https://www.energy.gov/fe/site-characterization-promising-geologic-formations-co2-storage
82 https://www.sciencedirect.com/science/article/pii/S1876610217319318
83 https://www.shell.ca/en_ca/media/news-and-media-releases/news-releases-2019/quest-ccs-facility-reaches-major-milestone.html
84 https://www.globalccsinstitute.com/news-media/latest-news/quest-carbon-capture-and-storage-facility-in-canada-reaches-new-milestone/
85 https://www.shell.ca/en_ca/media/news-and-media-releases/news-releases-2019/quest-ccs-facility-reaches-major-milestone.html
86 https://www.nap.edu/read/25210/chapter/1#8
87 https://www.sciencedirect.com/science/article/pii/S1876610217317174
88 https://www.iea.org/topics/carbon-capture-and-storage/storage/
89 https://www.sciencedirect.com/science/article/pii/S187661021300492X
90 https://www.nap.edu/read/25210/chapter/1#8
91 https://www.netl.doe.gov/coal/carbon-storage/about-the-carbon-storage-program
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CHAPTER 7.
CO_2 UTILIZATION

CO_2 utilization, also referred to as carbontech[1] or carbon-to-value,[2] involves the direct use or conversion of captured CO_2 for various economic applications. CO_2 utilization is not a CDR pathway by itself but rather one possible disposition for the CO_2 that is removed from the environment from concentrated point sources or from DAC from dilute sources of CO_2 in the atmosphere. RD&D for CO_2 utilization for EOR is addressed in Chapter 6. RD&D needs for CO_2 utilization for conversion into valuable commercial products such as fuels, chemicals, and other products is the subject of this chapter.

The current global market for CO_2 is around 80 $MtCO_2$ per year, the majority of which is in North America.[3] This existing global market is small compared to the annual global emissions from fossil fuels and industrial activity of approximately 36.2 $GtCO_2$ (approximately 0.2 percent by volume).[4] Considerable uncertainty exists concerning the potential future scale of CO_2 utilization, both in terms of the total amount of CO_2 that could be utilized and the size of corresponding markets, but it could collectively approach at or near gigaton scale per year globally with further technological and RD&D advancements.[5]

CO_2 Utilization Process

The most common utilization approach is to use CO_2 in bulk form without any conversion, such as in CO_2-EOR, beverage carbonation, and food processing.[6] These applications have relatively few RD&D needs, since they are well understood and widely commercialized. Alternatively, CO_2 can be converted through carbon mineralization, chemical, or biological means for utilization.[7] Conversion introduces many technical challenges for CO_2 utilization, including the need for energy and additional materials, but it enables important new CO_2-based applications. There are relatively few fully commercialized processes for CO_2 utilization that involve conversion, and there is a correspondingly large range of RD&D needs to advance these technologies. The direct use and conversion of CO_2 for commercial applications and product development are shown in Figure 7-1.[8,9]

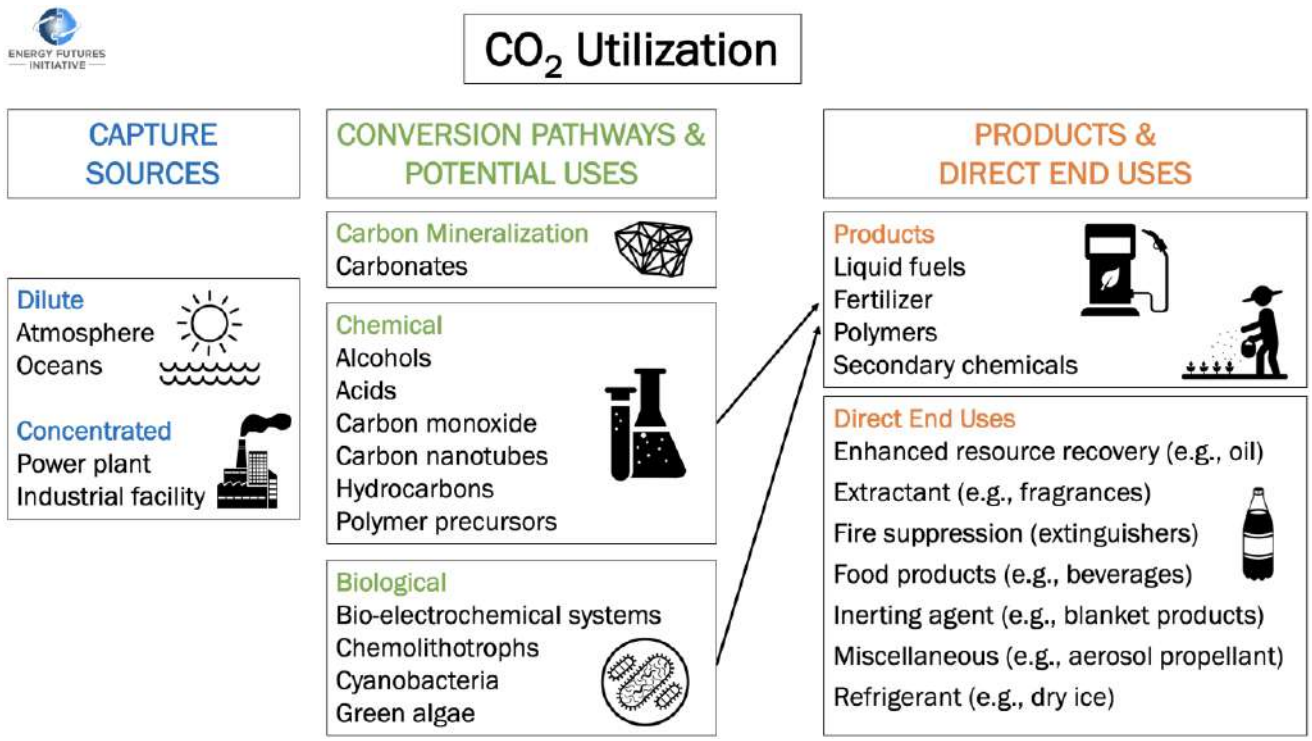
The feasibility of potential CO_2 utilization options depends upon a lifecycle analysis that includes emissions in the development of a product, energy requirements and source of energy, amount of carbon embedded in the product, total market size and product diffusion, product lifetime and disposal, and whether use of the product will result in the release of the embodied carbon.[10] Two of the major factors to consider in order to assess the net climate benefits of CO_2 utilization is permanence and displacement. Permanence refers to the amount of time a product can store CO_2; for example, cement can sequester CO_2 for centuries, whereas fuels are burned within days or weeks, releasing CO_2 back into the atmosphere. Long-lived CO_2 utilization products have the most beneficial climate impact, and RD&D on these products should therefore receive priority consideration. Displacement refers to the substitution of fossil-derived products (e.g., petroleum) with products that are derived from CO_2 utilization.[11] Displacing higher-emissions products can have substantial climate benefits, although this does not necessarily result in net CO_2

removal from the environment. For example, capture CO_2 can be used to produce quicklime, which could then be used to displace limestone in cement production and thereby reduce process emissions.[12]

Carbon Mineralization to Carbonates

Figure 7-1

Opportunities for CO_2 Utilization



CO_2 can be utilized through three main conversion pathways: carbon mineralization, chemical processes, and biological processes, or it can be used directly for certain applications. Source: EFI, 2019. Compiled using data from the National Academies of Sciences, Engineering, and Medicine. Graphics from Noun Project.

Carbon mineralization involves introducing CO_2 to certain reactive rocks and minerals to form inorganic carbonate minerals. (Carbon mineralization for purposes of atmospheric capture and disposition on land or the oceans is discussed in Chapter 4.) Carbon mineralization for utilization involves the conversion of CO_2 to carbonates that can be used in the construction industry in the form of carbonate-based mineral aggregates, binding agents, and concrete.

Carbonate minerals can be used for the production of cement and concrete, which have large, established global markets and long product lifetimes that enable long-term carbon storage.[13] At the global level, carbonates are used in the production of cement, aggregates, and concrete at a scale of approximately 4 Gt of cement and 26-30 Gt of aggregates (sand and gravel) per year.[14,15] Several benefits of this conversion pathway include existing markets, large market potential, high level of permanence, well-known conversion chemistry, and little-to-no energy input requirements for the exothermic carbonation reactions. Therefore, carbon mineralization is considered to be one of the most attractive CO_2 utilization techniques. However, a major challenge for this pathway is the need to increase the rate of carbonation reactions so that more CO_2 can be fixed on shorter timescales.[16]

Chemical Conversion

Chemical conversion involves reacting CO_2 with other molecules and/or providing energy inputs through electrochemical, photochemical, or thermochemical means to produce chemicals and fuels. CO_2 is a highly stable molecule (double bonds between carbon and oxygen atoms), and its chemical conversion is an endothermic process that requires considerable energy input (and often the addition of catalysts) to facilitate its chemical reduction and conversion by reducing heat requirements or increasing the rate of reaction.[17,18] The availability of abundant carbon-free electrical and thermal energy is therefore an important consideration for this endothermic conversion pathway, which can also pose a major cost.[19] One potential route is electrocatalytic synthesis of commodity chemicals from CO_2 using renewable electricity, which could be cost-competitive with fossil-derived chemicals at electricity costs below 4 cents per kW and conversion efficiencies above 60 percent.[20] Particularly in the context of producing fuels, this could provide a means to store variable renewable electricity on long (seasonal) timescales.[21] Currently, there are only a few chemicals that are commercially produced from CO_2, which represent a relatively small market size (Table 7-1).[22,23]

Table 7-1
Industrial-Scale Chemical Production from CO_2 (Global)

Chemical	Scale (ktCO_2 per year)
Urea	112,000
Polycarbonate	600
Ethylene carbonate	40
Propylene carbonate	40
Salicylic acid	30
Polyether carbonate	10

Source: Erdogan and Orhan, 2017; National Academies of Sciences, Engineering, and Medicine.

Box 7-1

CO_2 Feedstock from Carbon Capture from Concentrated Point Sources

In general, CO_2 utilization processes are indifferent to the source of captured CO_2—either concentrated or dilute—as long as purity and contaminant levels are acceptable, and are likely to source CO_2 from the lowest-cost source available (subject to transportation and other constraints). CO_2 utilization from CDR will therefore compete with CO_2 captured from other sources.

There is a potential for CO_2 capture at the gigaton scale from concentrated point sources, but the purity of point-source CO_2 capture could limit its utilization potential. Across the United States, there are thousands of power plants and industrial facilities that could provide a feedstock for CO_2 utilization at various levels of purity (Table 7-2).[24,25] As of December 2017, there were 8,652 power plants in the U.S. with a nameplate capacity of at least 1 MW,[26] of which coal- and gas-fired power plants typically have flue gas CO_2 concentrations of 12 percent to 15 percent and 3 percent to 4 percent, respectively.[27] However, contaminants can occur in thermal power plant flue gas streams that include fly ash, heavy metals, nitrogen oxides, and sulfur oxides,[28] which can serve as an impediment to CO_2 utilization and thus requires removal. In contrast, flue gas streams from industrial facilities typically contain higher concentrations of CO_2 and fewer contaminants.[29] Given that CO_2 waste streams can contain various levels of contaminants and detailed gaseous composition data are not widely available, there is a need for a systematic mapping of CO_2 waste streams throughout the economy to better match different CO_2 feedstocks with appropriate CO_2 utilization opportunities and separation and purification needs.[30]

Table 7-2

Selection of CO_2 Feedstocks, Purity, and Contaminants

Source	U.S. Emissions Level, 2017 ($MtCO_2$)	Composition	Associated Chemical Species and Contaminants
Ammonia production	13.2	>98%	Carbon monoxide, hydrogen, nitrogen, water
Cement, iron/steel, and glass	83.4	20-35%	Carbon monoxide, nitrogen and nitrogen oxides, particulates, sulfur oxides
Fossil fuel combustion	4,912	3-15%	Nitrogen, nitrogen oxides, particulates, sulfur oxides

Sources: National Academies of Sciences, Engineering, and Medicine and the Environmental Protection Agency.

In the absence of regulatory requirements or economic incentives, any increased demand for CO_2 for the purposes of utilization might simply be met by increased production from natural sources or CO_2 captured from concentrated point sources. Ensuring that CDR-provided CO_2 is used for utilization purposes could require additional policy measures to support deployment, such as expanded regulatory requirements or some other factor, such as locational availability.

Biological Conversion

Biological conversion involves the synthesis of bio-based products from CO_2 through photosynthesis and other metabolic processes to produce chemicals and fuels. This utilization pathway has the advantage of not requiring a high-purity CO_2 feedstock and has a wide variety of potential products that can be developed, including biofuels and fertilizers. Given its unique resource requirements and opportunities for value creation, this conversion pathway could become a significant opportunity for CO_2 utilization. Two of the primary challenges for this pathway include the need to increase biological utilization rates and improve scale potential.[31]

Box 7-2

CO_2 Utilization via Solar-to-Fuels

Artificial photosynthesis is a technology pathway that involves biological or chemical conversion of CO_2 to make fuels using the same inputs as natural photosynthesis in plants: water, CO_2, and energy from the sun.[32] Natural photosynthesis produces glucose (and oxygen) as byproducts; artificial photosynthesis research is attempting to create a process that produces energy-dense fuels such as methanol. Artificial photosynthesis provides multiple carbon benefits: in addition to providing a carbon utilization option, it also avoids emissions associated with fuel production, and provides a way to harness solar energy in a fashion that is potentially more compatible with the daily solar cycle.[33]

There are multiple pathways that fall under the umbrella of artificial photosynthesis. The process typically involves "splitting" water into hydrogen and oxygen via photocatalysis. This involves a photoelectrochemical cell, comprised of photoelectrodes and catalysts immersed in water.[34] A key subject for R&D is new catalyst materials; currently used materials such as semiconductors or precious metals are uneconomic for large-scale application. Hydrogen and CO_2 can then be converted endothermically into fuels by using either inorganic chemical conversion or biological conversion (such as using microorganisms that consume hydrogen and CO_2).[35] Other processes are being pursued that skip the water-splitting step in the process.[36] These processes often use pure CO_2 streams,[37] which could in the future come from point-source carbon capture or from CDR technologies such as DAC and BECCS.

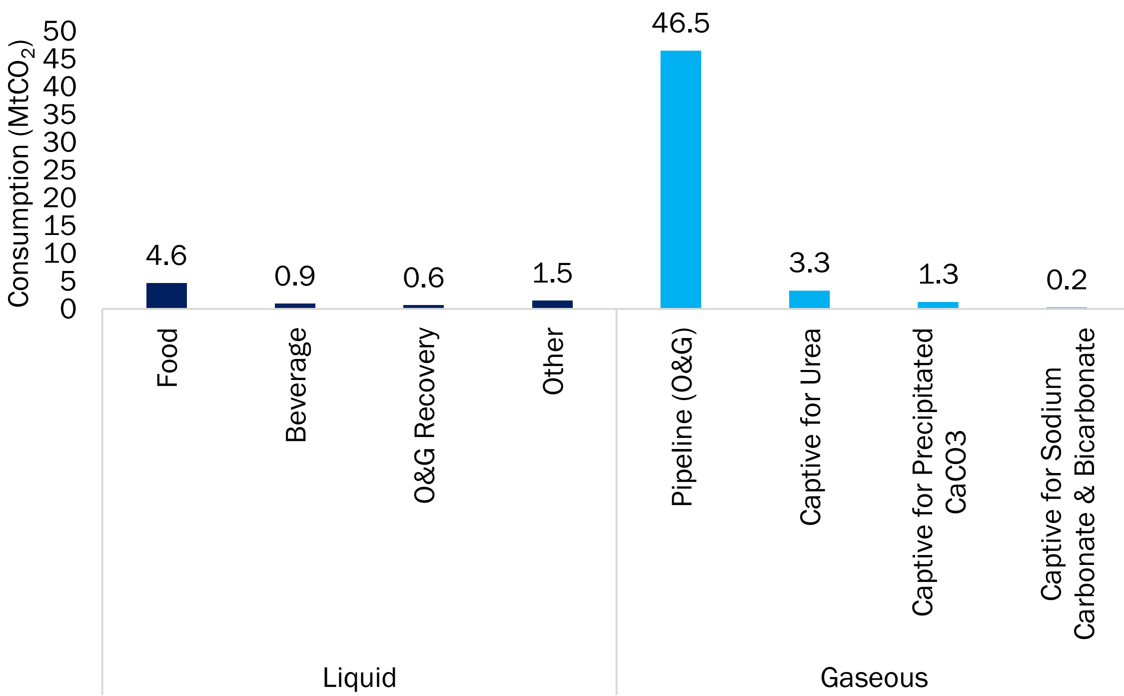
Artificial photosynthesis is still in early-stage R&D. The major R&D program is the DOE's Joint Center for Artificial Photosynthesis (JCAP), an Innovation Hub in the Basic Energy Sciences Program (BES). JCAP is managed by the California Institute of Technology, with Lawrence Berkeley National Laboratory as lead partner.[38] The other JCAP collaborator institutions are SLAC National Accelerator Laboratory and the University of California campuses at Irvine and San Diego. JCAP's first phase, which ran from 2010 to 2015, was focused on solar hydrogen generation. A second five-year phase is focused on solar CO_2 reduction with inorganic chemistry. JCAP is scheduled for funding at $75 million over five years, subject to Congressional appropriations.

Current and Emerging CO_2 Utilization Market Characteristics

The current global market for CO_2 is around 80 $MtCO_2$ per year, the majority of which is in North America.[39] In the United States, it is estimated that the total consumption of both liquid and gaseous CO_2 in 2014 was 59 $MtCO_2$, the majority of which was for gaseous CO_2 (Figure 7-2).[40]

Figure 7-2

Liquid and Gaseous CO_2 Consumption in the United States, 2014



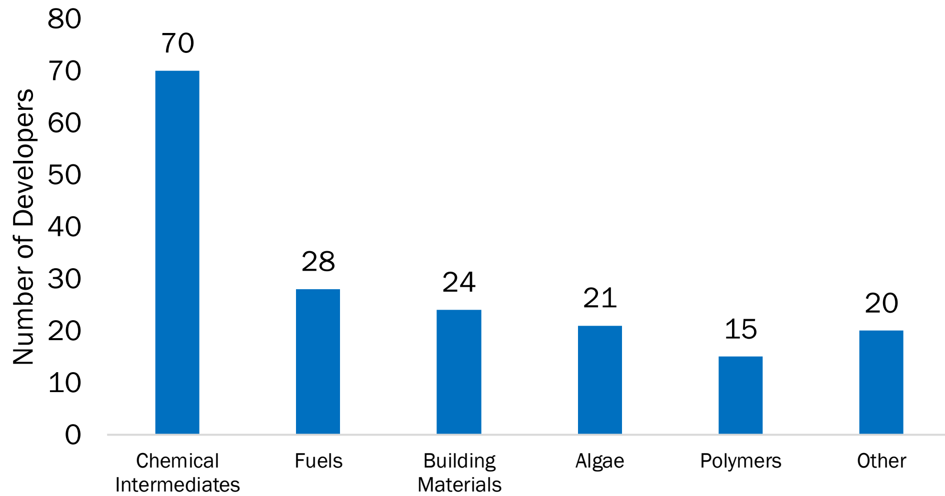
Approximately 59 $MtCO_2$ were consumed in the United States in 2014. Source: Suresh et al., 2014.

Almost all of the current market demand for CO_2 is provided by natural sources (i.e., geological accumulations of CO_2 that are mined to produce the gas).[41] While small quantities of high-grade CO_2 used for specialty purposes are sold at premium prices, the bulk (pipeline) price has previously been estimated at \$10 to \$25 per tCO_2.[42]

A previous assessment of developers already operating in the CO_2 utilization space found that the majority worked on chemical intermediates, followed by fuels and building materials (Figure 7-3).[43] The assessment also identified the most commonly studied conversion pathways based on the number of developers in that space and found the greatest saturation in catalytic conversion (e.g., production of chemical intermediates, fuels), carbon mineralization, and electrochemical conversion (Figure 7-4).[44]

Figure 7-3

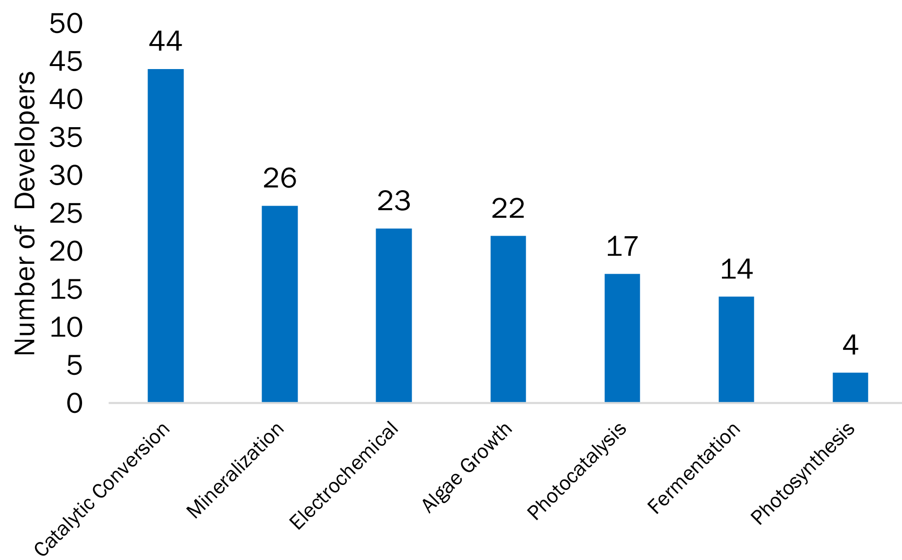
Developers Operating in the CO_2 Utilization Market by Product Type



Chemical intermediates are a relatively large market segment for entities operating in the CO_2 utilization space. Source: EFI, 2019. Compiled using data from the Global CO_2 Initiative.

Figure 7-4

Developers Operating in the CO_2 Utilization Market by Conversion Pathway

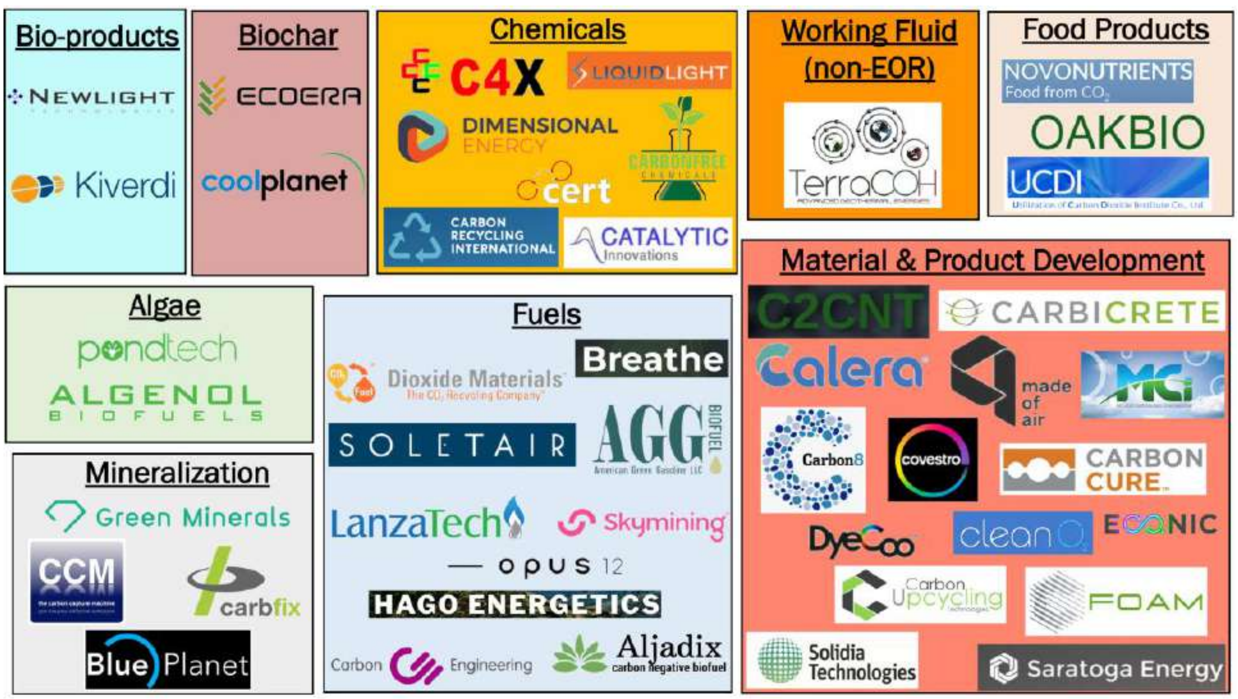


Catalytic conversion is a relatively more common conversion pathway used by developers in the CO_2 utilization space. Source: EFI, 2019. Compiled using data from the Global CO_2 Initiative.

The potential for carbon capture, from both concentrated point sources and CDR, to provide a large new supply of CO_2 has led to significant private sector interest in the emerging field of CO_2 utilization, with dozens of companies investing in a wide variety of technologies (Figure 7-5).[45,46,47] The Carbon XPRIZE, a competition that will award $20 million to a team that develops the best breakthrough technologies for CO_2 conversion into valuable commodity products such as building materials and fuels,[48] has also helped spur interest and launch companies working on CO_2 utilization. If CO_2 utilization processes can be conducted at sufficiently low cost, it is possible that utilization could provide substantial revenues to support CDR companies and incentivize further investments in CDR deployment.

Figure 7-5

Examples of CO_2 Utilization Companies



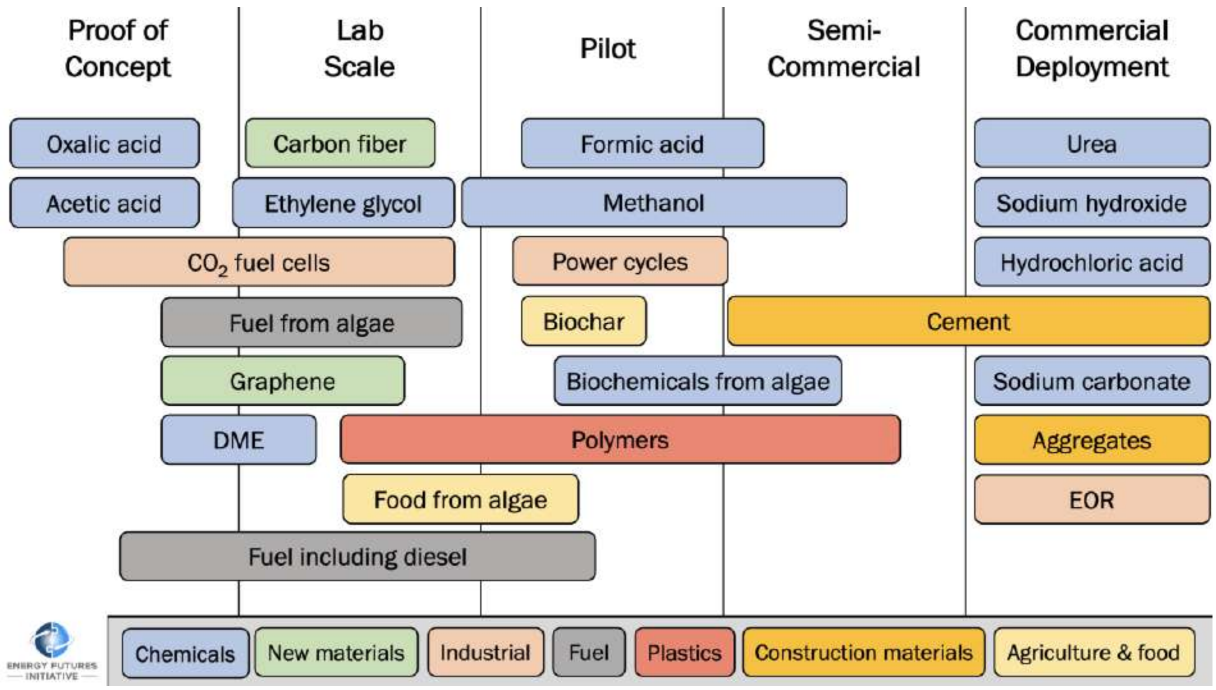
Here are examples of companies that are pursuing CO_2 utilization business opportunities. Source: EFI, 2019. Compiled using data from Air Miners, the Carbon Utilization Alliance, and Columbia University.

Status of CO_2 Utilization Research

The stage of technical maturity of CO_2 utilization technologies varies widely by utilization pathway and type of product. A recent technology assessment (Figure 7-6)[49] shows, for example, that carbon mineralization processes are already operating on a small commercial scale and are relatively closer to commercial readiness than other utilization pathways.[50] The technology readiness for CO_2-based products from chemical and biological conversion varies, as research activity is ongoing across numerous stages of the RD&D process.[51,52]

Figure 7-6

Technology Readiness and Potential RD&D Needs for CO_2-Based Products

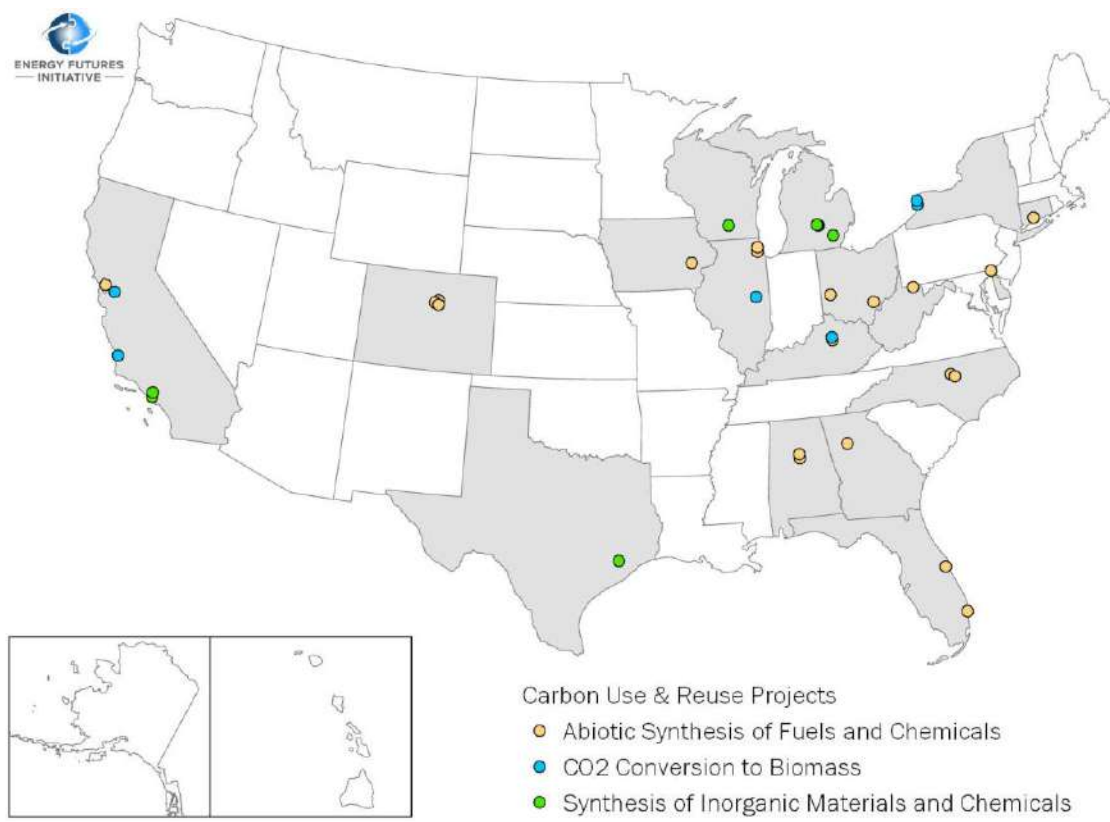


Many CO_2-based products are in need of further RD&D to reach commercial deployment. Source: David, B.J., the Global CO_2 Initiative.

U.S. government support for CO_2 utilization technologies has historically been very limited, although CO_2 utilization research projects have been supported in three separate federal departments and agencies, including DOE, DOD, and NSF. The principal federal program has been the DOE Carbon Use and Reuse Program, housed within the DOE/NETL Carbon Capture Program.[53] The program focuses on systems integration between CO_2 utilization processes and power plants or carbon capture projects[54] and currently covers three primary CO_2 utilization pathways: abiotic synthesis of fuels and organic chemicals, CO_2 conversion to biomass, and synthesis of inorganic materials and chemicals.[55] CO_2 feedstocks used for R&D projects in this program have previously been captured from coal-fired power plants.[56] At least 33 projects have been conducted to date, mostly through the abiotic synthesis of fuels and organic chemicals (Figure 7-7).[57] The Carbon Use and Reuse Program received a total of \$24 million in funding from fiscal year 2012 to fiscal year 2017—a little more than \$4 million, on average, annually (Figure 7-8)[58]—a relatively low funding level compared with other DOE R&D programs. In 2018, 17 projects were selected to receive funding in the amount of \$18.7 million for cost-shared R&D.[59]

Figure 7-7

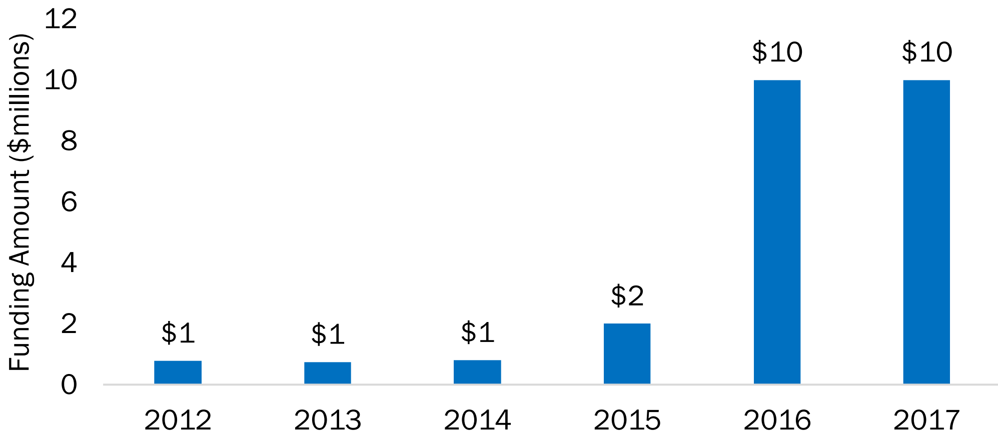
DOE Carbon Use and Reuse Program R&D Projects



More than 30 projects have been conducted through the Carbon Use and Reuse Program across 17 states. Source: EFI, 2019. Compiled using data from the National Energy Technology Laboratory.

Figure 7-8

Annual Funding Levels for the DOE Carbon Use and Reuse Program, FY2012-2017



The Carbon Use and Reuse Program received approximately $24 million in funding from fiscal year 2012 to fiscal year 2017. Source: EFI, 2019. Compiled using data from the National Energy Technology Laboratory.

Box 7-3

Examples of DOE-Funded CO_2 Utilization Research Projects

CO_2 to Bioplastics. The purpose of this project was to use CO_2 captured from coal-fired power plants to produce a variety of bio-based products such as chemicals, fuels, and plastics using microalgae. The project sought to develop a multipurpose biomass utilization strategy that could produce these products simultaneously from different feedstocks. DOE contributed 80 percent of funding for the project.[60,61]

Electrochemical Conversion of CO_2 to Alcohols. The purpose of this project was to develop a method for converting CO_2 to various alcohols (e.g., ethanol, propanol) using CO_2 from the flue gas of coal-fired power plants. The electrochemical conversion process used a CO_2 electrolyzer to produce carbon monoxide (CO) and a CO electrolyzer to produce the alcohols. DOE contributed 80 percent of funding for the project.[62,63]

Hawaii Department of Transportation. The purpose of this project is to test the viability of CO_2-injected concrete compared with traditional concrete for use in a Hawaii Department of Transportation road construction project. The CO_2 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. Estimates suggest that the CO_2-injected concrete could reduce the embodied carbon by 25 pounds per cubic year and save 1,500 pounds of CO_2 emissions.[64] Given that concrete is the second-most consumed material in the world,[65] government procurement standards could help drive market formation and demand for CO_2-injected concrete.

Upcycled CO_2-Negative Concrete. The purpose of this project was to use alkaline industrial wastes from iron and steel production to serve as reactive feedstocks for carbon mineralization using CO_2 captured from coal-fired power plants. Carbonate minerals produced through this process were used for the development of construction materials that could demonstrate mechanical properties similar to traditional methods of cement and concrete production. DOE contributed 74 percent of funding for the project.[66]

CO_2 Utilization RD&D Portfolio

The overarching RD&D objective for CO_2 utilization is to accelerate development of innovative carbon conversion processes and new carbon-based materials through carbon mineralization and chemical and biological conversion. This will include RD&D efforts such as fundamental research on carbon mineralization reactions and materials development for carbonation conversion, catalyst and new materials development for chemical conversion, and genetic manipulation and bioprospecting for biological conversion. The proposed funding level for this CO_2 disposition pathway is $900 million over 10 years, with RD&D roles and responsibilities divided among six federal agencies: DOE, USDA, DOI, Department of Transportation (DOT), NIST within the DOC, and NSF (Table 7-3).

The overarching RD&D objective for CO_2 utilization is to accelerate development of innovative carbon conversion processes and new carbon-based materials through carbon mineralization and chemical and biological conversion.

The proposed RD&D portfolio includes a mix of fundamental and applied R&D, with the potential to scale up to demonstration funding in the cross-cutting demonstration program discussed in Chapter 8. It is assumed that many of the individual research projects will be industry-led, with significant nonfederal cost-sharing, reflecting an assessment of technical risk and market potential. NASEM has recommended that CO_2 utilization RD&D be coordinated with private and public sector entities in the United States and abroad, along with the use of transparent and consistent evaluation criteria to assess technology performance, benefits, and readiness.[67]

Recommended RD&D Portfolio Elements

Carbon Mineralization. Carbon mineralization is a CO_2 utilization pathway whose underlying science and technology processes are relatively well understood compared to chemical and biological conversion processes. However, there are a range of technical, economic, and social science challenges associated with carbon mineralization that require further RD&D to maximize its market potential. Such challenges include slow chemical reaction rates, variations in reaction kinetics between different reactive feedstocks, CO_2 availability and purity, and the ability to meet or exceed current performance standards for construction materials to gain public acceptance.[68] Another important issue in carbon mineralization is the source of alkaline solids. A wide range of sources have been proposed, including desalination brines, demolition waste, industrial waste (including fly ash, slag, and cement kiln dust), and various minerals and rocks. Research is needed to better characterize the potential of these and other sources and identify low-emissions approaches to providing them for mineralization purposes.

Carbonation Conversion, Portfolio Element 7.10, is composed of five budget planning estimate line items that seek to advance fundamental research on carbonation reactions, integrate carbonation with capture systems, develop alkaline feedstocks, and test new products.

- **Fundamental Research, Portfolio Element 7.11,** involves fundamental research on controlling carbonation reactions, accelerating carbonation, and understanding structure-property relationships. This effort is proposed to be jointly managed by DOE/BES and NSF/MPS.
- **Process Integration, Portfolio Element 7.12,** involves R&D and studies of the integration of carbonation with CO_2 capture processes. This effort is proposed to be jointly managed by DOE/FE and NSF/Directorate for Engineering (ENG).
- **Alkalinity Sources, Portfolio Element 7.13,** involves developing new low-emissions sources of alkalinity for carbon mineralization. This effort is proposed to be jointly managed by DOE/AMO and DOI/USGS.
- **Construction Materials, Portfolio Element 7.14,** involves the development, testing, and certification of carbonate materials for construction markets. This effort is proposed to be jointly managed by the DOE/Building Technologies Office (BTO) and DOC/NIST.
- **Transportation Infrastructure, Portfolio Element 7.15,** involves field testing of CO_2 utilization cements and aggregates for transportation infrastructure. This effort is proposed to be managed by the DOT Federal Highway Administration (FHWA). DOT also has a Sustainable Pavements Program that could assist with related CO_2 utilization RD&D.[69]

Chemical CO_2 Conversion. RD&D needs for the chemical conversion and utilization of CO_2 to assist commercialization efforts include improved catalysts for conversion, avoidance or limited use of additives, systems integration between CO_2 capture and conversion technologies, new product and catalyst development, performance and cost breakthroughs for electrolysis, and improved electrolyzers.[70]

Chemical CO_2 Conversion, Portfolio Element 7.20, involves chemical CO_2 conversion and is composed of three budget planning estimate line items that seek to advance fundamental research on catalysts and chemical reactions, develop new materials, and promote integrated systems designs.

- **Fundamental Research, Portfolio Element 7.21,** involves fundamental research on impurity-tolerant catalyst development, coupled reduction and oxidation reactions, and reduced additives. This effort is proposed to be jointly managed by DOE/BES and NSF/MPS.

- **New Materials, Portfolio Element 7.22,** involves the development of new materials, including materials with carbon-carbon bonds (e.g., carbon nanotubes). This effort is proposed to be jointly managed by DOE/BES and NSF/MPS.
- **Systems Integration, Portfolio Element 7.23,** involves integrated catalyst-reactor design and systems integration. This effort is proposed to be managed by DOE/BES and DOE/AMO.

Biological CO_2 Conversion. RD&D needs for the biological conversion and utilization of CO_2 to assist commercialization efforts include improved photosynthetic efficiency, genetic modification of biological organisms for greater CO_2 fixation,[71] assessment and mitigation of natural resource needs (e.g., land requirements), and clean hydrogen availability.[72]

Biological CO_2 Conversion, Portfolio Element 7.30, involves biological CO_2 conversion and is composed of three budget planning estimate line items that seek to improve genetic modeling and manipulation, screen for new organisms for CO_2 conversion, and develop new products.

- **Genetic Research, Portfolio Element 7.31**, involves improving CO_2 uptake and conversion through genetic manipulation. This effort is proposed to be jointly managed by DOE/BER and NSF/Directorate for Biological Sciences (BIO).
- **Bioprospecting, Portfolio Element 7.32,** involves bioprospecting by using tools and high-throughput screening methods for organisms with unique attributes related to CO_2 conversion. This effort is proposed to be jointly managed by USDA/ARS and DOE/BER.
- **New Materials, Portfolio Element 7.33,** involves the development of new CO_2 utilization products and valorization of coproducts for feed, fuel, and other uses. This effort is proposed to be jointly managed by DOE/BETO and USDA/ARS.

Cross-Cutting Needs for CO_2 Utilization. There are several cross-cutting needs and priorities that could help support CO_2 utilization efforts, including clean energy availability, enabling technologies and infrastructure, and standardized lifecycle analyses (LCAs) and techno-economic analyses (TEAs). These elements are addressed in other chapters of the RD&D portfolio.

- Gigaton-scale carbon management through CO_2 utilization will require substantial amounts of zero-carbon energy to facilitate the conversion of captured carbon to usable products,[73] as CO_2 utilization can require hydrogen, heat, and electricity.[74] Clean hydrogen (for chemical reactions) and zero-carbon electricity are two important sources of energy that could help facilitate CO_2 conversion for product development.[75]
- Enabling technologies and infrastructure could assist with the development of markets for CO_2 utilization such as gas separation, purification, compression, and transport systems.[76] For example, gas separation technologies are an important enabler of CO_2 utilization due to contaminants that can naturally occur during CO_2 capture (e.g., hydrogen sulfide),[77] while transport infrastructure such as CO_2

pipelines will also be an important enabler of CO_2 utilization at scale to transport the feedstock to locations of conversion or use.[78]

- LCAs will be needed to properly assess the net climate benefits of a product derived through CO_2 utilization, of which more work is needed to develop a standardized methodology that can be applied industrywide for such accounting.[79]

Table 7-3
CO_2 Utilization RD&D Portfolio ($millions)

Portfolio Element	Funding Agency	Funding Office or Organization	Year 1	5-Year Total	10-Year Total
7.10 Carbonation Conversion					
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
7.20 Chemical CO_2 Conversion					
7.21 Fundamental research	DOE	SC (BES)	$3	$35	$75
	NSF	MPS	$3	$32	$72
7.22 New materials development and applications	DOE	SC (BES)	$3	$23	$48
	NSF	MPS	$2	$22	$47
7.23 Systems engineering and process design	DOE	EERE (AMO)	$5	$45	$65
7.20 Subtotal, Chemical CO_2 Conversion			$16	$157	$307
7.30 Biological CO_2 Conversion					
7.31 Genetic modeling and tools	DOE	SC (BER)	$2	$20	$45
	NSF	BIO	$2	$20	$45
7.32 Bioprospecting	USDA	ARS	$2	$20	$45
	DOE	SC (BER)	$2	$20	$45
7.33 New materials development and applications	DOE	EERE (BETO)	$2	$20	$45
	USDA	ARS	$2	$20	$45
7.30 Subtotal, Biological CO_2 Conversion			$12	$120	$270
TOTAL, CO_2 Utilization			$50	$450	$900

Source: EFI, 2019.

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26 https://www.eia.gov/tools/faqs/faq.php?id=65&t=2
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41 http://www.co2conference.net/wp-content/uploads/2012/12/1.2_Report_NETL-DiPietro_Sources_of_CO2_Supply_for_EOR_-12-11.pdf
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CHAPTER 8.
CROSS-CUTTING PROGRAMS

There are several activities that span all of the CDR capture technology pathways and CO_2 disposition pathways within the CDR RD&D initiative portfolio. These elements include systems analysis and large-scale demonstrations, both of which are technology-neutral to support the four capture technology pathways and two CO_2 disposition pathways.

Systems Analysis

Systems analysis includes data collection, modeling and assessments, and decision science research to support the CDR RD&D initiative across all capture technology pathways and CO_2 disposition pathways. These functions will allow for comprehensive data collection and comparative analyses of lifecycle CO_2 flows, technology cost and performance, technology operability at a systems level, identification of potential social and economic impacts of CDR, social acceptance, and the need for public engagement.

CDR Lifecycle Data Collection

There are currently several CO_2-related data collection programs in various federal agencies (Table 8-1), many of which are targeted to a particular issue or aspect of the carbon cycle. An effective CDR RD&D initiative will necessitate a comprehensive picture of carbon stocks and flows throughout the environment and economy, as well as lifecycle analyses across all capture technology pathways and CO_2 utilization, to better understand carbon fates and permanence. A comprehensive CO_2 data collection effort within the CDR RD&D initiative will therefore serve several purposes: (1) provide additional insights to guide the development and prioritization of CDR RD&D projects, (2) provide evidence for the effectiveness of CDR measures, (3) fill the gaps in existing federal data collection programs, and (4) serve as a single clearinghouse for all CO_2-related data collected by the federal government.

Consideration will also be given to collecting or purchasing data from entities external to the CDR RD&D initiative throughout the private sector and academia, which could help amplify federal data collection efforts and inform programmatic direction. Efforts will be made to make all data publicly available, but will ultimately be determined by the source of the data. For example, data purchased from private sector entities may be proprietary, therefore limiting its availability to the public.

The new data collection effort is proposed to be led by the Department of Energy (DOE) Office of Fossil Energy (FE) and is proposed to receive funding of $20 million annually (after start-up period) for the new data collection program. DOE/FE leadership will ensure that the data collection efforts are designed in a fashion to serve the major uses. Some portion of the actual data collection may be implemented as an augmentation to other current CO_2 data collection programs identified in Table 8-1.

Table 8-1
Selection of Federal Data Collection Related to CDR (Not Exhaustive)

Entity	Data Type(s)	CDR Category
Department of Agriculture (USDA)	• Provides greenhouse gas (GHG) inventory data to the EPA for land use, land-use change, and forestry (LULUCF) sector including fluxes associated with: forest land; soils in croplands; grasslands; and settlements[1] • National Resources Inventory and Forest Inventory and Analysis databases used to track land management[2]	• Terrestrial & Biological
Department of Energy (DOE)	• Geologic sequestration potential[3]	• Geologic Sequestration
Department of the Interior (DOI)	• Geologic sequestration potential[4] • Carbon mineralization potential[5] • Landsat Program for LULUCF research jointly managed with NASA[6]	• Geologic Sequestration • Carbon Mineralization • Terrestrial & Biological
Environmental Protection Agency (EPA)	• Carbon stock accounting in LULUCF sector including for forests, cropland, grassland, wetlands, settlements, coastal wetlands, peatlands, soils (drained organic, settlement, forest)[7]	• Terrestrial & Biological
National Aeronautics and Space Administration (NASA)	• Orbiting Carbon Observatory 2 (OCO-2) is first satellite dedicated to CO_2 measurements from space[8] • Landsat Program for LULUCF research jointly managed with DOI[9] • Moderate Resolution Imaging Spectroradiometer (MODIS) for remote sensing of the land and oceans[10]	• Terrestrial & Biological • Coastal & Oceans
National Oceanic and Atmospheric Administration (NOAA)	• Provides GHG inventory data to the EPA for LULUCF sector including: land-use change; soil carbon stocks and stock change; aquaculture in coastal wetlands[11] • Terrestrial and oceanic carbon fluxes[12,13] • Atmospheric CO_2 measurements at Mauna Loa Observatory[14]	• Terrestrial & Biological • Coastal & Oceans
Smithsonian Environmental Research Center (Coastal Carbon Research Coordination Network and Coastal Carbon Working Groups)	• Provides GHG inventory data to the EPA for LULUCF sector including: land-use change; soil carbon stocks and stock change; aquaculture in coastal wetlands[15,16]	• Terrestrial & Biological • Coastal & Oceans
Multi-Agency Collaborations	• Multi-Resolution Land Characteristics Consortium National Land Cover Dataset used to track land management[17,18]	• Terrestrial & Biological

Source: EFI, 2019.

CDR Integrated Modeling and Assessments

The modeling and assessments component will evaluate the systems-level impacts of large-scale CDR deployment (environmental, economic, and social) and facilitate independent techno-economic analyses to compare alternative pathways. Integrated carbon systems modeling will include the modeling of anthropogenic CO_2 emissions, removals, and system impacts, as well as the integration of CDR with mitigation and other science- and technology-relevant goals.

A major ongoing issue for integrated assessment models (IAMs) is the uncertainty of how well certain factors related to CDR such as carbon storage permanence and saturation limits are represented in carbon cycle models.[19] The activities supported within this portfolio element will enhance the understanding of the potential effectiveness of various CDR options. Furthermore, a systems-level modeling effort is warranted to provide insights into supply chain issues and integration issues, such as the compatibility and operational characteristics between existing energy infrastructure and new infrastructure that would support CDR objectives (e.g., direct air capture [DAC] plants). A major integrated assessment modeling effort will improve understanding of the intertwined infrastructures, resources, facilities, and economics.

Techno-economic assessments will provide an independent inter-comparison of the costs and performance of CDR pathways, which can assist with merit-order determinations for the large-scale demonstration projects. Techno-economic assessments have the ability to not only assess the potential of individual discrete CDR pathways, but also consider the potential for optimization of hybrid CDR options. As interest grows in CDR, new ideas are emerging regarding the potential benefits of hybrid approaches, such as DAC/carbon mineralization and bioenergy with carbon capture and sequestration (BECCS)/DAC hybrid systems. Such hybrids may provide ways to optimize performance among net carbon removal, energy requirements, and economics. The techno-economic assessments will enable program managers to identify new opportunities that might not otherwise be apparent from RD&D on discrete pathways.

This portfolio element is proposed to ramp up to an annual funding level of $30 million per year. The program activity is proposed to be managed by DOE/FE. Much of the work will draw upon the existing extensive capabilities and expertise within the DOE National Laboratory system. Several of the National Laboratories have deep experience in large-scale modeling applicable to this challenge.

Decision Science

The decision science component will assess socio-economic, stakeholder engagement, and public acceptance issues associated with the deployment of gigaton-scale CDR and large-scale geologic sequestration.

Historical socio-economic research on CDR has focused on BECCS, afforestation, and reforestation, with comparatively little social science research on other pathways such as DAC and carbon mineralization. Consequently, more socio-economic research is needed on a broader range of CDR pathways and issues such as land use constraints, competition for land resources (e.g., food production), impacts on food prices, and the interrelationship between CDR and mitigation.[20]

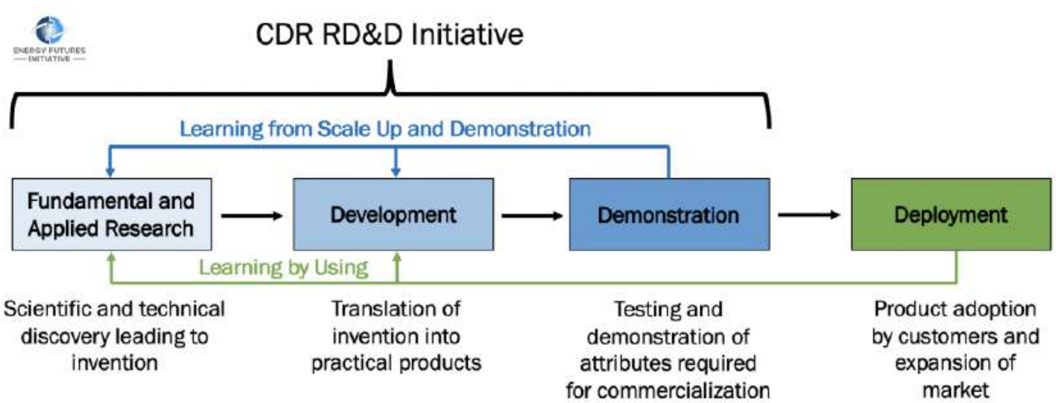
Social acceptance related to CDR also warrants further research, as CDR pathways that are perceived to tamper with nature to a greater degree (e.g., DAC) have previously been viewed as less favorable than those perceived to tamper with nature to a lesser degree (e.g., afforestation and reforestation).[21]

Decision science research in the CDR RD&D initiative will focus on the social and economic dimensions of CDR and address the need for public engagement given the paucity of previous research and scale of the CDR challenge (e.g., public attitude surveys on siting and stewardship). Regulatory frameworks to help guide the large-scale demonstration projects (and assist future deployment) will also be considered within the decision science portfolio element. Decision science is proposed to ramp up to a level of $15 million annually. Elements of the program will be implemented through the National Science Foundation (NSF) (Division of Social and Economic Sciences [SES]), EPA (Office of Research and Development [ORD]), DOE (FE), and Department of Agriculture.

CDR Large-Scale Demonstration Projects

Demonstration projects are an essential element of the innovation process for testing technologies at scale with full integration of components and sub-systems, and will serve as an important component of the CDR RD&D initiative (Figure 8-1). The learning by doing achieved through demonstration projects is an essential two-way street, enabling any necessary fine-tuning as technologies enter commercial deployment as well as providing important feedbacks to guide further research priorities.

Figure 8-1
Focus of CDR RD&D Initiative



The process of moving innovations into the marketplace generally follows these four stages; however, this process can be non-linear as a result of feedbacks stemming from technology scale up, demonstrations, and learning by using. Source: EFI, 2019.

The proposed demonstration program component of the CDR RD&D initiative will allow for learning from technology scale up and demonstrations, which can provide critical information to guide more targeted fundamental research objectives and promote continuous technology improvement. The design of the proposed CDR demonstration program has five key elements that distinguish it from past technology demonstration programs.

1. ***The proposed CDR demonstration program is technology-neutral***. The design assumes that the alternative CDR technologies, both pathway-specific and hybrid ideas, will compete for demonstration project funding based on specified criteria. As a starting point, suggested criteria are listed in Table 8-2.

2. ***The demonstration program is financed through a single, technology-neutral demonstration fund of $2 billion.*** Consolidating the demonstration project funding in a single fund avoids the presumption of funding demonstration activities for each CDR pathway. Not all CDR pathways may merit large-scale demonstrations given the inherent uncertainty of technology characteristics such as scalability, cost, environmental and social impacts, and overall performance.

3. ***The timing for the CDR RD&D initiative is designed to take advantage of early R&D***. It is assumed that the demonstration program will be initiated toward the end of the first 5-year period, in order to take advantage of early R&D results. This reduces the potential of initiating large-scale demonstration projects prematurely before all of the necessary supporting R&D "homework" is completed.

4. ***The CDR demonstration project cost-sharing requirements should be innovative and flexible***. The $2 billion proposed budget planning estimate assumes significant non-federal cost sharing on the order of 50-50 in line with the requirements set forth under Section 988 of the Energy Policy Act (EPAct) of 2005. The Act does provide flexibility for the Secretary of Energy to provide waivers, and the waiver authority should be exercised for CDR demonstration projects to facilitate innovative financing arrangements.[22] The existence of the Section 45Q tax credit may allow for more flexible cost sharing levels, where the federal share could be set on the basis of the incremental cost necessary to make CDR projects financially viable after application of the 45Q credit. DOE also should consider cost-sharing arrangements that link the federal cost share to demonstration project construction and operational performance rather than provide a fixed cost share for upfront construction activities that may not lead to successfully completed projects.

5. ***CDR demonstration projects should be centrally managed in a program office staffed with project management expertise***. The management of DOE large-scale demonstration projects has a checkered history.[23] DOE has taken steps in recent years to strengthen the project management oversight of DOE funded and managed projects—establishing a high-level Energy Systems Acquisition Advisory Board (ESAAB), creating a centralized office to conduct independent cost analysis,

and strengthening the oversight process for project development through DOE Order 413.3b.[24] These measures do not currently apply uniformly to DOE cost-shared technology demonstration projects. Also, in many of the DOE program offices, R&D managers also may be assigned as technology demonstration project managers, although demonstration projects present a range of additional issues and challenges that fall outside traditional R&D management precepts. The CDR demonstration projects selected for funding are proposed to be managed under a single new demonstration project management office comprised of staff with project management expertise. The recommendation assumes that this office would be organized within FE with overall responsibilities for the CDR RD&D portfolio planning. If Congress were to re-establish the Office of Under Secretary for Science and Energy, this function could be assigned to a separate office higher in the organization.

Other studies have recommended much broader measures to improve the funding and management of large-scale energy technology demonstration projects. These include the establishment of a government corporation or some other form of quasi-private organization to assume responsibility for demonstration project management, with special financing arrangements that involved dedicated funding sources or funding outside the annual appropriations process (or both).[25] Further consideration should be given to examining a broader array of public-private partnerships (e.g., government-sponsored entity) that could be put in place within the first five years of the CDR RD&D initiative as the R&D on various CDR pathway alternatives reaches the stage where large-scale demonstration projects may be appropriate.

Table 8-2

Criteria for Demonstration Project Eligibility (Not Exhaustive)

Techno-economic	Socio-economic and Deployment
Ecological impacts	Current and former private sector investment support
Estimated net CO_2 removal costs	Economic opportunities (e.g., new industries, jobs, export markets)
Level of storage permanence	Federal policy support needs
Lifecycle analysis (LCA) performance	Legal and regulatory issues (including in the international context)
Monitoring, reporting, and verification (MRV) requirements	Opportunities for deployment co-benefits (e.g., food production)
Opportunities for RD&D co-benefits (e.g., DAC and carbon capture on power plants and industrial facilities)	Public perception and social acceptance
Supply chain requirements and critical materials	Removal scale potential
Technologies that could provide optionality and flexibility for interfacing with existing energy infrastructure and systems	

Source: EFI, 2019.

Cross-Cutting Programs RD&D Portfolio

The RD&D portfolio for the cross-cutting programs include RD&D efforts on systems analysis and large-scale demonstration projects. The proposed funding levels for these cross-cutting programs are $575 million for systems analysis and $2 billion for large-scale demonstration projects, with RD&D roles and responsibilities for systems analysis divided among three federal agencies including DOE, NSF, and EPA (Table 8-3).

Recommended RD&D Portfolio Elements

Data Collection, Portfolio Element 7.10, involves data collection and is comprised of one budget line item that seeks to consolidate and publish data related to CDR.

- **CDR Data Collection and Publication, Portfolio Element 7.11,** involves collecting, aggregating, and publishing economywide CO_2 flux data and ecosystem CO_2 flux data. This effort is proposed to be managed by DOE/FE.

Modeling and Assessments, Portfolio Element 7.20, involves integrated carbon systems modeling and independent technology assessments.

- **Technology Cost and Performance, Portfolio Element 7.21,** involves the independent tracking, analysis, and inter-comparison of costs and performance of CDR technologies and methods. This effort is proposed to be managed by DOE/FE.
- **Integrated Carbon Systems Modeling, Portfolio Element 7.22,** involves integrated modeling of anthropogenic CO_2 emissions, removals, and system impacts. This effort will be managed by DOE/FE.

Decision Science, Portfolio Element 7.30, involves decision science and related research.

- **Research on Decision Science, Portfolio Element 7.31,** involves research on decision science, social impacts, and public engagement for CDR technologies and methods. Implementation of this effort is proposed to be shared by DOE/FE, NSF/SES, EPA/ORD.

Large-Scale Demonstration Projects, Portfolio Element 8.10, involves large-scale demonstration projects and is comprised of one budget line item.

- **Large-Scale Demonstration Projects, Portfolio Element 8.11,** establishes a central funding pool to cost-share demonstration projects competitively across all capture technology pathways and CO_2 disposition pathways. This effort is proposed to be managed by a new DOE demonstration program office within DOE/FE.

Table 8-3
Cross-Cutting Programs RD&D Portfolio ($millions)

Portfolio Element	Funding Agency	Funding Office or Organization	Year 1	5-Year Total	10-Year Total
7.00 Systems Analysis					
7.10 Data Collection					
7.11 CDR data collection & publication	DOE	FE	$5	$80	$180
7.10 Sub-total, Data Collection			$5	$80	$180
7.20 Modeling and Assessments					
7.21 Technology cost and performance	DOE	FE	$4	$40	$90
7.22 Integrated carbon systems modeling	DOE	FE	$5	$80	$180
7.20 Sub-total, Modeling and Assessments			$9	$120	$270
7.30 Decision Science					
7.31 Research on decision science	DOE	FE	$2	$18	$43
	NSF	SES	$2	$18	$43
	EPA	ORD	$2	$14	$39
3.30 Sub-total, Decision Science			$6	$50	$125
TOTAL, Systems Analysis			$20	$250	$575
8.00 Large-Scale Demonstration Projects					
8.10 Large-Scale Demonstration Projects					
8.11 Large-Scale Demonstration Projects	TBD	TBD	$0	$175	$2,000
8.10 Sub-total, Large-Scale Demonstration Projects			$0	$175	$2,000
TOTAL, Large-scale Demonstration Projects			$0	$175	$2,000

Source: EFI, 2019.

1 https://www.epa.gov/sites/production/files/2019-04/documents/us-ghg-inventory-2019-main-text.pdf
2 https://www.epa.gov/sites/production/files/2019-04/documents/us-ghg-inventory-2019-main-text.pdf
3 https://www.netl.doe.gov/coal/carbon-storage/strategic-program-support/natcarb-atlas
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7 https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks
8 https://climate.nasa.gov/climate_resources/99/graphic-measuring-carbon-dioxide-from-space/
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12 https://sos.noaa.gov/datasets/carbon-flux/
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14 https://www.esrl.noaa.gov/gmd/ccgg/trends/full.html
15 https://www.epa.gov/sites/production/files/2019-04/documents/us-ghg-inventory-2019-main-text.pdf
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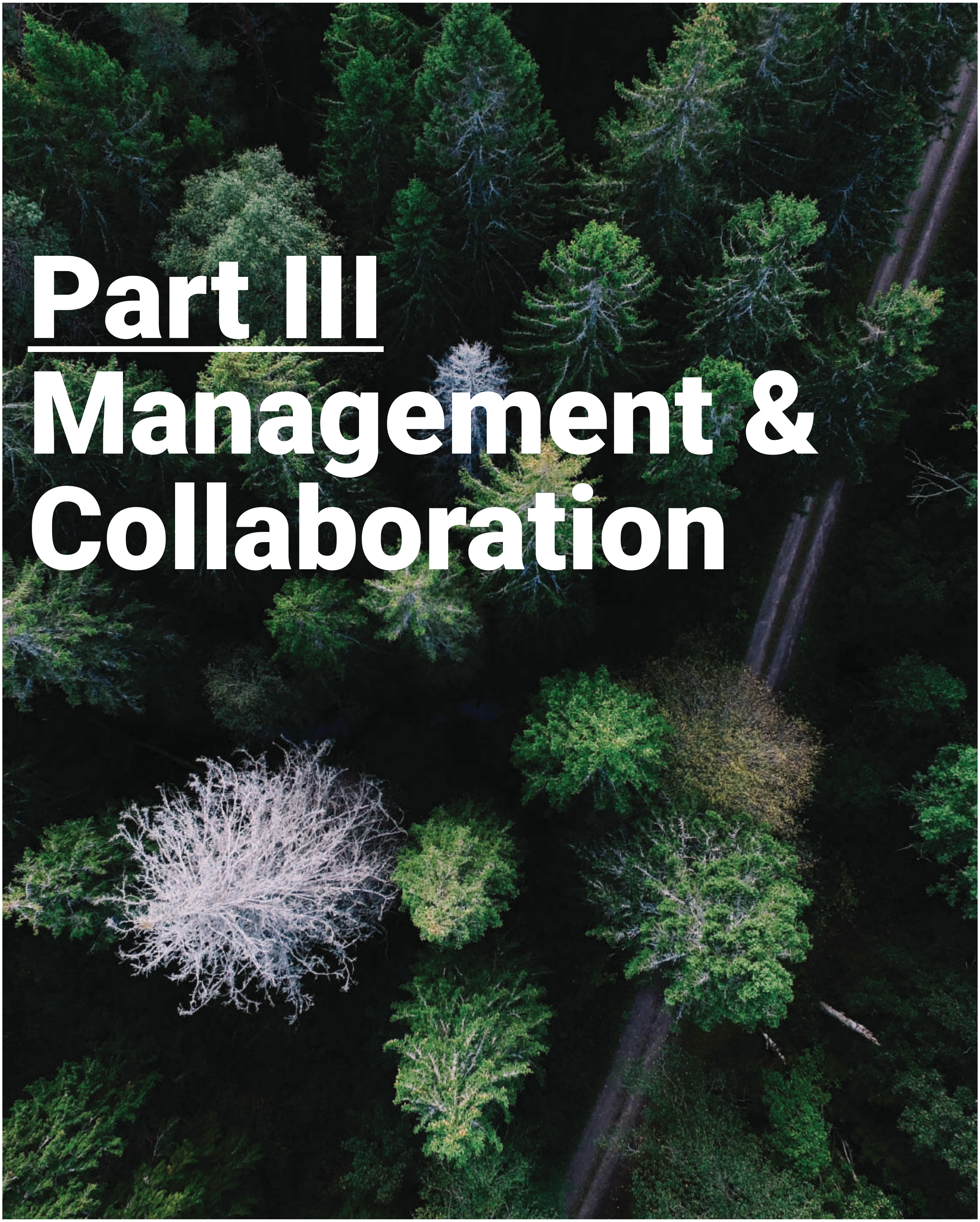
21 https://link.springer.com/epdf/10.1007/s10584-019-02375-z?author_access_token=xTWRsw_B8iGXp2_z8rcyY_e4RwlQNchNByi7wbcMAY4dQACT6eeohHSRLHL7h9tO3NRJ4Mv14flictWrvpxQGl8rsgnayjF5uNb5s75S9GYCy68tZv_GEMdyPMd7KM4tCKGoeVfakhVw3Z_uoqiLdw%3D%3D

22 https://www.energy.gov/sites/prod/files/GuidetoFinancialAssistance.pdf
23 https://www.gao.gov/products/GAO-08-641
24 https://www.directives.doe.gov/directives-documents/400-series/0413.3-BOrder-b
25 https://www.brookings.edu/wp-content/uploads/2016/07/05_energy_corporation_deutch_paper.pdf



Part III Management & Collaboration

CHAPTER 9.
BUDGET AND MANAGEMENT

The success of the CDR RD&D initiative requires adequate budget support and clear delineation of organization and management responsibilities. The organization and management challenges are considerable and will necessitate a whole-of-government approach.

The discussion of each CDR RD&D portfolio element in the preceding chapters includes a table with budget planning estimates and identifies the federal departments and agencies proposed with lead responsibility for implementation. A complete summary can be found in Appendix A. There also are a number of organizational placement issues within departments and agencies as well as issues related to planning and coordination within each department and agency. These latter issues are discussed in this chapter.

Recommended Budget Planning Estimates

The total budget planning estimate for the CDR RD&D initiative is $10.7 billion over 10 years, of which $325 million represents the first full year of implementation, $4,100 million (38 percent) is allotted in total over the first five years, and $6,600 million (62 percent) is planned for the second five years, contingent upon the results of an independent program performance evaluation during the first five years (Table 9-1).

Table 9-1
Proposed Budget Estimates by CDR RD&D Initiative Element ($millions)

Initiative Element	1st Year Total	5-Year Total	10-Year Total
Direct Air Capture	$50	$750	$1,600
Terrestrial and Biological	$90	$750	$1,575
Carbon Mineralization	$20	$325	$700
Coastal and Oceans	$45	$750	$1,750
Geologic Sequestration	$50	$650	$1,600
CO_2 Utilization	$50	$450	$900
Systems Analysis	$20	$250	$575
Large-scale Demonstration Projects	$0	$175	$2,000
Total	**$325**	**$4,100**	**$10,700**

Source: EFI, 2019.

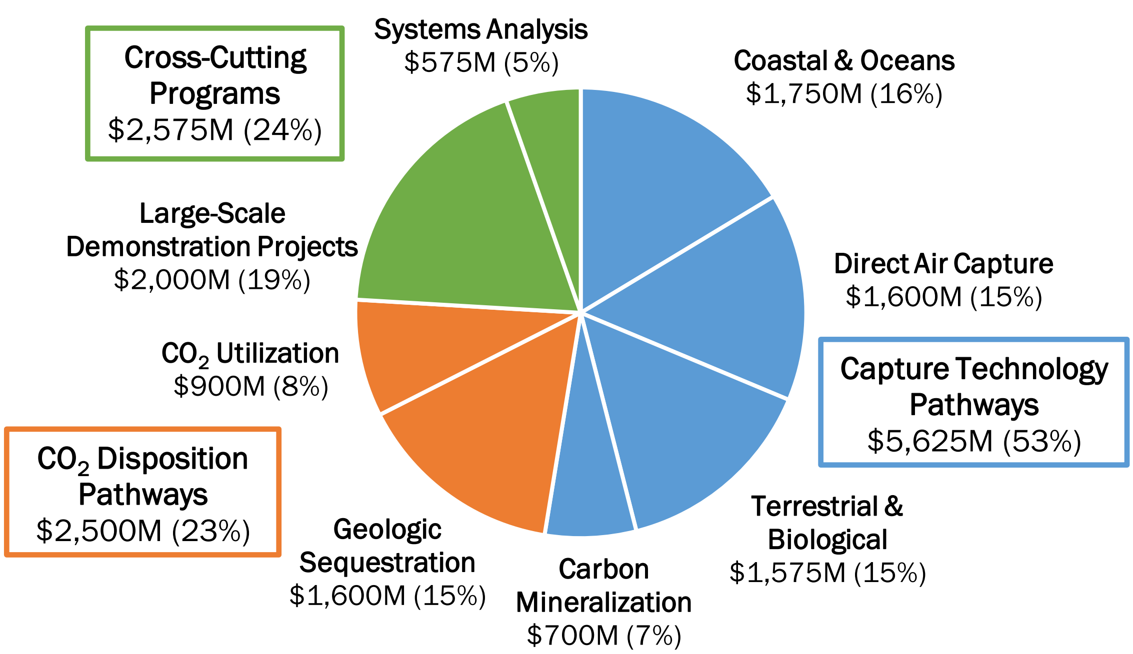
Budget planning estimates for each portfolio element level were derived from a combination of NASEM costing assumptions[1] and parametric and notional budget estimates. Budget planning estimates for fundamental research activities are estimated on a level-of-effort basis. Budget planning estimates for applied R&D programs, including scale-up of R&D results, are projectized to the extent possible with finite schedules. The budget planning estimates for the consolidated CDR technology demonstration program represent a pool of funds deemed reasonable to cost-share a suite of demonstration projects spanning all technological CDR pathways. The budget planning estimates are intended to serve as initial planning guidance for more detailed

RD&D road-mapping and budget formulation that would be conducted during the first year of the RD&D initiative.

Dedicated funding allocations of up to 5 percent of the proposed 10-year budget planning estimates will also be recommended for high-risk, high-reward CDR concepts within the capture technology pathways and CO_2 disposition pathways. These funds will support the pursuit of disruptive research and novel concepts related to CDR that may inherently assume greater RD&D risks but could ultimately prove to have a high-impact potential. This effort and funding allocation will be channeled through AGARDA within the terrestrial and biological capture technology pathway but will not be executed through an already established entity within the other capture technology pathways and CO_2 disposition pathways.

As illustrated in Figure 9-1, the proposed budget planning estimates support a diversified and balanced portfolio of RD&D across all CDR pathways. Funding for the four capture technology pathways total $5,625 million over 10 years (53 percent), while funding for the two CO_2 disposition pathways and two cross-cutting programs total $2,500 million (23 percent) and $2,575 million (24 percent), respectively (Figure 9-1).

Figure 9-1
CDR RD&D Initiative Proposed Total Funding by Portfolio Categories

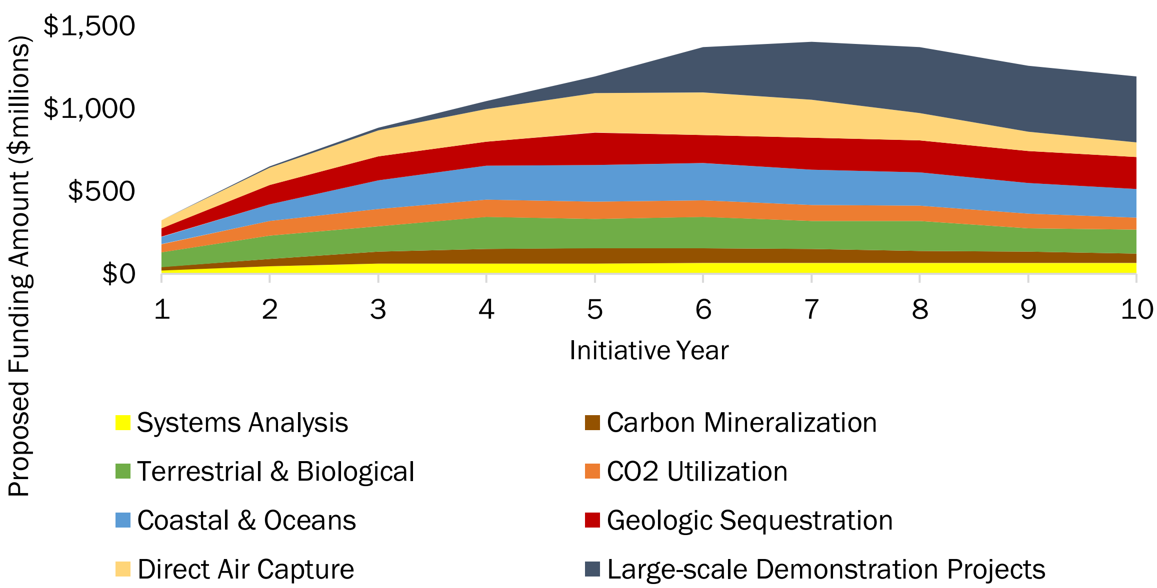


Source: EFI, 2019.

The ramp rate for the total annual funding estimate for the initiative is ambitious but achievable. The proposed budget planning estimate for the first full year of the program is estimated at $325 million, ramping to an annual level of more than $1 billion in Year 4, peaking at $1,404 million in Year 7, with an annual average of $1,320 million in the latter five years (Figure 9-2).

Figure 9-2

CDR RD&D Initiative Proposed Total Funding by Year



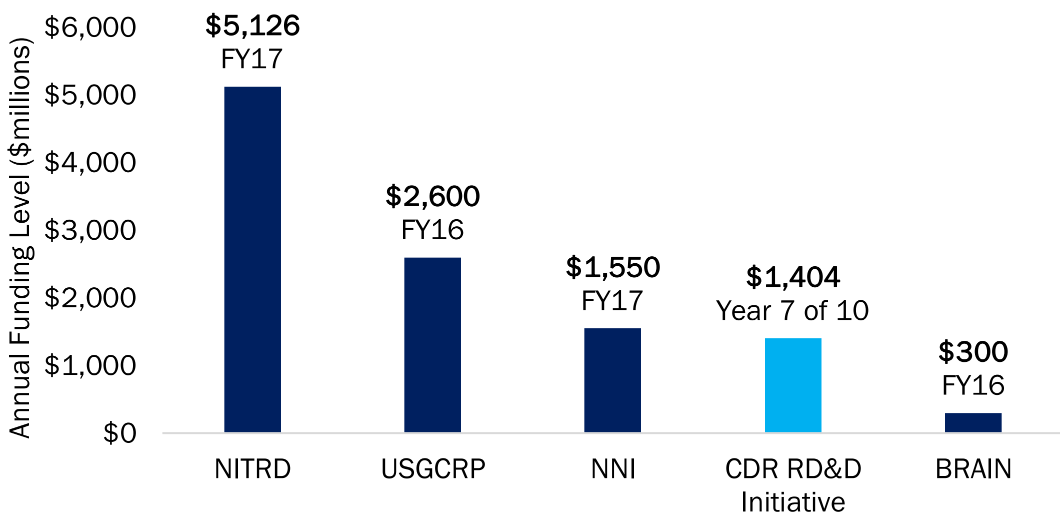
Funding ramps to $325 million in the first year and peaks at $1,404 million in the seventh year. Source: EFI, 2019.

The estimated funding levels represent a substantial new federal budget commitment. The viability of the initiative is dependent upon adequate, stable, and predictable funding. The viability of the recommended budget planning estimates was assessed from four perspectives:

1. How does the scale of the recommended funding estimates compare with other previous federal interagency R&D initiatives?
2. How does the recommended peak annual budget planning estimate for each of the major CDR RD&D agencies compare with current base R&D budgets?
3. Can the recommended funding estimates for DOE, the largest component of the recommended funding, be accommodated within a budget-doubling scenario for DOE science and energy technology innovation?
4. What would be the size of a new revenue source if half or more of the recommended initiatives were to be funded from dedicated revenues outside the annual appropriations process?

Overall, the recommended budget planning estimates for the CDR RD&D initiative are on a scale comparable to other major federal interagency R&D initiatives (Figure 9-3). These include the Networking and Information Technology Research and Development Program (NITRD; $5,126 million in fiscal year 2017);[2] U.S. Global Change Research Program (USGCRP; $2,600 million in fiscal year 2016);[3] National Nanotechnology Initiative (NNI; $1,550 million in fiscal year 2017);[4] and Brain Research Through Advancing Innovative Neurotechnologies Initiative (BRAIN; $300 million in fiscal year 2016).[5]

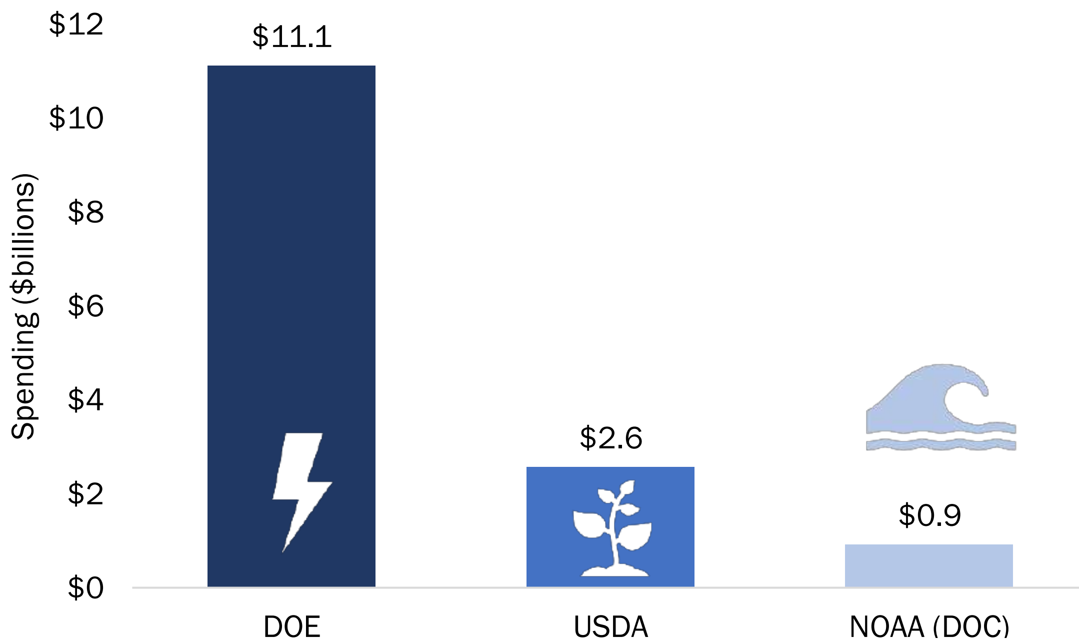
Figure 9-3
Relative Size of Interagency R&D Initiatives



The peak annual funding level for the CDR RD&D initiative is lower than previous interagency R&D initiatives. Source: EFI, 2019.

A second way to assess the feasibility of the recommended budget planning estimates is to compare peak year funding estimates with current base budgets for the participating research agencies. By Year 5 of the proposed 10-year initiative, the total budget reaches about $1.1 billion and the individual agency budgets (other than the proposed CDR demonstration program) reach peak levels. In total, the entire CDR RD&D budget planning estimate represents about 15 percent of the total current federal energy innovation budget. The agency-specific funding comparisons are shown in Figure 9-4 for the three principal CDR research agencies: for DOE, recommended CDR RD&D funding comprises 6.5 percent of the current total DOE energy and science budget; for USDA, the CDR RD&D Year 5 increment is 4 percent of its current research budget; and for NOAA, the estimated Year 5 CDR research budget planning estimate represents 13.8 percent of its current research budget.

Figure 9-4
FY2018 R&D Spending at CDR-Related Agencies

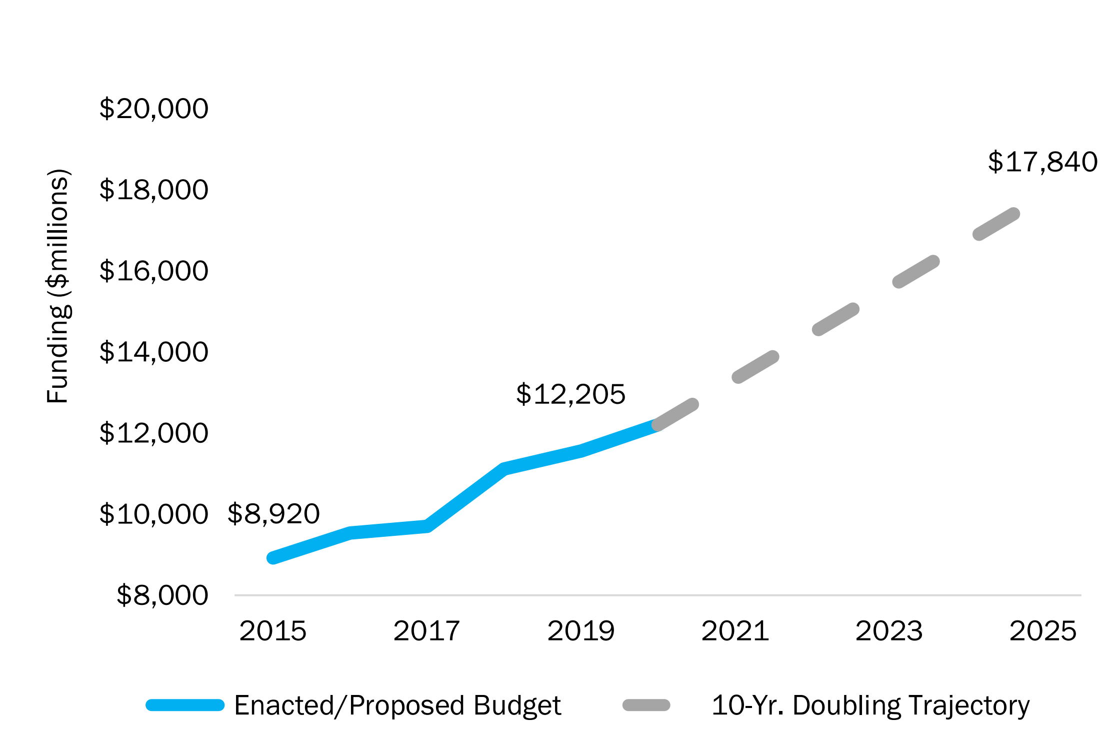


DOE, USDA, and NOAA had relatively large R&D budgets in fiscal year 2018. Source: EFI, 2019.

The third way to assess the feasibility of the recommended budget planning estimates is to assess the DOE estimates relative to a potential doubling of the DOE science and energy technology innovation budget. The DOE total science and energy R&D budget has increased 30 percent over the past five years and could be positioned for a 10-year doubling trajectory from 2015 to 2025 (Figure 9-5) given further support through congressional appropriations. This would create a budget planning "wedge" of $5.6 billion at the end of the next five years. The proposed budget planning estimates for DOE-supported CDR RD&D would fit within that wedge but would be subject to significant competition from other program initiatives. A faster rate of doubling, such as the five-year doubling proposed initially in the Mission Innovation initiative, would ease the budgeting challenge. In any event, future funding levels remain subject to considerable uncertainty due to the application of budget caps and the annual appropriations process (de novo reviews each year).

Figure 9-5

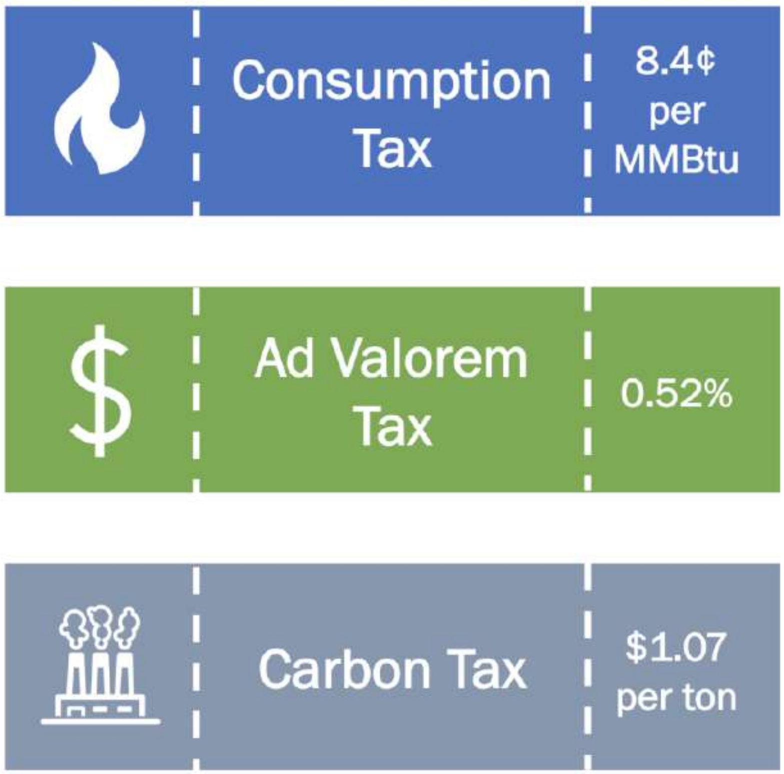
Doubling the DOE Science and Energy R&D Budget



DOE science and energy budget could be on a 10-year doubling trajectory by 2025. Source: EFI, 2019.

The uncertainties in the annual appropriations process have led to various proposals to establish a dedicated funding stream for energy innovation investments across the board, which could help support DOE in the CDR RD&D initiatives. It is unrealistic to assume that Congress would allow the entire DOE science and energy innovation budget to be fully funded from a dedicated revenue source and be placed completely outside the purview of the annual appropriations process. One way to consider the possibility of establishing a new dedicated funding source would be to consider what it would take to fund 50 percent—or $5 billion—of the recommended CDR RD&D budget planning estimate through a new dedicated revenue stream. A $5 billion revenue charge could be levied on fuels, including electricity, natural gas, gasoline, diesel, and jet fuel, in different ways. There are several ways to apply such a charge—by amount of energy consumed, by amount of revenue generated (ad valorem), or by the amount of CO_2 produced. Raising $5 billion through these methods (given current consumption information of the five energy sources named above) would end up with a relatively small tax (relative to current gas taxes) or carbon pricing proposals that seek to change emitting behavior (Figure 9-6).

Figure 9-6
Getting to $5 Billion: Three Methods



The consumption and carbon taxes each work out to slightly less than 1 cent per gallon of gasoline. Source: EFI, 2019.

Federal Agency Participation in the CDR RD&D Initiative

The CDR RD&D initiative will involve the participation of 27 offices or organizations across 10 federal agencies—in addition to the Office of Science and Technology Policy (OSTP) and Office of Management and Budget (OMB)—with a prominent role for DOE, USDA, and NOAA (Table 9-2). DOE is proposed to receive more than $4.8 billion in funding (45 percent of the total), while NSF, USDA, and NOAA are each proposed to receive roughly $1 billion. Funding would be enacted through six appropriations bills: Agriculture; Commerce, Justice, and Science; Defense; Energy and Water; Interior and Environment; and Transportation, Housing, and Urban Development.

Table 9-2
Proposed Total Funding by Federal Agency and Office/Organization ($millions)

Funding Agency	Funding Office/Organization	Total Funding
Department of Agriculture	Agriculture Advanced Research and Development Authority (AGARDA)	$100
	Agricultural Research Service (ARS)	$542
	National Institute of Food and Agriculture (NIFA)	$224
	Natural Resources Conservation Service (NRCS)	$34
	U.S. Forest Service (USFS)	$77
	Subtotal, USDA	**$977**
Department of Commerce (NOAA and NIST)	National Oceanic and Atmospheric Administration/Fisheries (NOAA/Fisheries)	$435
	National Oceanic and Atmospheric Administration/Oceanic and Atmospheric Research (NOAA/OAR)	$471
	National Institute of Standards and Technology (NIST)	$40
	Subtotal, DOC	**$946**
Department of Defense	U.S. Army Corps of Engineers (USACE)	$235
	U.S. Army Research Laboratory (ARL)	$79
	U.S. Naval Research Laboratory (NRL)	$79
	Subtotal, DOD	**$393**
Department of Energy	Energy Efficiency and Renewable Energy/Advanced Manufacturing Office (EERE/AMO)	$181
	Energy Efficiency and Renewable Energy/Bioenergy Technologies Office (EERE/BETO)	$477
	Energy Efficiency and Renewable Energy/Building Technologies Office (EERE/BTO)	$30
	Office of Fossil Energy (FE)	$3,451
	Office of Science/Biological and Environmental Research (SC/BER)	$340
	Office of Science/Basic Energy Sciences (SC/BES)	$377
	Subtotal, DOE	**$4,856**
Department of the Interior	U.S. Geological Survey (USGS)	$152
	Subtotal, DOI	**$152**
Department of Transportation	Federal Highway Administration (FHWA)	$57
	Subtotal, DOT	**$57**
Environmental Protection Agency	Office of Research and Development (ORD)	$281
	Subtotal, EPA	**$281**
National Aeronautics and Space Administration	Earth Sciences Division (ESD)	$30
	Subtotal, NASA	**$30**
National Science Foundation	Directorate for Biological Sciences (BIO)	$45
	Directorate for Engineering (ENG)	$26
	Directorate for Geosciences (GEO)	$583
	Directorate for Mathematical and Physical Sciences (MPS)	$281
	Directorate for Social, Behavioral, and Economic Sciences (SBE)	$30
	Division of Social and Economic Sciences (SES)	$43
	Subtotal, NSF	**$1,008**
TBD (Demonstrations)	N/A	$2,000
	Subtotal, TBD (Demonstrations)	**$2,000**
Total	N/A	**$10,700**

Ten agencies and 27 offices or organizations are proposed to receive funding through the CDR RD&D initiative. Source: EFI, 2019.

Three federal agencies in particular—DOE, USDA, and NOAA within the DOC—will be responsible for the bulk of the initiative. The organization of the CDR RD&D initiative within these three federal agencies is described in more detail below.

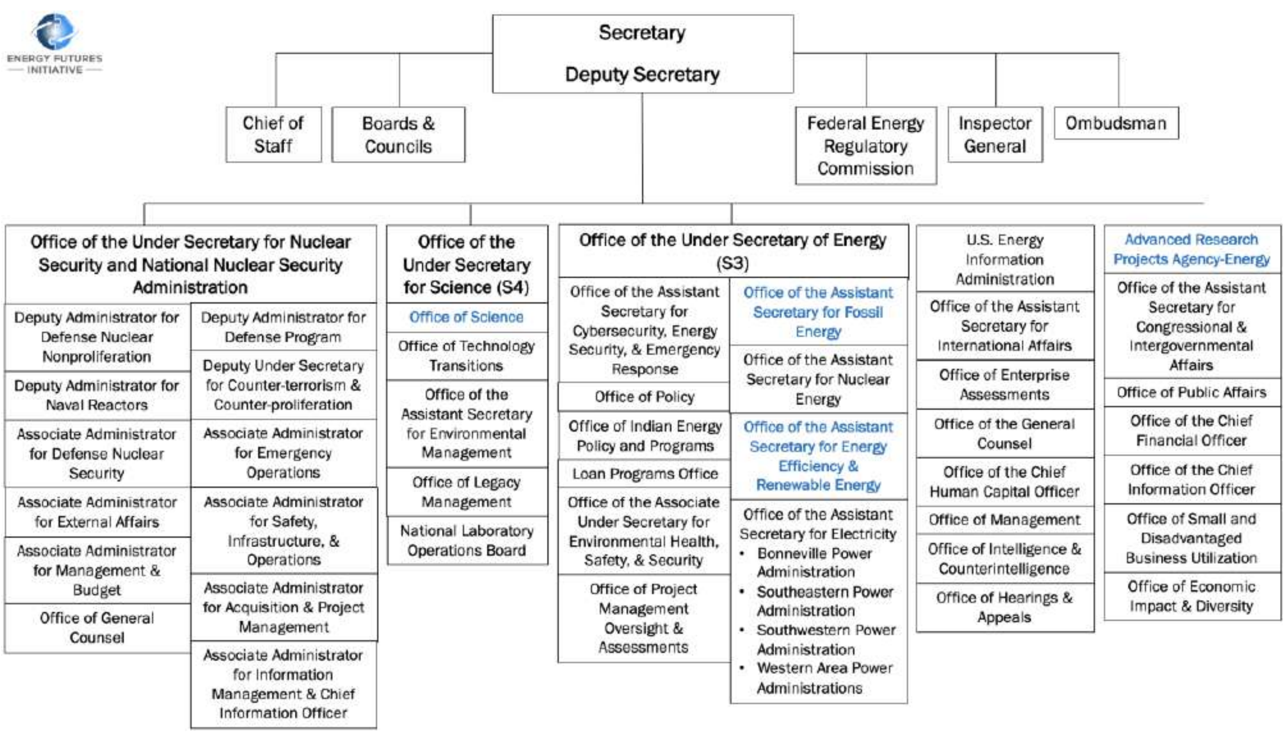
Three federal agencies in particular—DOE, USDA, and NOAA within the DOC—will be responsible for the bulk of the initiative.

Department of Energy

The DOE mission involves providing leadership on issues at the intersection of energy, environment, and nuclear security.[6] DOE was established in 1977[7] and has a fuels-based organizational structure (Figure 9-7),[8] which was adopted in response to major global oil supply disruptions that occurred during that era. Consequently, end-use-related and energy market issues typically require significant cross-agency coordination efforts.

Figure 9-7

Current DOE Organization Highlighting Offices That Could Support the CDR RD&D Initiative (Not Exhaustive)

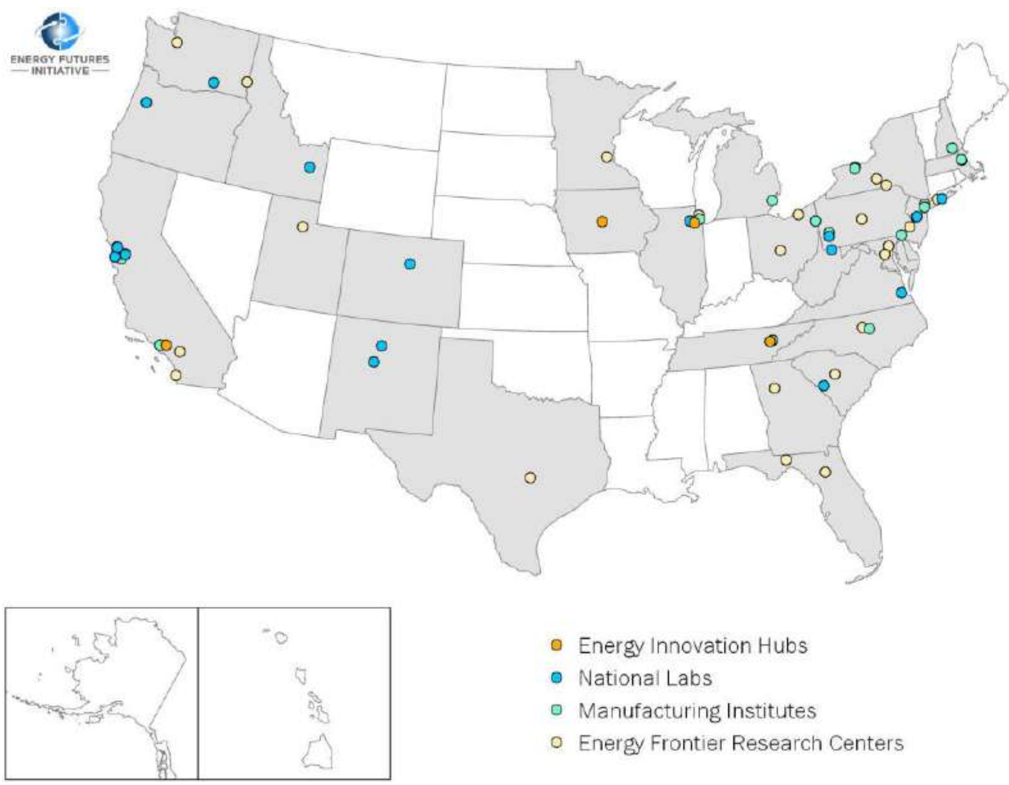


There are at least four DOE offices and organizations that could support the CDR RD&D initiative (blue). Source: EFI, 2019. Compiled using data from the Department of Energy.

DOE has historically supported some CDR-related RD&D activities in BETO within EERE. RD&D on carbon capture from concentrated point sources, as well as work on geologic sequestration, has been the responsibility of FE. Fundamental CDR-related research in biology and chemistry has been supported in the BES and BER programs within SC. Cross-cutting research on subsurface science and engineering, an important foundational research area for carbon sequestration, was previously supported through a special cross-cutting R&D initiative known as the Subsurface Science, Technology and Engineering Research, and Development (SubTER) initiative,[9] but that effort appears to have dissolved in the past several years. Despite the involvement of several DOE offices in historically supporting CDR-related RD&D, there is currently no organizational home within DOE for several key pathways for CDR RD&D, including DAC, oceans-based CDR, and carbon mineralization, even though DOE has potentially important scientific and technical capabilities to support RD&D in these areas.

Figure 9-8

DOE-Supported Research Infrastructure



The DOE research network spans across 27 states. Note: Points may overlap and appear as one point. Source: EFI, 2019. Compiled using data from the Department of Energy.

DOE research programs are implemented through an extensive network of 17 National Laboratories across 15 states, 46 EFRCs across 22 states, four Energy Innovation Hubs across four states, and 14 Manufacturing Institutes across 11 states (Figure 9-8).[10,11,12,13] DOE RD&D activities are implemented primarily through its National Laboratories, but it also provides grants for university-based research and engages in cost-sharing for applied RD&D projects with the private sector. The DOE National Laboratory system represents the largest single concentration of science and technology expertise in the United States and houses most of the nation's large-scale science instruments (e.g., light sources, neutron sources, particle accelerators).

Advanced Research Projects Agency-Energy

ARPA-E represents a special case within the CDR RD&D initiative. ARPA-E has been on the leading edge of advancing innovation in CDR-related RD&D through the ROOTS and MARINER programs, with 10 active projects in ROOTS[14] and 18 active projects in MARINER.[15] The ARPA-E model is well-suited to continue to identify and support innovations in CDR and has successfully functioned without advanced earmarking of program solicitations in its budgetary process. New areas for solicitations are established only after a rigorous planning effort, including outreach to a broad range of science and technology experts to solicit expert opinion on emerging priority areas for ARPA-E support.

Previous studies have documented the effectiveness of ARPA-E in accelerating the energy innovation process and have recommended that federal funding for ARPA-E be expanded from current levels ($366 million in fiscal year 2019)[16] to $1 billion.[17] This report assumes that Congress will continue to expand funding for ARPA-E on a path to $1 billion per year and that within that funding envelope ARPA-E will continue to identify and implement new solicitations for CDR-related technology R&D. The specific budget planning estimates in this report exclude any earmarking of funding for ARPA-E. The final decision on the number, timing, and scope of new CDR-related R&D solicitations will be determined by ARPA-E.

Intra-Agency Coordination for the Department of Energy

The establishment of a new DOE CDR office (Box 9-1) offers considerable opportunities to advance CDR mission objectives but also poses several challenges. The proposed arrangement will require establishing a new office with a simultaneous major expansion in funding for DOE CDR RD&D programs. This challenge is partly mitigated by the fact that the new office would be focused on carbon capture, geologic sequestration, DAC, and carbon mineralization RD&D programs. Although SC and EERE would retain their responsibilities for CDR RD&D consistent with overall programmatic missions, establishing strong leadership within the new office in FE will be a high priority. Further consideration should be given to: (1) making the new Deputy Assistant Secretary (DAS) position a career executive or an EJ or EK pay plan exempted position rather than a political appointee, (2) appointing an initial DAS who has demonstrated federal R&D program management expertise, and (3) possibly making the DAS a term-limited appointment with a term that spans presidential administrations.

The scope of responsibilities for large-scale carbon management ultimately should be elevated within the department by re-establishing the position of Under Secretary for Science and Energy. This arrangement also would allow for consideration of consolidating other departmental CDR-related RD&D, such as research currently within BES and BER, under the new higher-level large-scale carbon management organization.

Department of Energy Recommendations

Based on the analysis and findings from this report, the recommendations for DOE CDR implementation are described in Box 9-1.

Box 9-1

DOE Recommendations for CDR RD&D Initiative

Under Secretary for Science and Energy

- Re-establish the Office of Under Secretary for Science and Energy to oversee all Departmental large-scale carbon management programs and activities. Pending action on Departmental-level reorganization, the following interim steps are recommended.

Office of Fossil Energy (FE)

- Establish DAC as a technology mission responsibility for FE. In addition, FE should assign NETL lead responsibility within the department for planning and managing DOE-wide RD&D related to DAC.
- Establish RD&D related to carbon mineralization CDR as a technology mission responsibility within FE.
- As an interim step, establish a new Office of Large-Scale Carbon Management within FE, to be headed by a Deputy Assistant Secretary (DAS) reporting to the Secretary through the Assistant Secretary for FE. The new office would incorporate the existing carbon capture and sequestration research programs within FE It also would be responsible for four new broad-based DOE-wide and government-wide CDR responsibilities, including:

1. CDR portfolio planning and budget crosscut coordination for all DOE CDR-related RD&D programs. As part of this effort, the new office would become the primary point of contact for interagency CDR RD&D planning and coordination, including interfacing with EOP.
2. CDR systems analysis and technology assessment, spanning the entire government-wide CDR RD&D portfolio. This activity would draw upon the world-class modeling and simulation capabilities of the National Laboratories to undertake techno-economic assessments and systems-level analyses of CDR systems to assess lifecycle performance.
3. Expanded CO_2 data collection and database management. This activity would develop and maintain a comprehensive database on the global carbon cycle and carbon flows throughout the economy, and expand upon current point-source emissions inventories to provide a more complete and accurate picture of CO_2 emissions from all sources and sinks.
4. Provide project management services for all demonstration-scale projects emerging from the technological CDR RD&D portfolio. All projects would be subject to rigorous project management requirements and procedures modeled after DOE Order 413.3b.

Office of Energy Efficiency and Renewable Energy (EERE)

- Establish DAC as a research priority within the Advanced Manufacturing Office (AMO). The budget planning estimates in this report include funding for research to develop a U.S. manufacturing technology base for DAC. This research should be closely coordinated with the Office of Fossil Energy (FE) research program on DAC technology options.

- Incorporate terrestrial and biological CDR as a research objective in the Bioenergy Technologies Office (BETO) biomass energy program, including research on biopower and biofuels pathways. Budget planning estimates in this report include increased funding for this effort. In addition, the biomass research program should include research on soils and biomass CDR, building upon the research and analysis from Lawrence Livermore National Laboratory, which should be closely coordinated to complement the CDR RD&D initiative in soils research programs of USDA.

Office of Science (SC)

- Incorporate CDR scientific objectives into the program planning for fundamental research in the Basic Energy Sciences program (BES) and Biological and Environmental Research program (BER), with appropriate funding increases.
- Within BER, expand the existing Memorandum of Understanding (MOU) with USDA to incorporate CDR research objectives within the scope of the current genomics research program.
- Within BES, initiate three to four new Energy Frontier Research Centers (EFRCs) focused on key CDR scientific research topics. (The EFRC program currently supports 46 centers in total, with funding of about $2-4 million per year over a 3-4 year period. Early evaluation of the program suggests that this relatively new research business model has been effective in accelerating the pace of innovation in specific technology areas.)

Advanced Research Projects Agency-Energy

- Maintain established policies and procedures for R&D planning and prioritization; do not earmark CDR as a research priority, with the expectation that CDR topics will emerge over time as a priority for new research solicitations.
- Encourage ARPA-E to identify CDR opportunities for future funding opportunity announcements (FOAs), following established policies and procedures, with an expectation that ARPA-E will identify over time new CDR related R&D funding opportunities.
- Future CDR FOAs funded within ARPA-E total budget, with the assumption that Congress will consider ramping the total budget for ARPA-E to a level of $1 billion per year.

Departmental-Wide Considerations

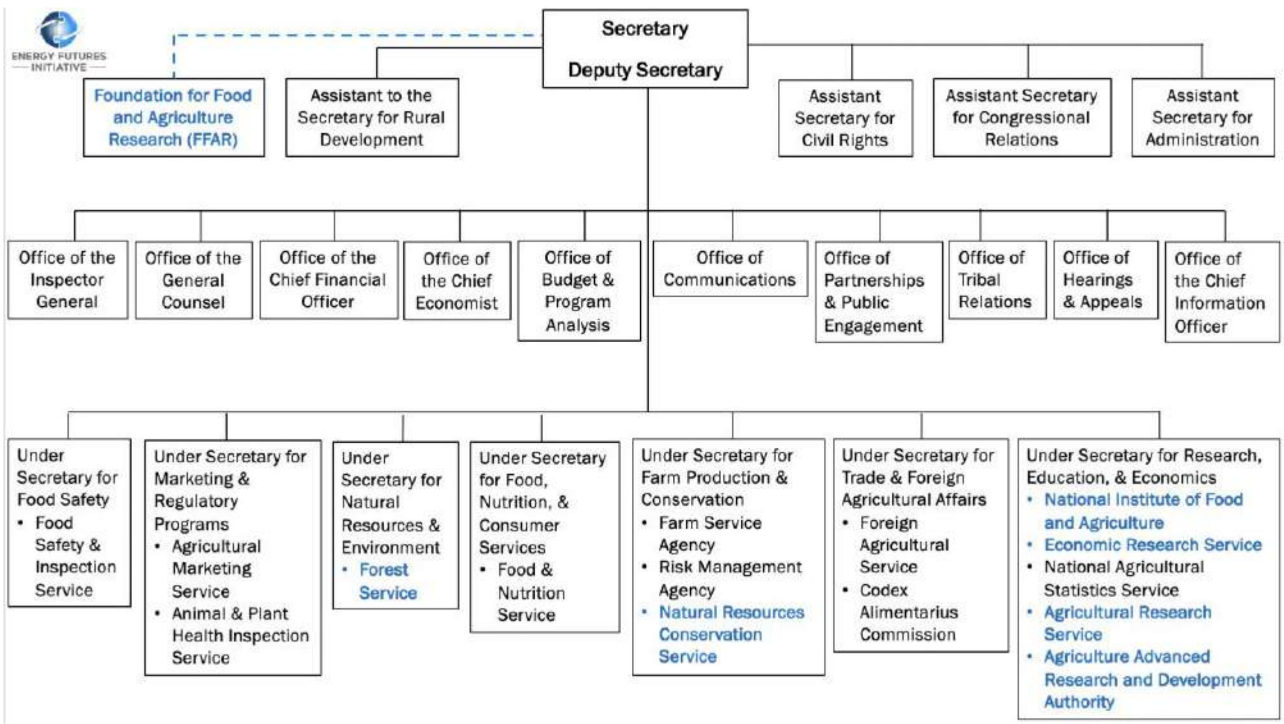
- Reinstate the Subsurface Science, Technology and Engineering Research, and Development (SubTER) initiative across multiple DOE offices and organizations to assist in applying cross-disciplinary science and technology expertise to geologic sequestration and carbon mineralization applications.

Department of Agriculture

The USDA mission involves providing leadership on issues such as agriculture, food, and natural resources,[18] which includes all aspects of research on soils, crops, forests, and other terrestrial systems. The USDA was established in 1862 and is composed of a large network of approximately 29 agencies and offices (Figure 9-9),[19] 100,000 employees, and 4,500 locations across the United States.[20] For the CDR RD&D initiative, it is recommended that USDA incorporate CDR as an explicit mission objective across all research programs and organizations to help guide strategic planning efforts, which could also help achieve co-benefits with other departmental priorities such as increasing plant yields, fertilizer productivity, and water-use efficiency.

Figure 9-9

Current USDA Organization Highlighting Offices That Could Support the CDR RD&D Initiative (Not Exhaustive)

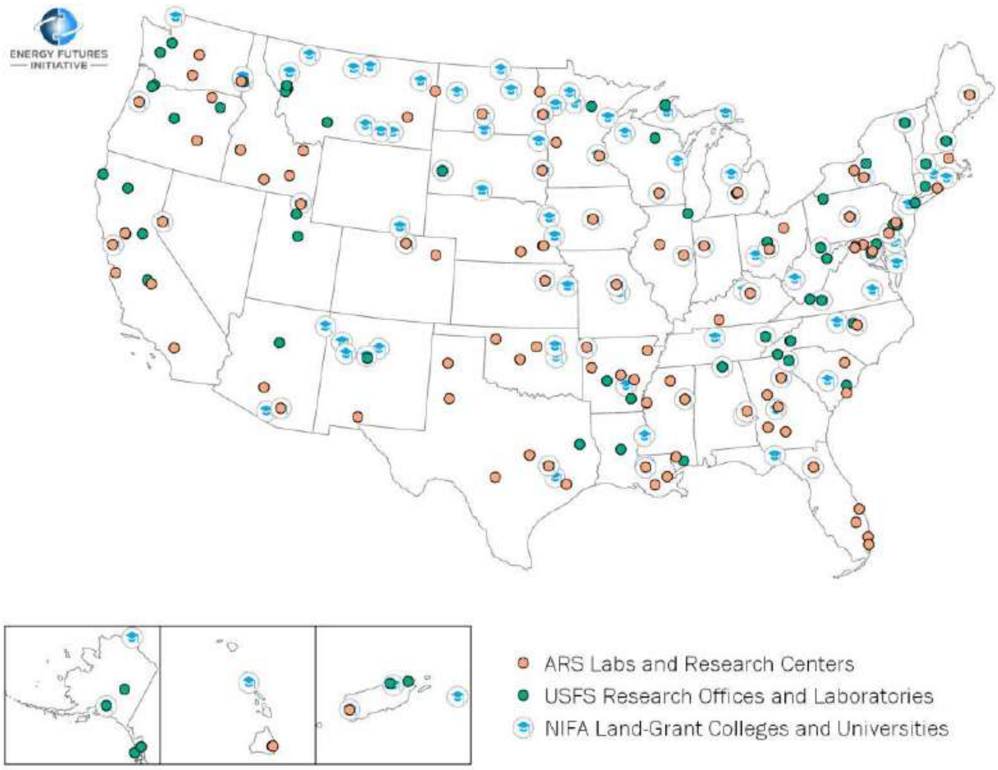


There are at least seven USDA offices and organizations that could support the CDR RD&D initiative (blue); they are managed by three separate undersecretaries. Source: EFI, 2019. Compiled using data from the Department of Agriculture.

USDA research programs are implemented through an extensive network of 93 ARS laboratories and research centers across 41 states and Puerto Rico, 78 USFS research offices and laboratories across 39 states and Puerto Rico, and 112 NIFA land-grant colleges and universities across all states and U.S. territories (Figure 9-10).[21,22,23,24] Projects have historically supported CDR-related RD&D on topics such as carbon sequestration, bioenergy production, and plant genetics (Table 9-3 and Figure 9-11).[25] The full range of the USDA research network should be engaged in the implementation of the CDR RD&D initiative to help advance terrestrial and biological CDR and CO_2 utilization.

Figure 9-10

USDA-Supported Research Infrastructure



The USDA research network spans across all U.S. states and territories. Not shown: American Samoa, Guam, Northern Marianas, Federated States of Micronesia. Note: Points may overlap and appear as one point. Source: EFI, 2019. Compiled using data from the Department of Agriculture.

Table 9-3

Agricultural Research Service National Programs That Could Support CDR RD&D

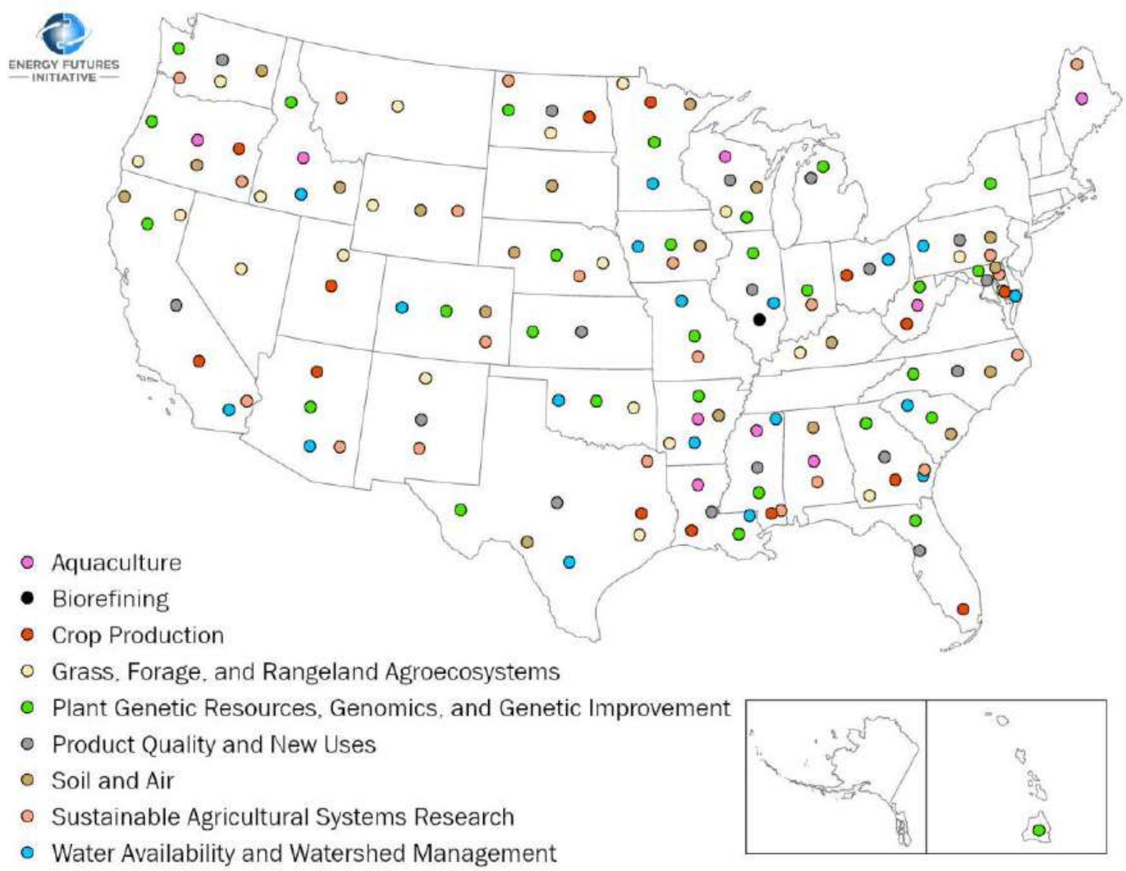
National Program	Research Scope	Number of States
Plant Genetic Resources, Genomics, and Genetic Improvement	Crop genetic improvements; crop biological and molecular processes	29
Sustainable Agricultural Systems Research	Sustainable bioenergy production methods	21
Grass, Forage, and Rangeland Agroecosystems	Ecosystem and agroecosystem restoration and conservation; land-use change; bioenergy	20
Soil and Air	Carbon management through mitigating agricultural emissions and sequestering carbon; soil resource maintenance and enhancement	19

Water Availability and Watershed Management	Degradation prevention of riparian zones and wetlands	18
Product Quality and New Uses	Biorefining; harvest and process agricultural materials; new value-added product creation	17
Crop Production	Sustainable crop production systems; crop efficiency and productivity; environmental quality	14
Aquaculture	Nutrient requirements	9
Biorefining	Agricultural feedstock conversion into fuels and other commodity products; economic opportunities for existing industrial biorefineries	1

There are at least nine ARS National Programs that could support CDR RD&D. Source: EFI, 2019. Compiled using data from the Department of Agriculture, 2019.

Figure 9-11

Agricultural Research Service National Programs That Could Support CDR RD&D



There are at least nine ARS National Programs that could support CDR RD&D, of which research is currently being conducted across 40 states. Source: EFI, 2019. Compiled using data from the Department of Agriculture.

Department of Agriculture Recommendations

Based on the analysis and findings from this report, the recommendations for USDA CDR implementation are described in Box 9-2. Several issues underlying some of these recommendations were based on a supplemental report commissioned by EFI on USDA organization and programs that could assist CDR RD&D.[26]

Box 9-2

USDA Recommendations for CDR RD&D Initiative

Departmental Mission

- USDA should incorporate technological CDR research objectives into its Departmental Strategic Plan as complementary to its food and fiber mission responsibilities.

Agriculture Advanced Research and Development Authority (AGARDA)

- USDA should implement the new Agriculture Advanced Research and Development Authority (AGARDA), with a major mission emphasis on CDR. The budget recommendations in this report assume that AGARDA is fully funded at its authorization level, with CDR RD&D activities allocated at a budget level of $100 million over the 10-year initiative.

Foundation for Food and Agriculture Research (FFAR)

- USDA should request that the Foundation for Food and Agriculture Research (FFAR) include CDR within its program scope.

Under Secretary for Research, Education, and Economics

- The Under Secretary for Research, Education, and Economics (REE) should be designated as the lead coordinator for all CDR RD&D activities within the Department. REE, which is also the Office of the Chief Scientist, should be assigned responsibility for review and advice on all USDA program office CDR RD&D budget proposals in addition to oversight and evaluation of CDR RD&D initiatives and projects. The REE office should also be the principal point of contact with Congress, EOP, and other federal agencies on all USDA CDR RD&D issues. In taking on these new responsibilities, REE should seek to pursue research strategies that build upon well-established agriculture research infrastructure as well as pursue CDR RD&D objectives through new research models.
- REE should work to incorporate CDR RD&D programs and projects within the scope of the Agricultural Research Service (ARS), U.S. Forest Service (USFS), and other existing USDA program offices, as well as the research portfolios of the land-grant colleges and universities. The budget recommendations in this report assume a combination of improved allocation of existing CDR-related research funding to formally prioritize CDR research objectives and augment CDR RD&D with increased funding (relative to historical baseline levels).
- REE should work with the semi-autonomous National Institute of Food and Agriculture (NIFA) to incorporate CDR into its research portfolio. The budget recommendations in this report assume that NIFA is fully funded at its current statutory authorization level and that roughly half of those funds would be allocated to CDR RD&D.

Departmental-Wide Considerations

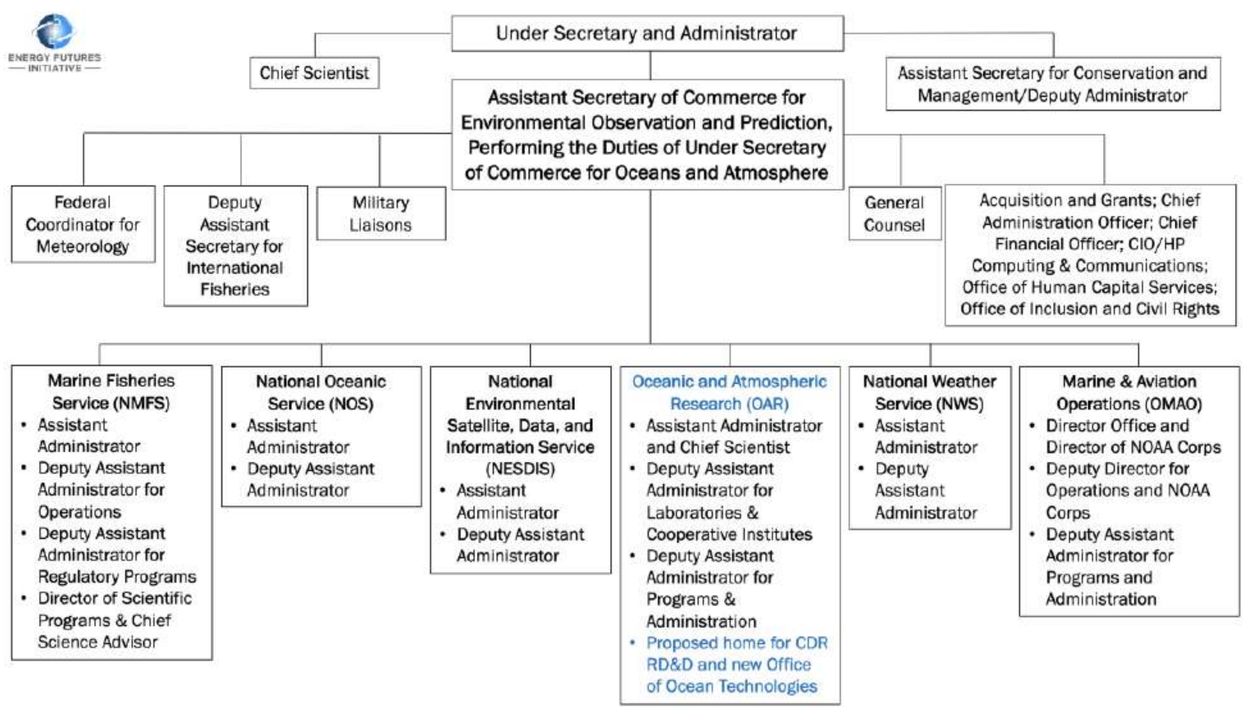
- The USDA should enter into an expanded Memorandum of Understanding (MOU) with DOE to incorporate CDR scientific objectives into current joint research on genomics and synthetic biology.

National Oceanic and Atmospheric Administration

The NOAA mission involves providing leadership on issues such as weather forecasts, climate monitoring, fisheries management, coastal restoration, and marine ecosystems.[27] NOAA (within DOC) was established in 1970[28] and is comprised of a large network of approximately 12,000 employees and 6,773 scientists and engineers around the world (Figure 9-12).[29] For the CDR RD&D initiative, it is recommended that NOAA incorporate CDR into its mission objectives to help guide strategic planning efforts and achieve co-benefits with other priorities such as coastal restoration and fisheries preservation.

Figure 9-12

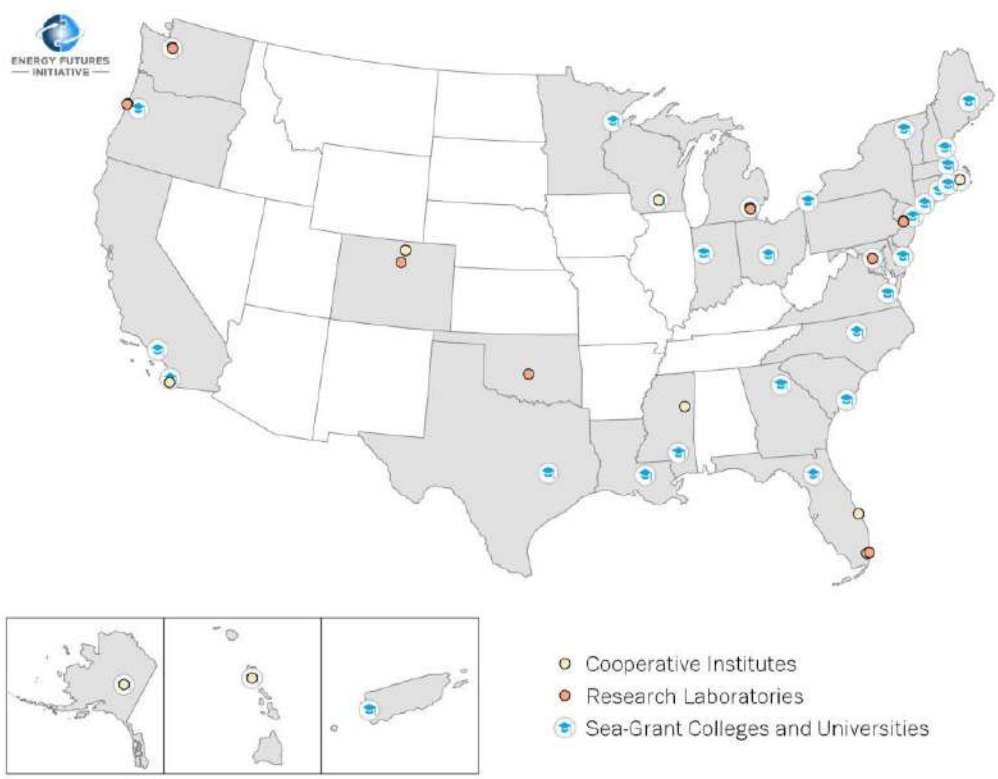
Current NOAA Organization Highlighting Offices That Could Support the CDR RD&D Initiative (Not Exhaustive)



The Office of Oceanic and Atmospheric Research is the proposed home for CDR RD&D and the establishment of a new Office of Ocean Technologies. Source: EFI, 2019. Compiled using data from the National Oceanic and Atmospheric Administration.

NOAA research programs fall under the jurisdiction of the assistant administrator for OAR, which is designated as the NOAA chief scientist. NOAA research programs are implemented through an extensive network of 16 Cooperative Institutes across 14 states, seven research laboratories (in eight sites) across eight states, and 33 colleges and universities that comprise the network of sea-grant colleges and universities across 29 states and two U.S. territories (Figure 9-13).[30,31,32] NOAA has historically supported projects on CDR-related RD&D topics such as terrestrial and oceanic carbon fluxes, carbon stocks, and atmospheric CO_2 measurements.

Figure 9-13
NOAA-Supported Research Infrastructure



The NOAA research network spans across 31 states and two U.S. territories. Not shown: Guam. Note: Points may overlap and appear as one point. Source: EFI, 2019. Compiled using data from the National Oceanic and Atmospheric Administration.

National Oceanic and Atmospheric Administration Recommendations

Based on the analysis and findings from this report, the recommendations for NOAA CDR implementation are described in Box 9-3.

Box 9-3

NOAA Recommendations for CDR RD&D Initiative

Strategic Mission Objective

- CDR scientific objectives should be incorporated into the NOAA mission responsibilities for oceans and coastal area programs, which could be implemented by incorporating CDR RD&D programs and projects into the NOAA R&D plan.

Office of Ocean Technologies

- NOAA should establish a new Office of Ocean Technologies that would report to the Assistant Administrator for Oceanic and Atmospheric Research (OAR). The new office should be responsible for CDR RD&D on technologically-enhanced ocean carbon capture, conversion, and storage. This would include carefully designed, limited-scope field experiments on ocean pH modification, ocean fertilization, and aquatic biomass harvesting and conversion.
- The new office should seek to utilize the ocean research assets of NOAA, the National Science Foundation (NSF), and the U.S. Coast Guard in implementing research projects, and could become the locus for other oceans-related technology development research.
- The Assistant Administrator for OAR should exercise oversight of these programs to coordinate with appropriate international entities and ensure compliance with all current international agreements (including voluntary compliance with agreements where the U.S. is not an official signatory) and also seek joint sponsorship for experiments.
- Existing ocean acidification monitoring and data collection programs should be integrated into the technological CDR RD&D research portfolio of the new office, and existing ocean acidification program plans should be modified to incorporate CDR research objectives.

Coastal Ecosystem Restoration

- CDR RD&D on blue carbon should be incorporated into the existing NOAA programs for supporting research and field work on regional coastal ecosystems. The budget recommendations in this report assume that some existing CDR-related research funding can be more directly focused on CDR scientific objectives, with some augmentation of funding through increased funds above historical baseline budgets.

Interagency Coordination

The recommended CDR RD&D initiative portfolio targets expanded and new programs in 10 agencies; other agencies may also support more limited CDR-related RD&D efforts, in addition to interagency coordination facilitated through OSTP and OMB (Figure 9-14). A centralized process will be essential to maximize the effectiveness of this whole-of-government approach. To be effective, the coordination process will need to cover the full span of RD&D strategic planning, priority setting, coordination of multiagency research projects, program evaluation, and reporting to Congress and the general public.

An immediate important issue will be to establish coordination policies and procedures. The recommendations below are drawn from best practices identified from a detailed assessment of past federal multiagency R&D initiatives including BRAIN, Human Genome Project (HGP), Interagency Arctic Research Policy Committee (IARPC), NNI, NITRD, Partnership for a New Generation of Vehicles (PNGV), and the U.S. Global Change Research Program (USGCRP). Best practices were identified through a survey of lessons learned by experts involved in the implementation of these prior R&D initiatives.

Figure 9-14
Federal Participation in CDR RD&D Initiative

Federal participation in the CDR RD&D initiative includes 10 agencies and the EOP. Source: EFI, 2019.

Based on this assessment, there are several clear and compelling lessons learned that form the framework for the recommended interagency coordination process. In particular, the experience of past interagency R&D initiatives highlights the critical role of EOP—specifically OSTP and OMB. The interagency coordination recommendations are framed on the basis of OSTP and OMB roles and responsibilities and are described in Box 9-4.

Box 9-4
Interagency Coordination Recommendations for CDR RD&D Initiative

Office of the President
- It is recommended that the President issue an Executive Order to initiate the proposed technological CDR RD&D initiative. The Executive Order would establish goals and objectives, organization, and procedures that reflect the recommendations in this report.

Congress
- It is recommended that Congress consider comprehensive authorization legislation that would codify the major elements of the proposed CDR RD&D initiative. The legislation also could provide multi-year authorizations to guide future appropriations. Congress may wish to consider additional options to expand the scope of the recommendations, such as establishment of a quasi-governmental entity to manage the program and establishment of a dedicated funding source.

Office of Science and Technology Policy
- Formation of a Committee on Large-Scale Carbon Management under the auspices of the National Science and Technology Council (NSTC). The Committee would have an Executive Committee of multiple co-chairs, including the Associate Director of OSTP for Science, the

DOE Under Secretary for Science and Energy, the USDA Under Secretary for Research, Economics and Education, and the DOC Under Secretary for Oceans and Atmosphere.

- The Task Force would be supported by a small full-time secretariat comprised of staff drawn on term assignments from the principal CDR RD&D agencies.
- The Task Force would be empowered through an Executive Order to undertake the following functions: (1) develop and update a government-wide CDR RD&D strategic plan, (2) oversee implementation of the CDR RD&D strategic plan through integration of the plan elements into individual agency programs and budgets, (3) support an annual CDR RD&D budget crosscut as part of the formulation of the President's budget, (4) develop and issue an annual report on the government-wide CDR RD&D initiative implementation and accomplishments, (5) oversee a periodic (e.g., every 3-5 years) independent evaluation of the CDR RD&D initiative performance, to be conducted by an appropriate organization (potentially NASEM), and (6) identify candidate CDR technologies for large-scale demonstration projects.

Office of Management and Budget

- The Executive Order for the CDR RD&D initiative should direct OMB to conduct an annual budget crosscut of CDR RD&D budget proposals as part of the President's budget formulation process. The crosscut would be implemented under a formal Terms of Reference that would specify the roles and responsibilities of the agencies, the CDR RD&D Task Force, and OMB in developing, reviewing, prioritizing, and setting funding levels for CDR RD&D initiative activities consistent with the strategic program plan. The Terms of Reference established in the early years of USGCRP would serve as the model for this effort. Finally, OMB would publish the results of the budget crosscut in supporting documents for the President's budget.

General

- To further assist with interagency coordination efforts, periodic workshops could be convened under the auspices of the committee to help organize, manage, and implement the CDR RD&D initiative.

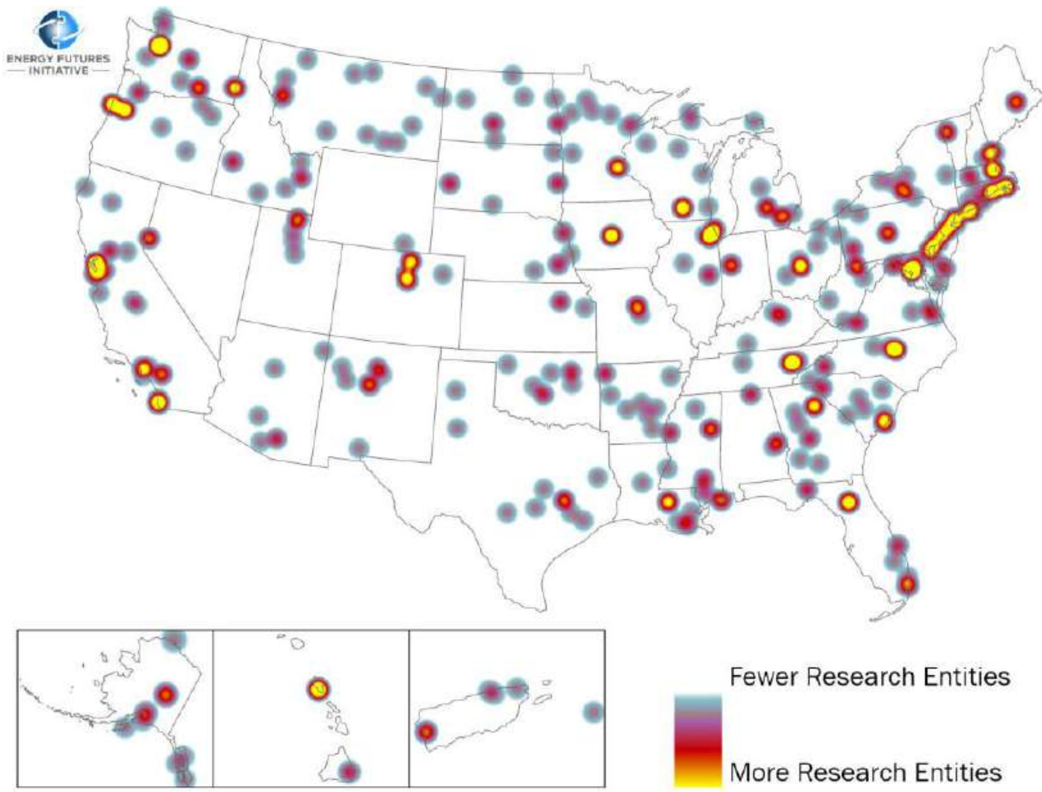
Opportunities to Leverage Existing Federal Research Infrastructure to Support a New CDR RD&D Initiative

The federal government has extensive RD&D capabilities across numerous agencies and research areas. Although most of this research infrastructure has not previously supported CDR-related RD&D, a sizeable portion could be leveraged to support the goal and objectives of the proposed CDR RD&D initiative and could also receive new funding. Research infrastructure that could factor prominently into the CDR RD&D initiative include those supported by DOE (Table 9-4), USDA (Table 9-5), and NOAA (Table 9-6), which collectively span across all 50 states and most U.S. territories (Figure 9-15).[a]

[a] Data include research locations from DOE (EFRCs, Energy Innovation Hubs, Manufacturing Institutes, National Laboratories), USDA (ARS labs and research centers, land-grant colleges and universities, USFS research offices and laboratories), and NOAA (Cooperative Institutes, research laboratories, sea-grant colleges and universities). Federal maritime vessels across DOD (Coast Guard and Navy), EPA, NOAA, and NSF are also included according to their home port. Excludes colleges and universities not affiliated with land-grant and sea-grant programs and private sector entities.

Figure 9-15

DOE, USDA, and NOAA Research Infrastructure and Federal Maritime Vessels to Support CDR RD&D Initiative



There is a large research network throughout the U.S. and its territories that could support CDR RD&D. Not shown: American Samoa, Guam, Northern Marianas, Federated States of Micronesia. Source: EFI, 2019. Compiled using data from Department of Energy, Department of Agriculture, and National Oceanic and Atmospheric Administration.

Department of Energy. DOE is the lead federal agency supporting RD&D on climate change mitigation technologies. DOE implements its RD&D programs primarily through its network of National Laboratories. DOE has also supported new RD&D institutional arrangements such as Energy Frontier Research Centers (EFRCs), Energy Innovation Hubs, and Manufacturing Institutes. Given its expansive research network and competencies in managing RD&D, DOE will be a lead agency in the CDR RD&D initiative across several capture technology pathways, CO_2 disposition pathways, and cross-cutting programs.

Table 9-4
DOE-Supported Research Infrastructure

Type	Description	No. Sites	No. States
National Laboratories	National Laboratories serve as leading institutions for scientific innovation and technological development across numerous disciplines, and contain world-class instrumentation and research capabilities.[33,34]	17	15
Energy Frontier Research Centers (EFRCs)	Started in 2009 through the Office of Basic Energy Sciences within the Office of Science to address a range of scientific challenges related to the advancement of energy technologies.[35] Some EFRCs are housed at National Laboratories.[36]	46	22
Energy Innovation Hubs	Started in 2010 and modeled after the management characteristics of AT&T Bell Laboratories. These multidisciplinary research centers focus on single national issues that are of critical importance to DOE through a combination of fundamental and applied R&D and engineering.[37,38]	4	4
National Network for Manufacturing Innovation (NNMI)	NNMI is an interagency initiative that consists of a network of Manufacturing Institutes that help advance manufacturing technologies with broad applications.[39]	14	11

Source: EFI, 2019.

Department of Agriculture. USDA conducts RD&D relevant to CDR including topics such as carbon sequestration, bioenergy, forestry, soil management, and plant genetics.[40] This research is carried out through multiple entities throughout the USDA network including Agricultural Research Service (ARS) laboratories and research centers, National Institute of Food and Agriculture (NIFA) land-grant colleges and universities, and U.S. Forest Service (USFS) research offices and laboratories. ARS specifically conducts research according to 16 National Programs, of which at least nine could support RD&D related to CDR.[41] This existing research network could play a critical role in terrestrial and biological CDR and CO_2 utilization RD&D.

Table 9-5
USDA-Supported Research Infrastructure

Type	Description	No. Sites	No. States
Agricultural Research Service (ARS) Labs and Research Centers	ARS is the primary scientific research entity within USDA and consists of 2,000 scientists and post-doctoral students, 6,000 additional employees, nearly 700 research projects, and an annual fiscal year budget of $1.2 billion.[42]	93	41
National Institute of Food and Agriculture	The Land-Grant University System (LGU) collaborates with NIFA to address pressing issues at the	112	50

(NIFA) Land-Grant Colleges and Universities	intersection of agriculture, food, and the environment.[43]		
U.S. Forest Service (USFS) Research Offices and Laboratories	USFS R&D is focused on the sustainable management of natural resources,[44] and is organized according to five priority areas: biomass and bioenergy; climate change; nanotechnology; urban natural resources stewardship; and watershed management and restoration.[45]	78	39
Source: EFI, 2019.			

National Oceanic and Atmospheric Administration. NOAA performs research related to CDR including the monitoring and data collection of carbon fluxes between the atmosphere, oceans, and terrestrial biosphere. Research is conducted across several entities including Cooperative Institutes, research laboratories, and sea-grant colleges and universities. This existing research network could play a critical role in coastal and oceans CDR RD&D.

Table 9-6
NOAA-Supported Research Infrastructure

Type	Description	No. Sites	No. States
Cooperative Institutes	Combination of 42 academic institutions and non-profit entities that conduct research specific to NOAA's mission goals and strategic plan through 16 Cooperative Institutes.[46]	16	14
Research Laboratories	Housed within the Office of Oceanic and Atmospheric Research, some of which are co-located with Cooperative Institutes. These laboratories are focused on research and technology development to better understand the atmosphere, oceans, and inland waterways.[47]	7	8
Sea-Grant Colleges and Universities	National Sea Grant College program was established in 1966 and consists of partnerships between NOAA and university-based programs,[48] with a mission to manage and conserve coastal, marine, and Great Lakes resources.[49]	33	29
Source: EFI, 2019.			

Proposed CDR RD&D Initiative Schedule

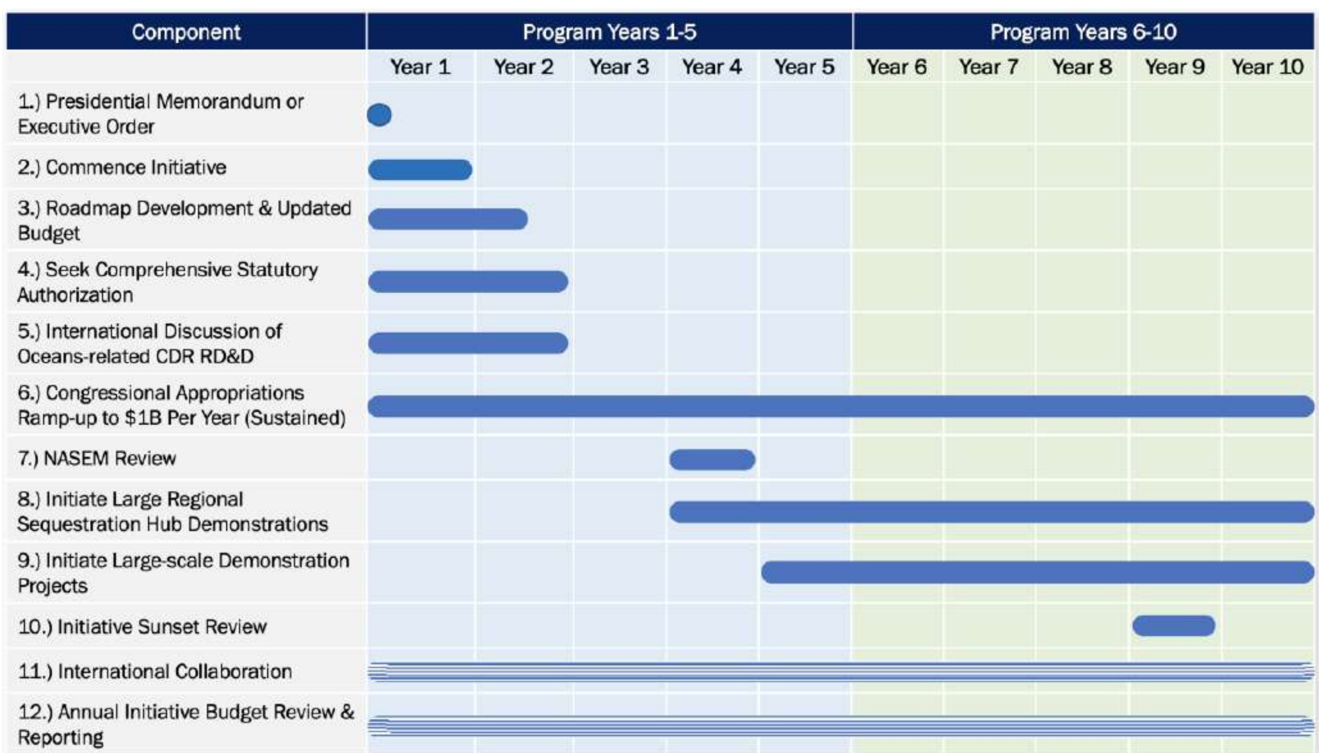
A proposed schedule of major components and milestones for the CDR RD&D initiative is shown in Figure 9-16 and includes:

1. Presidential Memorandum or Executive Order to launch the CDR RD&D initiative;
2. Commencement of the CDR RD&D initiative;
3. Detailed road-mapping exercise for each of the technology pathways and CO_2 management programs to determine specific programmatic goals for the RD&D portfolio and initial review of the CDR RD&D budget;

4. Dedicated effort to secure comprehensive statutory authorization for the entire CDR RD&D initiative;
5. International dialogue and collaboration to make strategic recommendations for coastal and oceans CDR RD&D;
6. Proposed CDR RD&D initiative funding that reaches a sustained level of more than $1 billion per year in Year Four through congressional appropriations;
7. NASEM evaluation of early research, which provides recommendations for mid-course corrections and feasibility of scale-up demonstration program;
8. Initiation of large-scale regional geologic sequestration hubs in Year 4;
9. Initiation of large-scale demonstration projects in Year 5;
10. NASEM evaluation of whether the program should continue or sunset;
11. Ongoing international collaboration to maximize CDR RD&D initiative effectiveness; and
12. Annual budget reviews throughout the duration of the CDR RD&D initiative.

Figure 9-16

Proposed CDR RD&D Initiative Schedule



These are the major components and milestones of the CDR RD&D initiative. Source: EFI, 2019.

1 https://www.nap.edu/catalog/25259/negative-emissions-technologies-and-reliable-sequestration-a-research-agenda
2 https://fas.org/sgp/crs/misc/R45150.pdf
3 https://www.globalchange.gov/about/budget
4 https://www.nano.gov/about-nni/what/funding
5 https://obamawhitehouse.archives.gov/sites/whitehouse.gov/files/documents/BRAIN%20Initiative%20FY17%20Fact%20Sheet.pdf
6 https://www.energy.gov/about-us
7 https://www.energy.gov/about-us
8 https://www.energy.gov/leadership/organization-chart
9 https://www.energy.gov/subsurface-science-technology-engineering-and-rd-crosscut-subter
10 https://www.energy.gov/science-innovation/innovation/hubs
11 https://www.energy.gov/maps/doe-national-laboratories
12 https://www.manufacturingusa.com/institutes
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16 https://www.energy.gov/sites/prod/files/2019/03/f60/doe-fy2020-budget-in-brief_0.pdf
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21 https://nifa.usda.gov/land-grant-colleges-and-universities-partner-website-directory?state=All&type=All
22 https://nifa.usda.gov/sites/default/files/resource/LGU-Map-03-18-19.pdf
23 https://www.fs.fed.us/research/locations/
24 https://www.ars.usda.gov/people-locations/find-a-location/
25 https://www.ars.usda.gov/research/programs/
26 Sanchez, DL & Jacobson, R. (2019). Present and Potential Research, Development and Demonstration Opportunities for Carbon Dioxide Removal within the United States Department of Agriculture. To be published on EFI website.
27 https://www.noaa.gov/about-our-agency
28 https://www.noaa.gov/our-history
29 https://www.noaa.gov/about-our-agency
30 https://ci.noaa.gov/Locations.aspx
31 https://ci.noaa.gov/NOAAResearchLaboratories.aspx
32 https://seagrant.noaa.gov
33 https://www.energy.gov/national-laboratories
34 https://www.energy.gov/science/science-innovation/office-science-national-laboratories
35 https://science.osti.gov/bes/efrc
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39 https://www.energy.gov/eere/amo/national-network-manufacturing-innovation
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43 https://nifa.usda.gov/land-grant-colleges-and-universities
44 https://www.fs.fed.us/research/research-topics/
45 https://www.fs.fed.us/research/priority-areas/
46 https://ci.noaa.gov
47 https://research.noaa.gov/Labs-Programs/OAR-Labs
48 https://seagrant.noaa.gov/About
49 https://seagrant.noaa.gov

CHAPTER 10. INTERNATIONAL COLLABORATION

The Need for International Collaboration on Carbon Dioxide Removal

An important component of a comprehensive federal research agenda for technological CDR will be a strategy for international collaboration. Climate change is a global challenge, and the scale of CDR needed to meet that challenge—100 to 1,000 $GtCO_2$ on a global level cumulatively by 2100 according to the IPCC[1]--is more than one country can feasibly address within its own borders. Additionally, CDR pathways typically have few geographic requirements and can be carried out in nearly any country; pathways such as DAC and soil carbon sequestration would be suitable for any country on Earth. Coordinating the effort is also important because innovation in CDR technologies and approaches could be accomplished more effectively and rapidly if countries create durable RD&D collaborative frameworks that facilitate pooling of both scientific and monetary resources.

There are also facets of CDR that will specifically require international collaboration because they could have legal and regulatory impacts that cross borders. Several CDR pathways involve practices that are already governed by international law, including ocean fertilization[a] or biological sequestration with genetically modified organisms[b]. Other pathways pose issues that are common to any country contemplating deployment of geologic sequestration. These include technical issues such as induced seismicity as well as legal and regulatory issues such as monitoring, reporting, and verification (MRV) for sequestered carbon. Common legal and regulatory frameworks around these issues, built upon a shared understanding of the science and technology base, will be essential to ensure effective deployment of CDR on a gigaton scale globally.

Management of Intellectual Property

Another important component of building durable international collaboration efforts is establishing rules for the protection of IP. Safeguarding U.S. IP is crucial to stimulating innovation around CDR; without those protections, the economic motivation for innovation could be diminished. Stimulating international coordination on CDR while protecting U.S. IP interests could spur new markets for U.S. firms, enhancing U.S. economic competitiveness. At the same time, knowledge-sharing across international borders is important to global deployment of CDR methods. The federal agencies and offices participating in the CDR RD&D initiative need to determine procedures that will protect the IP of CDR RD&D performers while also facilitating the deployment of successful CDR technologies in other countries.

[a] The 1972 London Convention and 1996 Protocol to the London Convention. The U.S. ratified the London Convention in 1974; the U.S. signed the London Protocol in 1998 but has not ratified it. The U.S. actively participates in meetings of the London Convention and London Protocol Scientific Groups.

[b] The Cartagena Protocol on Biosafety to the Convention on Biological Diversity. The U.S. signed the Convention in 1993, but it has not been ratified. The U.S. has not signed the Cartagena Protocol.

There are also other IP concerns that need to be addressed for CDR related to the sharing of costs and benefits. These include free rider concerns that are similar to those involving other mitigation efforts (where other countries benefit from CDR occurring in the United States without investing any resources themselves) and protecting the IP of inventors who receive public funding while also providing returns to taxpayers. The questions around IP are too extensive to be answered here; it is, however, important that they be addressed by the proposed CDR RD&D initiative (see the recommendations section at the end of this chapter) and discussed in the appropriate international fora.

This chapter provides perspectives on international CDR collaboration in three parts. The first section provides information about current CDR RD&D outside the United States. The second section profiles relevant models of successful international scientific collaboration. The third section provides going-forward recommendations.

Overview of Current International Carbon Dioxide Removal Efforts

There is significant CDR innovation occurring around the world, often supported through public-private partnerships supported by foreign national governments. Detailed information on the scope of supporting CDR RD&D and levels of investment are less transparent. A review of the current demonstration and commercialization activity, however, illustrates the level of foreign government and science and technology community interest in CDR.

CDR R&D and deployment is a constantly shifting and evolving space. Information presented here is current as of June 2019.

Direct Air Capture

There are at least 10 DAC projects currently underway in Canada or Europe (Table 10-1), with one additional project in the United States.[2] These companies' DAC technologies differ in terms of the specific design and the chemical process used for removing CO_2 from air, but all draw on the basic processes described in Chapter 2.

Table 10-1
International DAC Projects

Project (DAC Provider)	Location	Project Partners	Description
Antecy	Netherlands	EU, European Regional Development Fund, Wageningen University, Mitsubishi Hitachi Power Systems	Antecy, founded by cleantech entrepreneur Paul O'Connor, is developing a pilot DAC plant to demonstrate its technology. Antecy says its adsorbent can be used for concentrated CO_2 sources in addition to dilute ones.
CarbFix2 (Climeworks)	Iceland	EU, Reykjavik Energy, French government, University of Iceland,	Testing is currently underway for a project that combines Climeworks' DAC module with CarbFix's technology for in situ carbon mineralization in basalt.

		AMPHOS 21 Consulting	
Carbon Engineering	Canada	Funding from governments of Canada and U.S. and provinces of British Columbia and Alberta. Equity investments from Bill Gates, BHP, Chevron, Occidental Petroleum, and others.	Carbon Engineering grew out of research projects at the University of Calgary and Carnegie Mellon University. In 2015, the company built a pilot plant that captures CO_2 from the atmosphere as well as from the natural gas combustion that fuels the plant. In 2017, a demonstration-scale fuel synthesis plant was built to test the company's fuel conversion process.
CELBICON (Climeworks)	Italy	Polytechnic University of Turin leads a consortium of 13 partners. Funded by the Swiss government and EU.	CELBICON is a project funded by the EU Horizon aimed at making cost-effective chemicals from electrochemical and biochemical conversion of CO_2. Climeworks' DAC systems provide the CO_2.
Climeworks Pilot Plant	Switzerland	EU, Swiss government, Audi	Climeworks built its first DAC pilot plant in Switzerland in 2017. It provides captured CO_2 to a nearby greenhouse and uses waste heat from an incinerator facility for energy.
Kopernikus (Climeworks)	Germany	Coalition led by RWTH Aachen University, Research Centre Julich, and Karlsruhe Institute of Technology	Kopernikus is a project aimed at synthesizing artificial petroleum from CO_2, water, and renewable energy. Climeworks' DAC systems provide the CO_2.
Nordic Blue Crude (Climeworks)	Norway	Four additional technical partners. Funders include Audi, Statkraft, and the EU.	A consortium of companies intends to use Climeworks' DAC technology at an existing Norwegian industrial cluster for an air-to-fuel process.
Skytree	Netherlands	Funders include the Dutch government and European Space Agency (ESA).	Skytree is a spin-off company from ESA, working on commercializing the Advanced Closed Loop System technology developed for the International Space Station. Skytree's technology captures water vapor in addition to CO_2. The terrestrial translation of the technology has yet to be constructed.
Soletair (Hydrocell)	Finland	Project managed by Lappeenranta-Lahti University of Technology and VTT	Hydrocell is a cleantech company that has previously developed products such as a heat recovery system and a methanol fuel cell. Its DAC technology is being used in a

		Technical Research Centre and primarily funded by the Finnish government; seven additional partners.	collaborative innovation project called Soletair, which has developed a pilot plant that involves an air-to-fuel process with a Mobile Synthesis Unit.
STORE&GO (Climeworks)	Italy	Eight additional technical partners. Funded by the Swiss government and EU.	STORE&GO is a European project focused on hydrogen storage and methanation, with three test sites in three different countries. The Italian test site combines an existing solar-powered electrolysis facility with Climeworks' DAC technology to produce methane.
Source: EFI, 2019. Compiled using data from Third Way, 2018; Geoengineering Monitor, 2019; Air Miners, 2019; and company and project websites.			

Most of the DAC projects plan to create economic value from the captured CO_2 through various utilization pathways and technologies (see Chapter 7, as well as the section later in this chapter on Carbon Dioxide Utilization, for more on these pathways). Many of these projects use an air-to-fuel process that reacts the captured CO_2 with hydrogen produced from electrolysis (often with renewable electricity) in order to create drop-in liquid fuels (Nordic Blue Crude, Carbon Engineering, Soletair),[3,4] natural gas (STORE&GO),[5] or petrochemicals and commercial products (Soletair).[6] Skytree is working on a process involving electro-biocatalytic conversion of CO_2 to methanol.[7] Another utilization option—mentioned by Skytree and Antecy[8] and used by Climeworks' demonstration plant in Switzerland[9]--is to use DAC as a source of CO_2 for specialized applications such as photosynthesis in greenhouse agriculture. Climeworks' partner for the Iceland project, CarbFix, has a process for geochemical sequestration that it intends to pair with DAC.[10]

Most of these projects have some government funding in addition to backing from universities and private industry. The projects described above have received funding from national and subnational governments in countries where the projects are located, as well as from the DOE, ESA, and various grant programs of the EU.[11]

Terrestrial and Biological Carbon Dioxide Removal

Terrestrial and biological CDR is advancing at a rapid pace and substantial scale around the world. For example, one source lists 101 active or completed projects outside the United States that are researching or deploying biochar for soil carbon sequestration, which is just one pathway for terrestrial CDR,[12] while other groups are focusing on the role of croplands for greater soil carbon sequestration.[13] These projects alone are occurring in more than 50 countries across all six inhabited continents. Many of these projects have support from government sources, including domestic governments, international organizations, and foreign-aid sources.[14]

Another biological CDR approach that is receiving significant interest globally is BECCS. Projects in the demonstration or deployment phase with BECCS are listed in Table 10-2. About half are in Europe, with the remainder in Canada, Japan, and Saudi Arabia.

Additional projects are being considered in Brazil, France, Norway, Sweden, and the UK.[15] Companies based outside the United States are also looking for opportunities for deployment in America; the Swedish company Biorecro, for example, has provided technology to several BECCS projects in the United States.[16]

Existing BECCS projects have involved biofuel and chemical production, biomass combustion, and waste incineration facilities (the latter are considered BECCS since a significant component of waste incineration emissions come from organic matter). Future projects include pulp and paper mills, gasification plants, and biogas plants.[17] All of the BECCS projects to date outside the United States have been retrofits of existing energy projects rather than new builds. As with DAC and biochar, the existing BECCS projects have focused on utilizing captured CO_2 for applications of economic value. There are, however, a number of projects in development that plan to geologically sequester their carbon.[18]

Table 10-2
International BECCS Projects

Primary Sponsor	Location	Project Partners	Description
Alco Bio Fuel	Belgium	ASCO CO_2, IJsfabriek Strombeek, Messer	Alco Bio Fuel is an ethanol biorefinery run as a joint venture of ethanol producer Alcogroup and three agriproduct suppliers. Since 2016, the plant has had a carbon capture system, installed by Swiss company ASCO CO_2. The captured CO_2 is used by a pair of industrial gas companies.
Cargill	United Kingdom	BOC Group	Cargill is a U.S.-based agribusiness company. Its ethanol plant in Manchester, UK, installed a CO_2 capture and purification system in 2017. The project is a joint operation with BOC Group, the UK's largest industrial and specialty gas provider. The CO_2 from the plant is converted into food-grade so it can be used in food and beverages. The Manchester plant does not currently produce ethanol for fuel, but the possibility of producing biofuels has been discussed.
Drax Group	United Kingdom	C-Capture, UK government	Drax, an electric power company, commissioned a pilot project (ongoing as of 2019) to add carbon capture to its biomass power plant, the largest power station in the UK. The plant previously was coal-fired until it was converted to use wood pellets in 2012. Carbon capture technology comes from C-Capture, a spin-off company from the University of Leeds, which has received funding from the UK government. It is unclear if there is any sequestration or utilization as part of the pilot project.

Husky Energy	Canada	Governments of Canada, Saskatchewan, and Alberta, plus additional private sector sponsors	Husky, an oil and gas company, retrofitted an ethanol plant with carbon capture technology in 2012. The captured CO_2 from the plant is used for EOR at other Husky facilities.
Lantmännen	Sweden	N/A	Lantmännen, an agricultural cooperative, has implemented CCUS at its ethanol refinery, the largest in the Nordic region. As part of its collaborative sustainability efforts at the Eco-Industrial Park in Norrköping, the plant's waste CO_2 is sent to a company called Norlic that converts it to food-grade and sells it.
Norcem	Norway	Government of Norway	Norcem, a major Norwegian cement manufacturer, retrofitted its Brevik plant to be fueled by a combination of coal and biomass. Gassnova, a state-owned energy company, funded a small-scale project testing carbon capture at the facility. Though the pilot project lacked an option for sequestration or utilization, an expanded project could include geologic sequestration in the North Sea.
Rotterdam Climate Initiative (RCI)	Netherlands	City of Rotterdam, Port of Rotterdam, DCMR (regional environmental protection agency), Deltalinqs, Abengoa, Shell	RCI is a collaboration among stakeholders at the Port of Rotterdam to reduce emissions. Its Organic Carbon Dioxide for Assimilation of Plants (OCAP) project has been utilizing captured carbon for greenhouses since 2011. Some of the CO_2 in the project is captured from fossil sources. The BECCS component is from an ethanol plant owned by Abengoa, a Spanish energy technology company. OCAP is looking to add more CO_2 sources in the future.
Saudi Basic Industries (SABIC)	Saudi Arabia	N/A	SABIC is a multiproduct manufacturing company whose majority owner is Saudi Aramco. In 2013, it hired German firm Linde to add carbon capture to two of its ethylene glycol plants. The captured CO_2 is transported by pipeline to other SABIC facilities to be used in methanol and fertilizer production.
Toshiba (Mikawa power plant)	Japan	Mizuho Information & Research Institute	Toshiba's Mikawa power plant (which runs on both coal and biomass) has had pilot-scale carbon capture since 2009. Toshiba and its partners have plans to scale-up capture to the remainder of the facility; a utilization or sequestration option has yet to be identified.
Toshiba (Saga City waste plant)	Japan	N/A	Toshiba retrofitted Saga City's municipal waste incineration plant with carbon capture in 2016.

			Captured CO_2 goes into agriculture, algae cultures, and other utilization options.
Twence	Netherlands	N/A	Twence, a waste-processing company that focuses on green solutions, has contracted Aker Solutions to install carbon capture on its waste-to-energy plant. Twence previously demonstrated carbon capture from its plant for CO_2 utilization (CO_2U) in sodium bicarbonate production.
This table only includes projects that are in the pilot testing, demonstration, or deployment phases.; it excludes projects in earlier stages of development. Source: EFI, 2019. Compiled using data from Third Way, 2018; Geoengineering Monitor, 2019; Carbon Sequestration Leadership Forum, 2018; Global CCS Institute, 2019; and company and project websites.			

Coastal and Deep Oceans Carbon Dioxide Removal

The main ocean CDR strategy emphasized by NASEM is coastal blue carbon.[19] On the international scene, there have been efforts to develop CDR pathways for deep oceans capture and conversion as well as coastal blue carbon. Projects that focus specifically on coastal blue carbon are concentrated in parts of the world where the relevant ecosystems are widespread, such as Central America, sub-Saharan Africa, South Asia, Southeast Asia, and Australia (Figure 10-1).[20] The UN Environment Programme-sponsored Blue Carbon Portal lists 33 projects, but it is likely not a comprehensive survey of the efforts on coastal blue carbon.[21]

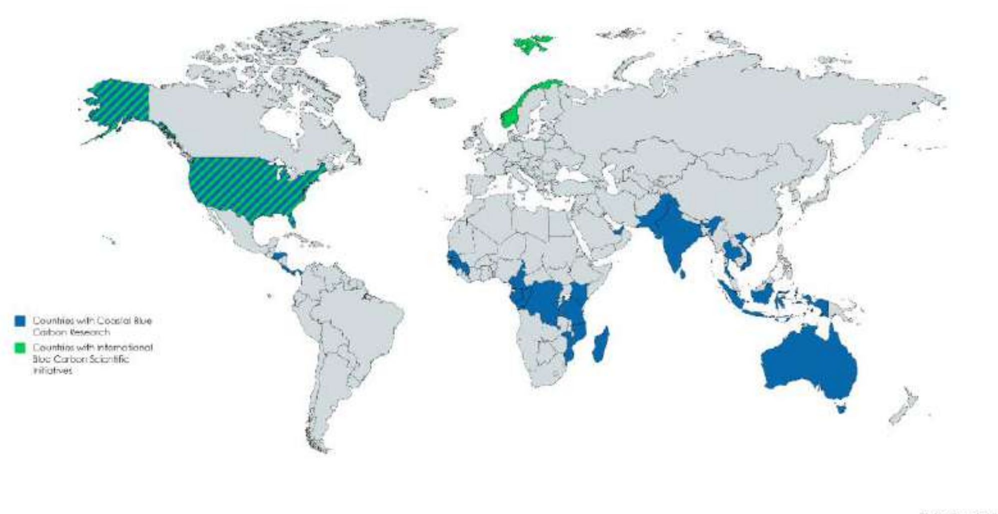
Current coastal blue carbon research takes a variety of approaches and addresses a broad set of scientific objectives in addition to CDR. Examples of these research approaches include:

- **Measuring Historical Carbon Removal:** Gulf of Nicoya Blue Carbon Stock Assessment in Costa Rica.[22] This project, from the Tropical Agricultural Research and Higher Education Center, has tracked changes in mangrove cover and carbon stocks since 1954.
- **Current Evolution of Coastal Ecosystems:** Sustainable Wetlands Adaptation and Mitigation Program (SWAMP) in Indonesia, sponsored by CGIAR (formerly the Consultative Group for International Agricultural Research) and USFS.[23] This project is examining how mangrove forests adapt to sea-level rise.
- **Innovative Ecosystem Restoration:** The government-sponsored Tomago Wetland Restoration Project in Australia. It involves reintroducing tidal waters to floodplains that were cut off from tides in the 1950s and 1960s.[24]
- **Economic Co-Benefits of Coastal CDR:** The Income for Coastal Communities for Mangrove Protection, an internationally funded initiative seeking to enable sustainable development by providing funding to local coastal communities in multiple countries in South and Southeast Asia.[25] Two multi-country projects in Central Africa[26] (funded by the UN) and East Africa[27] (funded by the World Wildlife Fund and the U.S. government) are seeking to study the economic value of mangrove

ecosystems in order to allow those countries to properly appraise those ecosystems in carbon reduction and reforestation efforts.

- **Cross-Border Collaboration on Coastal Blue Carbon:** The Canary Current Large Marine Ecosystem Mangrove Project in West Africa, sponsored by the UN and others. It seeks to create a multi-country agreement and plan for mangrove ecosystem management.[28]

Figure 10-1
Coastal (Blue Carbon) Research and Scientific Initiatives



There are coastal (blue carbon) research and scientific initiatives across several continents. Source: EFI, 2019. Compiled using data from Keeling et al., the Scripps Institution of Oceanography, 2019.

The scientific information being generated by these projects will form a firm foundation for further efforts to assess CDR pathways and carbon storage potential.

International research on CDR research also is addressing CDR pathways applicable to open ocean waters. For example, one source identified 34 research studies for pathways such as artificial upwelling and ocean fertilization, conducted by universities or national governments, many of which involved multinational collaboration.[29] Governments in China, South Korea, Japan, India, Australia, New Zealand, Mexico, Canada, Chile, South Africa, Israel, and several European governments (including the EU) have sponsored these experiments.[30] Some projects outside the United States involved collaboration between the U.S. (or U.S. institutions) and other governments.[31] These experiments have been going on since the 1970s but have often faced criticism around possible unintended ecological consequences.[32] Recent and upcoming projects are listed in Table 10-3.

Table 10-3
International Ocean Fertilization and Artificial Upwelling Projects Since 2010

Project	Location	Project Partners	Description
Kiel Off-Shore Mesocosms for Ocean Simulations (KOSMOS)	Germany, Spain	Project run by the Helmholtz Association, University of Las Palmas de Gran Canaria, and the Spanish government-funded Ocean Platform of the Canary Islands. Funding from two EU programs.	Field experiments under the pan-European KOSMOS program began in 2017 and are set to continue until 2022. The experiment involves testing the feasibility of upwelling by using “mesocosms” that are cordoned off from the larger ocean.[c] The experiments are taking place off the coast of the Canary Islands.
Korean Iron Fertilization Experiment in the Southern Ocean (KIFES)	South Korea	Led by Korea Polar Research Institute. Supported by a coalition of research institutions from South Korea, the U.S., Canada, and New Zealand.	KIFES planned to carry out iron fertilization experiments near Antarctica. The original plans were to carry out the experiments in 2018 and 2019, but the project failed to win approval under the London Convention, which regulates ocean dumping.
Oceaneos experiments	Canada, Peru, Chile	Seeking private investment for future experiments	Vancouver-based Oceaneos, formerly known as the Planktos Foundation, is a private organization that has been involved in ocean fertilization experiments involving iron compounds near Hawaii and Canada’s Pacific coast. The foundation has announced its intentions to carry out more experiments in Peru and Chile. The company has been criticized for using misleading tactics to secure permission for its experiments.
SINTEF experiments	Norway	SINTEF	The fisheries and aquaculture branch of SINTEF, a Norwegian research organization, carried out a pair of upwelling experiments in 2010 in Norwegian fjords. One involved a bubble curtain and the other involved the discharge of freshwater from a hydropower plant. The project was not focused specifically on CDR but did show positive effects in terms of toxic algae reduction and phytoplankton growth.

[c] The KOSMOS mesocosms are medium-sized (25 meters long) artificial environments constructed within plastic tubes that simulate a larger patch of ocean.

Zhejiang University experiments	China	Zhejiang University	Zhejiang University researchers tested a compressed air-based upwelling system between 2011 and 2014, first on a freshwater lake and later in the East China Sea. The experiments demonstrated the efficiency of the upwelling technology, but the researchers stated that more testing was needed to test environmental and CDR impacts.
Source: EFI, 2019. Compiled using data from Geoengineering Monitor, 2019, and project websites.			

Geochemical Carbon Dioxide Removal and Geologic Sequestration

Geochemical methods of CDR—specifically carbon mineralization and EW—are also receiving support in other countries. There are currently several projects employing geochemical methods, from small-scale field experiments to demonstration projects, mostly sponsored by European, Canadian, and Australian institutions. All of these projects (Table 10-4) involve magnesium-rich rocks such as peridotite and basalt, either in situ or ex situ. Some of the existing projects use CO_2 from concentrated sources,[33] though that research can help inform eventual negative-emissions applications using CO_2 from dilute sources.

Table 10-4
International Carbon Mineralization Projects

Project	Location	Project Partners	Description
CarbFix	Iceland	EU, Reykjavik Energy, French government, University of Iceland, AMPHOS 21 Consulting	CarbFix is a project led by the Icelandic company Reykjavik Energy that has developed a process for in situ geochemical sequestration in basalt formations. CarbFix has successfully demonstrated its process with CO_2 captured from a nearby power plant since 2014. The researchers behind CarbFix have also been conducting research into sequestration of CO_2 mixed with H_2S under the project name SulFix. Future plans involve pairing their technology with DAC; exploring new sites in Iceland, Germany, Italy, and Turkey; and developing the process so it can be used offshore.
Green Minerals	Netherlands	Heidelberg Cement, RWTH Aachen University, Potsdam Institute for Advanced	Dutch start-up Green Minerals is investigating a process to use olivine for EW (and ocean alkalinity modification) with CO_2 from concentrated sources.

		Sustainability Studies, German government	Green Minerals has proposed combining its process with cement, paper, and plastics manufacturing. The company's research could have implications for EW with atmospheric CO_2.
Oman Drilling Project	Oman	Government of Oman, coalition of domestic and international university researchers	The Oman Drilling Project is an international collaborative effort to drill into and research rock formations in the unique Samail Ophiolite in Oman. One of the thrusts of the research is exploring the possibility of in situ carbon mineralization in the peridotite. Drilling and research are underway, but no CO_2 injection is planned yet.
Project Minera	Canada, South Africa, Botswana	De Beers/Anglo American, Natural Environment Research Council, Canadian government, University of British Columbia, University of Cambridge, University of Oxford, University of Southampton, Cardiff University	De Beers and parent company Anglo American have been funding research by universities into CDR in mine tailings under the banner of Project Minera. That has included tests of kimberlite mine tailings at mines in Canada and South Africa, as well as assessments of diamond and platinum mines in Botswana and South Africa.
UBC-led mine tailings research	Canada, Australia	University of British Columbia, University of Alberta, Trent University, University of Queensland, Bond University	A coalition of Canadian and Australian universities is working on developing geochemical sequestration in magnesium silicate rock using mine tailings. Nickel, platinum, diamond, and asbestos mines produce these tailings; the mining process already crushes up the rock, enhancing its CO_2 uptake. Field trials at a BHP nickel mine in Australia showed how much CDR is already happening in these mine tailings and how changing how waste is handled and stored could increase CO_2 uptake.
University of Sheffield	UK, Australia, Malaysia	Leverhulme Trust, South East Asia Rainforest Research Partnership, James Cook University, University of Illinois	Researchers at the University of Sheffield are conducting field trials in the U.S., Australia, and Malaysia on applying crushed basalt to agricultural soils. Each multiyear trial is conducted with a local partner on different crops (e.g., sugarcane in Australia, oil palms in Malaysia).
Source: EFI, 2019. Compiled using data from Geoengineering Monitor, 2019; The New York Times, 2018; CIM Magazine, 2018; De Beers, 2019; and company and project websites.			

Many other countries also are gaining experience with geologic carbon sequestration. Currently, 11 companies in seven countries outside the United States use CO_2 for oil recovery (Table 10-5).[34] In addition, companies in nine countries use other gases for EOR and could potentially transition their operations to using CO_2.[35] Translating EOR techniques to enhance natural gas production (enhanced gas recovery or EGR) is also a possibility. EGR with CO_2 has been pilot-tested but not yet carried out at large scale.[36]

Table 10-5
Int'l Companies with CO_2-EOR Operations

Companies	Location
Petrobras	Brazil
Canadian Natural Resources, Whitecap Resources, Cardinal Energy, Pengrowth Energy	Canada
CNPC, Sinopec	China
MOL	Croatia
Saudi Aramco	Saudi Arabia
Turkish Petroleum	Turkey
ADCO	United Arab Emirates

Source: EFI, 2019. Compiled using data from the International Energy Agency, 2018.

There also are several important geologic sequestration projects underway in other parts of the world, particularly in saline aquifers. Large-scale geologic sequestration is occurring at four sites outside the United States: two in Canada and two in Norway.[37] There are more projects under development in Norway and Australia,[38] as well as smaller-scale sequestration facilities in Japan and China.[39] All of these sites (Table 10-6) use carbon captured from concentrated sources;[40] the technology, however, could easily be applied to CO_2 from dilute sources. Research is also underway on site characterization issues such as methods for improving candidate site identification, estimating the storage capacity of sites, and testing various MRV techniques.[41]

Table 10-6
International Large-Scale Facilities with Dedicated Geologic Sequestration

Project	Location	Project Partners	Description
Boundary Dam CCS	Canada	SaskPower, Petroleum Technology Research Centre, government of Saskatchewan	One of SaskPower's coal-fired units at the Boundary Dam power plant was retrofitted with carbon capture in 2014. Most of that CO_2 goes to Cenovus Energy for EOR, but a portion of it is geologically sequestered at the nearby Aquistore Project.
Gorgon CO_2 Injection Project	Australia	Chevron, ExxonMobil, Osaka Gas, Tokyo Gas, JERA	As part of the under-construction Gorgon offshore gas development, facilities are planned for CO_2 separation and geologic sequestration. The sequestration facilities are scheduled to come online in 2019.
Norway Full	Norway	Government of Norway	Norway Full Chain CCS is a possible government-funded CCS project that would be constructed in

Chain CCS			2023-2024. Captured carbon could come from waste-to-energy plants and cement production. Sequestration would be offshore and could involve both ship and pipeline CO_2 transport.
Quest	Canada	Shell, Chevron, Marathon	Existing steam methane reformers at the Scotford Oil Sands Upgrader were retrofitted in 2015 with carbon capture, which is transported by pipeline to a dedicated geologic storage facility.
Sleipner and Snohvit CO_2 Storage	Norway	Equinor, Petoro, Total, Engie, Norsk Hydro	As part of offshore gas development in Norway, Equinor has set up two geologic sequestration sites, Sleipner in 1996 (the first such site worldwide) and Snohvit in 2008. The Snohvit project was sponsored by a coalition of companies involved in offshore gas production. CO_2 is captured at gas processing facilities and then piped back out to storage reservoirs in the gas fields.
Source: EFI, 2019. Compiled using data from the Global CCS Institute, 2018.			

Carbon Dioxide Utilization

Many other countries are currently investigating opportunities for utilizing CO_2 to create economic value. As carbon capture becomes an increasingly important option for mitigating climate change, countries and companies that can lead in the commercialization of carbon-to-value technologies could achieve substantial national economic benefits, including increasing the economic productivity of existing infrastructure and job creation.

Foreign research into utilization is underway on a vast scale: One database run by an EU-sponsored project found 149 pilot and commercial projects in 18 countries outside the United States (including China, Canada, Israel, Japan, South Korea, and several in Europe).[42] The database also includes nine academic research projects, all in Europe, many of which are funded by EU grants. These commercial, pilot, and academic projects include CO_2U in agriculture, mineralization, and the production of fuels, chemicals, and building materials. Many of the projects discussed above (in areas such as DAC, BECCS, and mineralization) already include a utilization component.

A few large-scale CO_2U projects tracked by the Global CCS Institute, from several different countries, are listed in Table 10-7.[43] Most of these projects use or plan to use CO_2 from concentrated sources. As with geologic sequestration, many of these technologies could be translated to dilute sources where CO_2 becomes concentrated in the capture process (e.g., DAC). While some of these projects sell their CO_2 for utilization purposes, some of them are from companies that both produce emissions and can harness CO_2, such as chemical, energy, and manufacturing companies.

Table 10-7
International Large-Scale CO_2 Utilization Projects

Project	Location	Project Partners	Description
Alcoa Kwinana Carbonation Plant	Australia	Alcoa	Since 2007, Alcoa has been using a process that mixes bauxite residue from aluminum production with CO_2. In addition to CDR, this process (designed by the company's refining R&D department) improves the environmental quality of the residue, allowing it to be used in roads, buildings, and soil.
ArcelorMittal Steelanol Ghent	Belgium	ArcelorMittal, LanzaTech	ArcelorMittal, a steel manufacturing company, plans to produce bioethanol from CO_2 that is captured from steel blast furnaces. It will harness gas fermentation technology from LanzaTech, a CO_2U company.
Chinese CO_2U projects	China	Various, including Shougang Steel, China Power Investment Corporation, and Huaneng Group	There are at least 10 CO_2U facilities in China, some of which have been operating for more than a decade. These facilities use captured carbon from coal-fired power plants, steel mills, and other facilities. Utilization methods employed include ethanol production, use as an industrial fluid, and food and beverages.
Port-Jérôme Carbon Capture	France	Air Liquide	Air Liquide, an industrial gases production company, designed its own carbon capture process and retrofitted one of its hydrogen production facilities with CCUS in 2015. Captured carbon is utilized for the food and beverage industry.
Saint-Félicien Pulp Mill	Canada	CO_2 Solutions, Resolute Forest Products, Serres Toundra	Construction started in 2018 for the deployment of CO_2 Solutions' carbon capture technology on a pulp mill. Facilities will be constructed to transport CO_2 to a nearby vegetable greenhouse development.
Swayana Mpumalanga	South Africa	Swayana, LanzaTech	Swayana, a South African energy company, is seeking to add LanzaTech's gas fermentation technology to a ferroalloy plant. The project is scheduled to commence in 2020.
Tuticorin CCU Project	India	Tuticorin, Carbon Clean Solutions	Carbon Clean Solutions installed a CCU facility that uses captured carbon from a coal-fired power plant. The CO_2 is utilized by Tuticorin, a chemical production company, for soda ash production.
Valorisation Carbone Quebec (VCQ)	Canada	Managed by CO_2 Solutions and Hatch. Technical assistance and funding from	VCQ is an ongoing project hosted at ParaChem's chemical production facilities that involves lifecycle testing of various utilization options in production of chemicals, fuels, food, and materials. Currently, the project is

		public, private, and university partners.	constructing test facilities for methanol and dimethyl ether.
Source: EFI, 2019. Compiled using data from the Global CCS Institute, 2018, and company and project websites.			

Models for International CDR RD&D Collaboration

International RD&D collaborations have taken on many forms. Current RD&D collaborative efforts—both in the climate and energy space and outside it—can provide instruction on what makes such an effort successful. Future international joint efforts on CDR RD&D could even be housed within an existing structure.

Mission Innovation

Established in 2015, Mission Innovation (MI) is a ministerial-level initiative of 23 countries and the EU[d] that seeks to accelerate clean energy innovation. The initiative was announced at the 2015 UN Climate Change Conference (also known as COP21), where the Paris Agreement was negotiated. At its launch, members committed to doubling public sector clean energy investment, sharing information on clean energy technology development efforts, exploring opportunities for bilateral and multilateral R&D project collaborations, and increasing engagement with the private sector.[44] MI publishes annual reports on progress toward these goals, with updates from all member countries.[45] Other work of MI includes funding innovation, convening experts, and fostering new international collaborations.[46] Major priorities are set at annual Ministerials; operations are guided by a steering committee with representatives from a subset of participants; and different participants are appointed as leads for different project areas.

MI members have identified eight Innovation Challenges, one of which is focused on CCUS technologies. The CCUS Innovation Challenge triggered an experts' workshop (Box 10-1) and subsequent report on innovation priorities of CCUS. This effort, in turn, spawned $103 million in funding commitments for CCUS R&D from among the United States, EU, and the Accelerating CCS Technologies (ACT) consortium (more information on this can be found later in this chapter).[47] While most of the innovation priorities and funding established under the Innovation Challenge relate to concentrated source capture, MI's public materials describe "carbon negative solutions" as a goal of the challenge.[48] In addition, innovation priorities described in the workshop report include utilization and storage issues that are relevant to CDR.

International Energy Agency

The International Energy Agency (IEA) is an autonomous body within the Organization for Economic Cooperation and Development (OECD), established by treaty in 1974 in the wake of the oil crisis of 1973-1974. IEA membership is open to all OECD members; currently 30 OECD countries participate. "Association" countries that are outside the OECD and international organization also participate in IEA's efforts. Members contribute

[d] Represented by the European Commission.

funds to IEA's budget–€27.8 million in 2018 ($31.2 million[e])—proportional to the size of their economies through voluntary funding; publication revenues also make up a portion.[49] IEA activities primarily focus on information-gathering, analysis, and support for experts' networks;[50] it is not a funder or a work performer for RD&D. IEA's governing board is made up of ministers from all member countries or their representatives; there are also standing groups and committees for particular tasks.

Box 10-1

The Mission Innovation CCUS Experts' Workshop

The experts' workshop convened by MI for the CCUS Innovation Challenge provides a useful look into how a similar workshop or series of workshops might work for CDR. The workshop took place in Houston, Texas, over five days in September 2017. The cosponsors were the DOE and Saudi Arabia Ministry of Energy, Industry, and Natural Resources. Workshop leaders came from 14 different MI countries, and participants came from several additional countries. Participants and observers represented government agencies, major energy and technology companies, CCUS industry players, universities, DOE National Laboratories, and other research institutions.

The workshop was divided into three thematic areas corresponding with the basic components of CCUS: capture, utilization, and sequestration. Each of these focus areas was overseen by a cochair, and each focus area conducted panels on specific topics; there was an additional panel on cross-cutting issues. Each panel had a pair of leads, with each pair coming from two different MI member countries. The topics of the panels were:

- **Capture:** solvents, sorbents, looping systems, membranes, combustion, and other technologies
- **Utilization:** thermochemical conversion and hydrogenation, electrochemical and photochemical conversion, conversion to solid carbonates, biological conversion, and enhanced hydrocarbon recovery
- **Sequestration:** injectivity and capacity, MRV and performance metrics, induced seismicity, and well diagnostics

The cross-cutting panel tackled topics such as platform technologies (e.g., for modeling, advanced manufacturing), social aspects of decision-making, and techno-economic analytical angles.

Subsequent to the workshop, a report was produced that shared its findings.[51] The report was organized along the same lines as the conference. Each panel topic had a section of the report, with a review of current status, scientific challenges, and conclusions about innovation needs. For each larger thematic area (and for the cross-cuts section), the conclusions from each panel section were distilled into Priority Research Directions (PRDs). In total, the report included 30 PRDs, which were broadly aimed at making CCUS viable "at the scale that is expected to be needed in the period 2030–2050."[52]

[e] Average July 2019 exchange rate from OFX

CCUS is one of the research topic areas within the category of "fuels and technologies" that is tracked by IEA. The CCUS technology area also covers storage and utilization technologies that are relevant to CDR, and IEA describes CCUS as "the foundation for carbon removal."[53] CCUS and CDR are also the focus of one of the IEA-sponsored Technology Collaboration Programmes (TCPs), called the IEA Greenhouse Gas R&D Programme (IEAGHG).[54] TCPs are international groups of experts organized under IEA but operating autonomously. IEA provides a framework for implementing agreements that participants (which include IEA members, association countries, international organizations, private companies, and universities) sign onto to commit to international collaboration. TCP activities can include:[55]

- Collaborative projects spanning fundamental and applied research, technology development, and demonstration;
- Technology assessment, feasibility studies, environmental impact studies, market analysis, and policy analysis;
- Exchange of information, research results, scientists, databases, and models; and
- Experts' networks.

The IEAGHG TCP convenes and participates in workshops and conferences; prepares technical, policy, and informational analysis; lobbies; and promotes public awareness.[56]

Carbon Sequestration Leadership Forum and Accelerating CCS Technologies

The Carbon Sequestration Leadership Forum (CSLF) and ACT initiative are two CCUS-specific international collaborative efforts with U.S. participation (through the DOE). The CSLF, established in 2011, is a ministerial-level initiative dedicated to facilitating development and deployment of CCUS technology. The group has 26 members (from 25 countries and the EU); membership is open to all countries with ongoing CCUS efforts. The CSLF identifies RD&D areas of need, fosters collaborative projects and knowledge-sharing, and recognizes and tracks the CCUS projects of members.[57] It does not act as a separate source of funding for these projects, however. CSLF has produced technical reports on several CDR-related technology areas, including BECCS and CO_2U options.[58]

ACT, on the other hand, is a funding vehicle for public-private partnerships established under the EU's Horizon 2020 program. It was created in 2016 with only European members, though it is now open to other participants (the United States is currently the only non-European member). It currently funds eight CCUS R&D projects at between €1.2 million and €14.0 million ($1.3 million and $15.7 million[f]).[59] A new funding round is ongoing as of May 2019, with a budget between €22.05 million and €30.05 million ($24.7 million and $33.7 million[g]).[60] While most of ACT's current projects are devoted to concentrated source applications such as power generation and industry, certain projects could have relevance to CDR, such as research into geologic sequestration optimization[61]

[f] Average July 2019 exchange rate from OFX
[g] Average July 2019 exchange rate from OFX

and additive manufacturing for sorbents.[62] Future ACT-funded projects could also include projects that focus specifically on CDR options that fall within the overlap with CCUS.

CGIAR

CGIAR is a network of 15 nonprofit agricultural research centers around the world. It was established in 1971 with four centers. CGIAR centers carry out technical RD&D as well as analytical work. Unlike many of the other partnerships discussed here, CGIAR is not an intergovernmental entity, though it is supported by national and international governments (including the United States through the Agency for International Development, or USAID). The goals of CGIAR are reducing poverty, improving food and nutrition security, and improving natural resources and ecosystem services.[63] CGIAR is governed by a system council—made up of funders and developing countries that set high-level priorities—and a system management board elected by the centers. CGIAR's funders include national governments, international and supranational entities (e.g., the World Bank), and private foundations (e.g., the Bill & Melinda Gates Foundation); its revenue in 2017 was $849 million.[64]

CGIAR has established 11 separate research programs. The Research Program on Climate Change, Agriculture, and Food Security (CCAFS) is led by the International Center for Tropical Agriculture (headquartered in Colombia), with participation from other CGIAR centers. CCAFS RD&D has covered CDR topics such as soil carbon uptake and agroforestry's carbon impact.[65] In addition, at COP21, CGIAR launched the "4 per 1000" Initiative, which urges governments, companies, and other groups to commit to a goal of increasing soil carbon sequestration by 0.4 percent (greater than the 2015 total increase in atmospheric carbon).[66] The initiative encourages practices that improve carbon uptake in areas such as crop methods, pasture management, water and fertilizer management, agroforestry, and land restoration.[67] The Initiative's work involves promoting action plans by state and non-state actors, increased funding, and an international program for research and science collaboration.[68]

Bonn Challenge

The Bonn Challenge is an international effort focused on restoration of degraded and deforested lands. It was established in 2011 as a partnership between the German government and the International Union for Conservation of Nature (IUCN). In 2014, the challenge was extended and made official by the New York Declaration on Forests (NYDF) and signed by governments, companies, indigenous groups, and non-governmental organizations (NGOs). The NYDF set new goals of halving deforestation by 2020 and ending it by 2030, as well as restoring 350 million hectares of degraded and deforested land by 2030.[69] CDR is incorporated as a specific goal of the Bonn Challenge and the NYDF.[70] Fifty-eight individual national and subnational governments (including the United States), as well as companies, have made pledges under the Bonn Challenge.[71] Most of the pledges have come from the Americas, sub-Saharan Africa, and Central Asia. The United States is one of only four OECD countries (alongside the UK, Mexico, and Chile) with Bonn Challenge commitments. IUCN has been conducting analysis of policies, strategies, and technical planning for reforestation, but currently RD&D issues are not a major focus area for this effort.

InterAcademy Partnership

The InterAcademy Partnership (IAP) is a coalition of national academies of science, engineering, and medicine. It was established in 2016 as a result of the unification of the existing academy networks; it succeeded the previous organization also known as IAP, the InterAcademy Panel, whose work was specifically focused on science.[72] IAP has more than 140 members, which include national academies as well as regional academy networks. Member academies participate in triennial assemblies and elect the leadership of IAP. IAP's work is divided into three pillars—science, policy, and health. Each has an executive committee and cochairs elected by the membership. IAP funds projects that are specific, largely analytical research efforts conducted by member academies and affiliated organizations; programs that set priorities for academies and shape interactions between them, etc.; and events such as conferences and workshops. Two of IAP's topic areas are energy and environment and climate.

Bilateral U.S. Partnerships

In addition to participating in various multilateral international collaboration arrangements, the United States also participates in technology-specific bilateral partnerships.

One such program is the U.S.-China Clean Energy Research Center (CERC), established in 2011. CERC is made up of five research consortia, each of which has participants from institutions in both countries; it is co-funded by the two governments at $250 million over five years.[73] One of CERC's consortia is Advanced Coal Technologies—led by West Virginia University and Huazhong University of Science and Technology—for which CCUS RD&D is a major research priority.[74] The consortium has resulted in joint RD&D efforts, modeling innovations, and knowledge-sharing platforms.[75]

Another relevant bilateral partnership is the U.S.-Canada Clean Energy Dialogue (CED), established in 2009. One of the three collaboration priorities for the CED is "advancing carbon capture and storage projects and technologies."[76] This workstream has resulted in joint RD&D efforts and knowledge-sharing, particularly around geological issues for sequestration that apply throughout North America.[77]

Collaboration Models from Other Scientific Collaborations

Establishing an international collaboration strategy for CDR RD&D can also draw lessons from collaboration efforts outside the energy and climate space. Fields such as nuclear physics, space science, and genomics have seen highly successful international collaborative efforts in the form of the European Council for Nuclear Research (CERN), ISS, and HGP, respectively. All of these collaborations have tackled massive research efforts whose scales demand international cooperation—much like CDR.

CERN is one of the world's oldest and most robust international scientific collaborations, dating back to 1954. It is an international organization and laboratory facility that originated as a nuclear research facility but has evolved to focus on high-energy particle physics; it now operates the world's most advanced particle accelerators, including the Large Hadron Collider. It has also contributed to other scientific and technical advancements, such as the creation of the World Wide Web. Like IEA, its funding is derived from proportional contributions from its members. It also demonstrates the importance of having centralized, shared facilities for RD&D, something that is lacking in most other international collaborative RD&D efforts.

The ISS is a habitable artificial satellite in low Earth orbit, the result of an ongoing collaborative project of the U.S., Canadian, Japanese, Russian, and European space agencies. It serves as a research facility for space science and microgravity experiments. The project dates back to the 1980s, with the first components launched in 1998 and the first crew arriving in 2000; it has been continually inhabited since.[78] The ISS is a single, very large, integrated project; one interesting aspect of its collaborative model is the way in which different parts of the station's facilities and mission are assigned to different participants.[79] This allows participating space agencies to focus on smaller technical problems in service of a larger goal and creates a built-in accountability mechanism. It is also worth noting that research on the ISS is not limited to the project's collaborators—other nations are able to send astronauts to the station and conduct experiments.

HGP was a biomedical research project to sequence the entirety of the human genome. It was initiated in 1988, formally commenced in 1990, and completed its mission in 2003.[80] It produced numerous advances in genomics, as well as other areas of the biological and medical sciences. HGP was largely funded by the National Institutes of Health (NIH) and DOE, with participation from the UK, France, Germany, Japan, and China.[81] A highly instructive part of the success story of the HGP is that it started as a bottom-up international collaboration of individual scientists and research institutions that evolved into a government-funded effort.[82] Part of the project's success can be attributed to the fact that it harnessed these existing collaborative relationships.

Recommended Strategies for International CDR RD&D Collaboration

There are a wide variety of models that could serve as the basis for developing an international CDR RD&D collaboration. Moreover, these various models are not mutually exclusive. The design of a framework for international collaboration on CDR RD&D should take into account three factors:

- **Compatibility.** There is a substantial overlap between CDR and CCUS RD&D efforts; there are, however, key areas of CDR that are left out of a global conversation on CCUS (especially terrestrial and oceans-based approaches). Efforts to create collaboration on CDR RD&D can harness existing structures that focus on CCUS and should be able to do so in a way that does not detract from those existing RD&D efforts.
- **Feasibility.** Making CDR RD&D a higher priority in international science and technology collaborative efforts should be attractive to many countries, but the

mechanics of doing so could be challenging. Some new collaborations may be easier to put into action than others.

- **Effectiveness.** Not all international collaborations are created equal. This report underscores the necessity of a rapid and substantial upscaling of investment in CDR RD&D programs with gigaton-scale potential. The most effective international collaborations at advancing CDR RD&D are those that include the active involvement of multiple countries.

InterAcademy Partnership. OSTP should instruct NASEM to work with IAP to convene an international scientific conference on CDR. The purpose would be to discuss priorities and strategies for international collaborative RD&D efforts on CDR. Setting a research agenda for oceans CDR is an area where greater international discussion and understanding is particularly needed. In addition, IAP could initiate discussion of issues related to large-scale deployment of CDR, beginning with issues of IP management and development of common standards for various CDR applications. IAP may not necessarily become a vehicle for ongoing CDR RD&D collaboration, but it could serve as the catalyst to raise the level of global awareness and dialogue on CDR-related issues, thus providing an improved baseline for future international collaboration efforts. IAP's policy pillar is currently hosted at NASEM, facilitating easy collaboration on expanding NASEM's CDR research to the global level.

Mission Innovation. There is a fundamental need for international coordination on CDR. To that end, DOE (the U.S. agency that participates in MI) should work to add CDR as an additional Innovation Challenge for MI (or, less optimally, to modify the existing CCUS challenge to include CDR). A first step within this challenge could be instituting a series of workshops on key CDR technologies that require innovation and have breakthrough potential (e.g., DAC, mineralization). MI is a natural venue for this effort, in part because it involves a funding commitment that can boost CDR innovation. MI is well-suited to coordinating CDR efforts for several other reasons as well:

- It is already explicitly focused on technological innovation targeted to a goal of decarbonization of the global economy;
- It is the vehicle that can help guide RD&D priorities, plans, and budgets among the participating countries;
- It already cites CDR as a target for innovation and supports investment in related/complementary technologies under its CCUS workstream; and
- It encourages increased private investment in clean energy technologies, alongside public investment.

In summary, the four major recommendations for international collaboration are shown in Box 10-2.

Box 10-2

Recommended Strategies for International CDR RD&D Collaboration

In summary, the four recommendations for international CDR RD&D collaboration include:

1. The United States (through OSTP and NASEM) should seek to organize an international dialogue on CDR RD&D through the IAP.
2. The United States (through DOE) should seek to include CDR as the ninth Innovation Challenge area within the MI framework.
3. The United States should seek to expand the scope of current CCUS workstreams in existing international collaboration to include, at a minimum, DAC and BECCS CDR pathways. This should include both CCUS-specific organizations (e.g., CSLF, ACT) as well as current and future bilateral partnerships (e.g., CERC, CED) that have a CCUS focus.
4. Once activated, the proposed NSTC Committee on Large-Scale Carbon Management should commission a special working group to address IP issues, focusing on the need to balance the protections and incentives in current U.S. IP policies with the need to facilitate and encourage widespread global deployment of CDR approaches at Gt scale. The U.S. also should make this a priority agenda item for the IAP dialogue.

1 https://www.ipcc.ch/sr15/chapter/spm/
2 Based on a survey of data from the Global CCS Institute (https://co2re.co/FacilityData); Geoengineering Monitor (http://map.geoengineeringmonitor.org); Air Miners (http://www.airminers.org/)
3 https://www.greencarreports.com/news/1104452_blue-crude-synthetic-diesel-fuel-cuts-carbon-by-85-percent; https://carbonengineering.com/about-a2f/; https://www.greencarcongress.com/2017/08/20170808-soleetair.html
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6 http://www.neocarbonenergy.fi/wp-content/uploads/2017/06/Process-FINAL.pdf
7 https://www.skytree.eu/methanol-conversion/
8 https://www.skytree.eu/urban-greenhouses/; https://www.antecy.com/
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47 http://mission-innovation.net/our-work/innovation-challenges/carbon-capture/
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60 http://www.act-ccs.eu/calls
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Part IV
Appendices

APPENDIX A. DETAILED BUDGET ESTIMATES

Table A-1. Detailed Budget Estimates for CDR RD&D Initiative by Portfolio Element ($millions)

Portfolio Element	Recommendation Source		Description of Research Activities	Funding Source		Year 1	Year 2	Year 3	Year 4	Year 5	5-Year Total	Year 6	Year 7	Year 8	Year 9	Year 10	10-Year Total	NASEM 10-Year Total
	NASEM 2018a	Other		Agency	Office													
1.00 Direct Air Capture																		
1.10 Advanced Materials																		
1.11 DOE Energy Frontier Research Center	#22	ICEF: #1	Materials research and early-stage application of sorbents, solvents, membranes, and related DAC components.	DOE	SC (BES)	$0	$4	$4	$8	$8	$24	$4	$4	$0	$0	$0	$32	$200-300
1.12 Grants & cooperative agreements	#22	ICEF: #1	Materials research of sorbents, solvents, membranes, and related DAC components.	DOE	SC BES)	$5	$10	$10	$10	$15	$50	$15	$12	$5	$5	$2	$89	$200-300
1.13 NSF Engineering Research Center	#22	ICEF: #1	Materials research and early-stage application of sorbents, solvents, membranes, and related DAC components.	NSF	MPS	$0	$5	$5	$5	$5	$20	$5	$0	$0	$0	$0	$25	$200-300
1.14 Grants & cooperative agreements	#22	ICEF: #1	Materials research of sorbents, solvents, membranes and related DAC components.	NSF	MPS	$3	$6	$10	$10	$15	$44	$15	$15	$10	$5	$0	$89	$200-300
1.15 Materials testing & standards	#23	ICEF: #1	Standard reference materials for DAC; standard test procedures.	DOC	NIST	$2	$2	$2	$5	$5	$16	$5	$0	$0	$0	$0	$21	$30-50
1.10 Sub-total, Advanced Materials						$10	$27	$31	$38	$48	$154	$44	$31	$15	$10	$2	$256	
1.20 Engineering Development																		

1.21 Contactor design	#22	ICEF: #3	Improved air contactors with low pressure drop, high surface area, high longevity.	DOE	FE	$3	$5	$5	$5	$5	$23	$5	$5	$0	$0	$0	$33	$200-300
				DOE	EERE (AMO)	$0	$2	$5	$5	$5	$17	$5	$0	$0	$0	$0	$22	
1.22 Manufacturing improvement	N/A	N/A	Improved techniques for low-cost manufacturing of DAC components and materials.	DOE	EERE (AMO)	$2	$5	$10	$10	$10	$37	$10	$10	$10	$0	$0	$67	N/A
1.23 Low-carbon heat provision	N/A	ICEF: #2	Provision of low-carbon heat energy for DAC operation.	DOE	FE	$4	$5	$10	$10	$10	$39	$10	$10	$10	$0	$0	$69	N/A
1.24 Advanced systems & components	N/A	ICEF: #4	Advanced/unconventional system designs and components; handoff from ARPA-E.	DOE	FE	$0	$0	$5	$10	$10	$25	$15	$15	$15	$12	$10	$92	N/A
1.20 Sub-total, Engineering Development						$9	$17	$35	$40	$40	$141	$45	$40	$35	$12	$10	$283	
1.30 Pilot Plants, Test Facilities, & Demonstrations																		
1.31 Scale-up studies & pilot plants	#24, #26	ICEF: #4	Pilot-scale (>1,000 tCO_2/yr) experimental plants.	DOE	FE	$0	$5	$15	$30	$40	$90	$50	$50	$45	$35	$30	$300	$300-550
1.32 Operational data collection	N/A	N/A	Purchasing program for operational data from DAC companies.	DOE	FE	$0	$5	$5	$5	$5	$20	$5	$0	$0	$0	$0	$25	N/A
1.33 Engineering design support	#25	N/A	Cost-sharing for three scale-up FEED studies and public database on system costs and performance.	DOE	FE	$0	$0	$5	$10	$15	$30	$10	$5	$3	$2	$0	$50	$30-100
1.34 Regional & national test facilities	#27, #29	N/A	5 centers: Simulated and real-world exposure and aging testing for materials and full systems.	DOE	FE	$0	$10	$20	$30	$40	$100	$50	$50	$40	$30	$20	$290	$250-400
1.35 DAC demonstrations & National Air Capture Test Center	#28	N/A	Demonstration-scale (>10,000 tCO_2/yr) plants.	N/A	N/A	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$1,000
1.30 Sub-total, Pilot Plants, Test Facilities, & Demonstrations						$0	$20	$45	$75	$100	$240	$115	$105	$88	$67	$50	$665	

1.40 Environmental & Techno-economic Assessments																		
1.41 External techno-economic analysis	#23	N/A	Third-party analysis of complete system performance and costs.	DOE	FE	$3	$5	$5	$5	$5	$23	$5	$5	$5	$5	$5	$48	$30-50
1.42 Lifecycle analysis	#22	ICEF: #6	Full-system lifecycle analysis of emissions and other environmental impacts.	DOE	FE	$2	$3	$5	$5	$5	$20	$5	$5	$5	$5	$5	$45	$200-300
1.43 Environmental impacts and commercialization support	#22	ICEF: #5	Full-system environmental impact assessments.	EPA	ORD	$12	$13	$15	$15	$15	$70	$15	$15	$15	$15	$15	$145	$200-300
1.40 Sub-total, Environmental & Techno-economic Assessments						$17	$21	$25	$25	$25	**$113**	$25	$25	$25	$25	$25	**$238**	
1.50 Military Operational Energy Air/Water-to-Fuels Development																		
1.51 Forward operating base air-to-fuel system development	N/A	N/A	Deployable air-to-fuels system for DOD forward operating base (JP-8).	DOD	ARL	$7	$10	$10	$10	$14	$51	$14	$14	$0	$0	$0	$79	N/A
1.52 Seawater-to-fuel system development ("blue carbon removal")	N/A	N/A	Deployable seawater-to-fuels system for at-sea aviation fuel production.	DOD	NRL	$7	$10	$10	$10	$14	$51	$14	$14	$0	$0	$0	$79	N/A
1.50 Sub-total, Military Operational Energy Air/Water-to-Fuels Development						$14	$20	$20	$20	$28	**$102**	$28	$28	$0	$0	$0	**$158**	
TOTAL, Direct Air Capture						**$50**	**$105**	**$156**	**$198**	**$241**	**$750**	**$257**	**$229**	**$163**	**$114**	**$87**	**$1,600**	**$1,810-2,400**
2.00 Terrestrial and Biological																		
2.10 Forestry																		
2.11 Enhanced forest stock monitoring	#7	N/A	Supplement USFS forest monitoring system to include carbon and add remote monitoring.	USDA	USFS	$5	$5	$5	$5	$5	$25	$2	$2	$2	$2	$2	$35	$15
2.12 IAMs & forest impacts modeling	#8, #11	N/A	Technical, economic, and social modeling of impacts on land use from afforestation and forest management changes.	NSF	SBE	$3	$3	$3	$3	$3	$15	$3	$3	$3	$3	$3	$30	$40-143
				USDA	USFS	$3	$3	$3	$3	$3	$15	$3	$3	$3	$3	$3	$30	

2.13 Forest carbon management demonstration	#9	N/A	Projects for best practices to improve disposal of wood products after use.	USDA	USFS	$3	$3	$3	$0	$0	$9	$0	$0	$0	$0	$0	$9	$13.5
				EPA	ORD	$2	$2	$2	$0	$0	$6	$0	$0	$0	$0	$0	$6	
2.14 Preservation of harvested wood	#10	N/A	Design and demonstration of landfills for woody biomass disposal and carbon sequestration.	USDA	USFS	$1	$1	$1	$0	$0	$3	$0	$0	$0	$0	$0	$3	$7.2
				EPA	ORD	$1	$1	$1	$0	$0	$3	$0	$0	$0	$0	$0	$3	
2.15 Extension & outreach	#12	N/A	Social science programs on forest management practices uptake.	USDA	USFS	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$3
2.10 Sub-total, Forestry						$18	$18	$18	$11	$11	**$76**	$8	$8	$8	$8	$8	**$116**	
2.20 Soil Carbon Storage																		
2.21 Fundamental research	#18	N/A	Fundamental research on plant-root-fungi interactions, deep inversion of soils, and other topics.	USDA	ARS	$10	$10	$10	$10	$10	$50	$10	$10	$10	$10	$10	$100	$15-20
				DOE	SC (BER)	$5	$5	$5	$5	$5	$25	$5	$5	$5	$5	$5	$50	
				NSF	GEO	$5	$5	$5	$5	$5	$25	$5	$5	$5	$5	$5	$50	
2.22 Enhanced soil monitoring	#13	N/A	Augmentation of USDA National Resources Inventory (NRI) system to include additional sites, and a focus on CO_2 fluxes.	USDA	NRCS	$3	$3	$3	$3	$3	$15	$3	$3	$3	$3	$3	$30	$50
				NASA	ESD	$2	$2	$2	$2	$2	$10	$2	$2	$2	$2	$2	$20	
2.23 High-carbon-input crop phenotypes	#17	N/A	Development of advanced cultivars with enhanced carbon uptake and retention.	USDA	ARS	$5	$10	$30	$50	$50	$145	$50	$50	$50	$50	$50	$395	$400-500
[Baseline redirected funding - USDA]				USDA	ARS	$0	$0	-$15	-$25	-$25	-$65	-$25	-$25	-$25	-$25	-$25	-$190	N/A
2.24 Cultivation system optimization	#14	N/A	Research on regionally specific best practices for soil health and carbon retention. 10 sites at $0.8/M per site.	USDA	ARS	$5	$5	$6	$6	$6	$27	$7	$7	$7	$7	$7	$62	$60-90
2.25 Biochar impact studies	#19	N/A	Research on biochar longevity and impact on productivity, soil carbon retention,	USDA	ARS	$3	$3	$3	$3	$3	$15	$3	$3	$3	$3	$3	$30	$15-30

			nutrient/water use, and albedo.															
2.26 Reactive minerals in agricultural soils	#20	N/A	Research on impact of adding reacted carbonate minerals to agricultural soils (c.f. accelerated mineralization).	USDA	ARS	$3	$3	$3	$3	$3	$15	$3	$3	$3	$3	$3	$30	$30
2.27 Modeling & predictive tool development	#15	N/A	Simulation-based tools to predict and quantify soil carbon storage.	USDA	ARS	$5	$5	$5	$5	$5	$25	$0	$0	$0	$0	$0	$25	$25
				NSF	GEO	$5	$5	$5	$5	$5	$25	$0	$0	$0	$0	$0	$25	
2.28 Scaling up agricultural sequestration	#16	N/A	Projects to identify barriers to adoption.	USDA	NRCS	$0	$0	$0	$2	$2	$4	$0	$0	$0	$0	$0	$4	$6
2.20 Sub-total, Soil Carbon Storage						$51	$56	$61	$74	$74	$316	$63	$63	$63	$63	$63	$631	
2.30 Bioenergy with Carbon Capture & Sequestration (BECCS)																		
2.31 Algal biomass capture	N/A	N/A	Microalgae growth, dewatering, and conversion, including bioreactors and non-photosynthetic pathways.	DOE	SC (BER)	$2	$5	$7	$7	$7	$28	$7	$7	$7	$7	$7	$63	N/A
				DOE	EERE (BETO)	$2	$5	$7	$7	$7	$28	$7	$7	$7	$7	$7	$63	
2.32 Biomass supply, logistics, & pre-treatment	#38	N/A	Test facilities for treating biomass for use in fuels and electricity generation. Modeling and analysis of optimizing biomass gathering, upgrading, and supply.	USDA	NIFA	$2	$5	$10	$10	$10	$37	$10	$10	$10	$8	$5	$80	$265-615
				DOE	EERE (BETO)	$2	$5	$10	$10	$10	$37	$10	$10	$10	$8	$5	$80	
2.33 Biomass conversion to fuels with biochar	#21	N/A	Develop and test conversion pathways, including fast pyrolysis, and assess overall carbon removal potential.	DOE	EERE (BETO)	$4	$10	$15	$20	$20	$69	$20	$20	$15	$10	$10	$144	$400-1,030
				USDA	NIFA	$4	$10	$15	$20	$20	$69	$20	$20	$15	$10	$10	$144	
2.34 Advanced biomass-to-power conversion	#39	N/A	Advanced boilers and combustion processes.	DOE	FE	$5	$5	$10	$15	$15	$50	$25	$25	$25	$20	$9	$154	$390-940
2.35 Biomass to fuel with CCS	#40	N/A	Advanced cellulosic ethanol.	DOE	EERE (BETO)	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0

2.30 Sub-total, Bioenergy with Carbon Capture & Sequestration (BECCS)						$21	$45	$74	$89	$89	**$318**	$99	$99	$89	$70	$53	**$728**	
2.40 Disruptive Research/Novel Concepts																		
2.41 AGARDA	N/A	N/A	High-risk, high-reward agriculture-related CDR technology development.	USDA	AGARDA	$0	$20	$0	$20	$0	$40	$20	$0	$20	$0	$20	$100	N/A
2.40 Sub-total, Disruptive Research/Novel Concepts						$0	$20	$0	$20	$0	**$40**	$20	$0	$20	$0	$20	**$100**	
TOTAL, Terrestrial and Biological						**$90**	**$139**	**$153**	**$194**	**$174**	**$750**	**$190**	**$170**	**$180**	**$141**	**$144**	**$1,575**	**$1,594-3,188**
3.00 Carbon Mineralization																		
3.10 Research & Assessments																		
3.11 Fundamental research	#30, #31	N/A	Fundamental (lab, simulation) research on mineralization kinetics, geomechanics, rock physics; also utilization-oriented carbonation.	NSF	GEO	$2	$4	$10	$15	$15	$46	$15	$15	$15	$15	$15	$121	$225
				DOE	SC (BES)	$2	$4	$10	$10	$10	$36	$10	$10	$10	$10	$10	$86	
3.12 Resource assessments	#32, #35	N/A	Mapping and assessing geological resources and mine tailings as alkalinity sources for mineralization; public database of results.	DOI	USGS	$2	$5	$5	$5	$5	$22	$5	$5	$5	$5	$5	$47	$47.5
			Mapping and assessing industrial wastes, and other artificial surface alkalinity sources for mineralization.	DOE	FE	$0	$5	$5	$5	$5	$20	$0	$0	$0	$0	$0	$20	
3.10 Sub-total, Research & Assessments						$6	$18	$30	$35	$35	**$124**	$30	$30	$30	$30	$30	**$274**	
3.20 Field Experiments																		
3.21 Pilot studies of ex situ mineralization	#33	N/A	Broadcast of reactive minerals on soils, beaches, shallow ocean; desalination brine treatment.	DOE	FE	$2	$3	$6	$6	$6	$23	$6	$6	$3	$3	$1	$42	$35
				EPA	ORD	$2	$2	$4	$4	$4	$16	$4	$4	$2	$2	$1	$29	
3.22 Pilot studies of in situ mineralization	#34, #42	N/A	Field drilling and injection in reactive formations	DOE	FE	$2	$6	$12	$20	$25	$65	$25	$20	$18	$13	$7	$148	$200
				NSF	GEO	$1	$2	$3	$5	$5	$16	$5	$5	$2	$2	$2	$32	

			(peridotite and basalt).															
3.23 Tailings & waste mineralization	#41	N/A	Field experiments with mine tailing and industrial wastes (e.g., slags).	DOI	USGS	$1	$2	$3	$3	$3	$12	$3	$3	$2	$2	$2	$24	$10
				EPA	ORD	$1	$1	$2	$2	$2	$8	$2	$2	$1	$1	$1	$15	
3.20 Sub-total, Field Experiments						$9	$16	$30	$40	$45	$140	$45	$40	$28	$23	$14	$290	
3.30 Environmental Studies																		
3.31 Environmental impacts of mineralization products	#36	N/A	Impacts of broadcasting materials, tailings disturbance, etc.	EPA	ORD	$1	$3	$5	$5	$5	$19	$5	$5	$5	$5	$5	$44	$100
				DOI	USGS	$1	$3	$5	$5	$5	$19	$5	$5	$5	$5	$5	$44	
3.32 Environmental & social impacts of expanded mining for mineralization	#37	N/A	Impacts of an expanded mining industry for the purpose of mineralization.	NSF	GEO	$2	$4	$4	$4	$4	$18	$4	$4	$4	$4	$4	$38	$50
				DOI	USGS	$1	$1	$1	$1	$1	$5	$1	$1	$1	$1	$1	$10	
3.30 Sub-total, Environmental Studies						$5	$11	$15	$15	$15	$61	$15	$15	$15	$15	$15	$136	
TOTAL, Carbon Mineralization						$20	$45	$75	$90	$95	$325	$90	$85	$73	$68	$59	$700	$697.5
4.00 Coastal & Oceans																		
4.10 Coastal Systems (Blue Carbon)																		
4.11 Fundamental research	#1	N/A	Fundamental understanding of coastal ecosystem CO_2 sequestration.	DOC	NOAA (OAR)	$3	$3	$3	$3	$3	$15	$3	$3	$3	$3	$3	$30	$30-60
				NSF	GEO	$2	$3	$3	$3	$3	$14	$3	$3	$3	$3	$3	$29	
4.12 Resource assessment	#2	N/A	Coastal resource mapping and evaluation.	DOC	NOAA (OAR)	$1	$1	$1	$1	$1	$5	$1	$1	$1	$1	$1	$10	$20
				NASA	ESD	$1	$1	$1	$1	$1	$5	$1	$1	$1	$1	$1	$10	
4.13 Regional field trials	#3, #5	N/A	Monitored field trials of restoration optimized for CO_2 sequestration.	DOC	NOAA (Fisheries)	$10	$25	$50	$50	$50	$185	$50	$50	$50	$50	$50	$435	$500
				DOD	USACE	$10	$25	$25	$25	$25	$110	$25	$25	$25	$25	$25	$235	
4.14 National Coastal Wetland Data Center	#4	N/A	Integrate and manage data on coastal ecosystem CDR research.	DOC	NOAA (OAR)	$2	$2	$2	$2	$2	$10	$2	$2	$2	$2	$2	$20	$20
4.15 Coastal blue carbon project deployment	#6	N/A	Social science research on deployment incentives	N/A	N/A	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$50
4.10 Sub-total, Coastal Systems (Blue Carbon)						$29	$60	$85	$85	$85	$344	$85	$85	$85	$85	$85	$769	
4.20 Marine Biomass Capture & Storage																		

4.21 Aquatic biomass cultivation	N/A	GESAMP: #5.9	Management practices and phenotype selection for aquatic biomass production (primarily seaweed/macroalgae).	DOC	NOAA (OAR)	$1	$3	$5	$5	$5	$19	$5	$5	$5	$3	$3	$40	N/A
				DOE	EERE (BETO)	$1	$3	$5	$5	$5	$19	$5	$5	$5	$2	$2	$38	
4.22 Aquatic biomass energy conversion	N/A	GESAMP: #5.9	Technology development and pilots for aquatic biomass conversion and carbon capture. Possible large-scale ocean-based experiments in latter five years.	DOE	EERE (BETO)	$2	$5	$10	$15	$15	$47	$15	$15	$10	$10	$10	$107	N/A
4.20 Sub-total, Marine Biomass Capture & Storage						$4	$11	$20	$25	$25	$85	$25	$25	$20	$15	$15	$185	
4.30 Alkalinity Modification																		
4.31 Fundamental research	N/A	GESAMP: #5.13	Fundamental research in techniques for and impacts of artificial modification of ocean alkalinity.	NSF	GEO	$2	$5	$8	$8	$8	$31	$8	$8	$8	$8	$8	$71	N/A
				DOE	SC (BER)	$2	$5	$7	$7	$7	$28	$7	$7	$7	$7	$7	$63	
4.32 Applied alkalinity modification techniques	N/A	GESAMP: #5.13	At-sea, small-scale experiments on alkalinity enhancement techniques.	DOC	NOAA (OAR)	$0	$0	$5	$20	$40	$65	$40	$30	$20	$15	$5	$175	N/A
				NSF	GEO	$0	$0	$5	$10	$10	$25	$10	$10	$10	$5	$5	$65	
4.30 Sub-total, Alkalinity Modification						$4	$10	$25	$45	$65	$149	$65	$55	$45	$35	$25	$374	
4.40 Ocean Fertilization																		
4.41 Fundamental research	N/A	GESAMP: #5.1	Fundamental research and modeling on artificial enhancement of primary productivity and impacts on carbon cycle.	NSF	GEO	$2	$6	$8	$8	$8	$32	$8	$8	$8	$8	$8	$72	N/A
				DOC	NOAA (OAR)	$2	$3	$3	$3	$3	$14	$4	$4	$4	$4	$4	$34	
				DOE	SC (BER)	$0	$3	$3	$3	$3	$12	$3	$3	$3	$3	$3	$27	
4.42 Artificial ocean iron fertilization	N/A	GESAMP: #5.1	Small-scale experiments within internationally agreed frameworks.	DOC	NOAA (OAR)	$0	$0	$5	$10	$10	$25	$10	$10	$10	$10	$10	$75	N/A
				NSF	GEO	$0	$0	$5	$5	$5	$15	$5	$5	$5	$5	$5	$40	

4.43 Artificial ocean macronutrient fertilization	N/A	GESAMP: #5.2	Small-scale experiments within internationally agreed frameworks.	DOC	NOAA (OAR)	$0	$0	$5	$5	$5	$15	$5	$5	$5	$5	$5	$40	N/A
				NSF	GEO	$0	$0	$5	$5	$5	$15	$5	$5	$5	$5	$5	$40	
4.40 Sub-total, Ocean Fertilization						$4	$12	$34	$39	$39	$128	$40	$40	$40	$40	$40	$328	
4.50 Ocean Environmental Assessments																		
4.51 CO_2 impacts & fate in oceans	N/A	N/A	Monitoring, research, and modeling on ecological impacts of ocean CDR techniques.	DOC	NOAA (OAR)	$2	$5	$5	$5	$5	$22	$5	$5	$5	$5	$5	$47	N/A
				DOE	SC (BER)	$2	$5	$5	$5	$5	$22	$5	$5	$5	$5	$5	$47	
4.50 Sub-total, Ocean Environmental Assessments						$4	$10	$10	$10	$10	$44	$10	$10	$10	$10	$10	$94	
TOTAL, Coastal & Oceans						**$45**	**$103**	**$174**	**$204**	**$224**	**$750**	**$225**	**$215**	**$200**	**$185**	**$175**	**$1,750**	**$620-650**
5.00 Geologic Sequestration																		
5.10 Advanced Storage R&D																		
5.11 Reduction of seismic risk	#43	N/A	Experiments, modeling, and lab research to reduce risks of induced seismicity from CO_2 injection in saline aquifers.	DOE	FE	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$500
5.12 Injection site research & monitoring	#44	N/A	Research and monitoring program to accompany commercial injection at CarbonSAFE sites.	DOE	FE	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$450
5.13 Improved long-term monitoring systems	#45	N/A	Technology development and field demonstrations of low-cost, long-term monitoring systems for large-scale injection sites.	DOE	FE	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$500
5.14 Secondary trapping	#46	N/A	Modeling and improvements to secondary trapping	DOE	FE	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$250
5.15 Simulation for fate & transport	#47	N/A	Improving subsurface fate & transport simulation models.	DOE	FE	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$100

5.16 Assessing risk in compromised storage	#48	N/A	Assessing leakage risk on vadose zone and groundwater.	DOE	FE	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$200
5.17 Public engagement	#50	N/A	Social science research on public engagement for geologic sequestration.	DOE	FE	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$10
5.18 Cross-cutting storage R&D topics	N/A	N/A	To be allocated among 5.11-5.17.	DOE	FE	$20	$50	$50	$50	$50	$220	$50	$50	$50	$50	$50	$470	N/A
5.10 Sub-total, Advanced Storage R&D						$20	$50	$50	$50	$50	$220	$50	$50	$50	$50	$50	$470	
5.20 Regional Demonstrations																		
5.21 CarbonSAFE augmentation	N/A	N/A	Complete qualification process for up to 19 sites.	DOE	FE	$25	$50	$75	$50	$50	$250	$0	$0	$0	$0	$0	$250	N/A
5.22 Regional large-scale sequestration demonstrations	N/A	N/A	Development of up to 10 large-scale sequestration sites.	DOE	FE	$0	$0	$0	$25	$75	$100	$100	$125	$125	$125	$125	$700	N/A
5.20 Sub-total, Regional Demonstrations						$25	$50	$75	$75	$125	$350	$100	$125	$125	$125	$125	$950	
5.30 CO_2-intensive EOR																		
5.31 Co-optimizing CO_2 storage & oil recovery	#49	N/A	Modeling and experiments to develop improved methods for CO_2-intensive EOR, including in residual oil zones and shale oil reservoirs. Assumed 50% cost share.	DOE	FE	$5	$15	$20	$20	$20	$80	$20	$20	$20	$20	$20	$180	$500
5.30 Sub-total, CO_2-intensive EOR						$5	$15	$20	$20	$20	$80	$20	$20	$20	$20	$20	$180	
TOTAL, Geologic Sequestration						**$50**	**$115**	**$145**	**$145**	**$195**	**$650**	**$170**	**$195**	**$195**	**$195**	**$195**	**$1,600**	**$2,510**
6.00 CO_2 Utilization																		
6.10 Carbonation Conversion																		
6.11 Fundamental research	N/A	NASEM 2018b	Controlling carbonation reactions, accelerating carbonation, understanding structure-property relationships.	DOE	SC (BES)	$2	$5	$5	$5	$5	$22	$5	$5	$5	$5	$5	$47	N/A
				NSF	MPS	$3	$5	$5	$5	$5	$23	$5	$5	$5	$5	$5	$48	N/A
6.12 Integrated process design	N/A		Integration of carbonation with	DOE	FE	$2	$5	$5	$5	$5	$22	$5	$5	$5	$5	$0	$42	N/A

		NASEM 2018b; ICEF: #7	CO_2 capture processes	NSF	ENG	$2	$3	$3	$3	$3	$14	$3	$3	$3	$3	$0	$26	
6.13 Alkalinity source pathways	N/A	NASEM 2018b	Developing new, low-emissions sources of alkalinity for carbon mineralization.	DOE	EERE (AMO)	$3	$3	$3	$3	$3	$15	$3	$3	$3	$3	$0	$27	N/A
				DOI	USGS	$3	$3	$3	$3	$3	$15	$3	$3	$3	$3	$0	$27	
6.14 Construction materials	N/A	NASEM 2018b	Carbonate materials development, testing, and certification for construction markets.	DOE	EERE (BTO)	$3	$3	$3	$3	$3	$15	$3	$3	$3	$3	$3	$30	N/A
				DOC	NIST	$2	$2	$2	$2	$2	$10	$2	$2	$2	$2	$1	$19	
6.15 Transportation infrastructure materials	N/A	N/A	Field testing of CO_2U cements and aggregates.	DOT	FHWA	$2	$5	$10	$10	$10	$37	$10	$5	$5	$0	$0	$57	N/A
6.10 Sub-total, Carbonation Conversion						$22	$34	$39	$39	$39	$173	$39	$34	$34	$29	$14	$323	
6.20 Chemical CO_2 Conversion																		
6.21 Fundamental research	N/A	NASEM 2018b	Impurity-tolerant catalyst development, coupled reduction and oxidation reactions, reduced additives	DOE	SC (BES)	$3	$8	$8	$8	$8	$35	$8	$8	$8	$8	$8	$75	N/A
				NSF	MPS	$3	$7	$7	$7	$8	$32	$8	$8	$8	$8	$8	$72	
6.22 New materials development & applications	N/A	NASEM 2018b	Development of new materials, including materials with carbon-carbon bonds (carbon nanotubes, etc).	DOE	SC (BES)	$3	$5	$5	$5	$5	$23	$5	$5	$5	$5	$5	$48	N/A
				NSF	MPS	$2	$5	$5	$5	$5	$22	$5	$5	$5	$5	$5	$47	
6.23 System engineering & process design	N/A	NASEM 2018b	Integrated catalyst-reactor design, system integration. Impurity-tolerant catalyst development, coupled reduction and oxidation reactions, reduced additives	DOE	EERE (AMO)	$5	$10	$10	$10	$10	$45	$5	$5	$5	$5	$0	$65	N/A
6.20 Sub-total, Chemical CO_2 Conversion						$16	$35	$35	$35	$36	$157	$31	$31	$31	$31	$26	$307	
6.30 Biological CO_2 Conversion																		

6.31 Genetic modeling & tools	N/A	NASEM 2018b	Improving CO_2 uptake, conversion, and product accumulation through genetic manipulation.	DOE	SC (BER)	$2	$3	$5	$5	$5	$20	$5	$5	$5	$5	$5	$45	N/A
				NSF	BIO	$2	$3	$5	$5	$5	$20	$5	$5	$5	$5	$5	$45	
6.32 Bioprospecting	N/A	NASEM 2018b	Tools and high-throughput screening for organisms with unique attributes related to CO_2 conversion.	USDA	ARS	$2	$3	$5	$5	$5	$20	$5	$5	$5	$5	$5	$45	N/A
				DOE	SC (BER)	$2	$3	$5	$5	$5	$20	$5	$5	$5	$5	$5	$45	
6.33 New materials development & applications	N/A	NASEM 2018b	Development of new CO_2U products and valorization of co-products for feed, fuel, or other uses.	DOE	EERE (BETO)	$2	$3	$5	$5	$5	$20	$5	$5	$5	$5	$5	$45	N/A
				USDA	ARS	$2	$3	$5	$5	$5	$20	$5	$5	$5	$5	$5	$45	
6.30 Sub-total, Biological CO_2 Conversion						$12	$18	$30	$30	$30	$120	$30	$30	$30	$30	$30	$270	
TOTAL, CO_2 Utilization						**$50**	**$87**	**$104**	**$104**	**$105**	**$450**	**$100**	**$95**	**$95**	**$90**	**$70**	**$900**	**N/A**
7.00 Systems Analysis																		
7.10 Data Collection																		
7.11 CDR data collection & publication	N/A	N/A	Collecting, aggregating, and publishing economy-wide CO_2 flux data and ecosystem CO_2 flux data.	DOE	FE	$5	$15	$20	$20	$20	$80	$20	$20	$20	$20	$20	$180	N/A
7.10 Sub-total, Data Collection						$5	$15	$20	$20	$20	$80	$20	$20	$20	$20	$20	$180	
7.20 Modeling and Assessments																		
7.21 Technology cost & performance	N/A	N/A	Independent tracking, analysis and inter-comparison of costs and performance of CDR technologies and methods.	DOE	FE	$4	$6	$10	$10	$10	$40	$10	$10	$10	$10	$10	$90	N/A
7.22 Integrated carbon systems modeling	N/A	N/A	Integrated modeling of anthropogenic CO_2 emissions, removals, and system impacts.	DOE	FE	$5	$15	$20	$20	$20	$80	$20	$20	$20	$20	$20	$180	N/A
7.20 Sub-total, Modeling and Assessments						$9	$21	$30	$30	$30	$120	$30	$30	$30	$30	$30	$270	
7.30 Decision Science																		

7.31 Research on decision science	N/A	N/A	Research on decision science, social impacts, and public engagement on CDR technologies and methods.	DOE	FE	$2	$4	$4	$4	$4	$18	$5	$5	$5	$5	$5	$43	N/A
				NSF	SES	$2	$4	$4	$4	$4	$18	$5	$5	$5	$5	$5	$43	
				EPA	ORD	$2	$3	$3	$3	$3	$14	$5	$5	$5	$5	$5	$39	
7.30 Sub-total, Decision Science						$6	$11	$11	$11	$11	$50	$15	$15	$15	$15	$15	$125	
TOTAL, Systems Analysis						$20	$47	$61	$61	$61	$250	$65	$65	$65	$65	$65	$575	N/A
8.00 Large-Scale Demonstration Projects																		
8.10 Large-Scale Demonstration Projects																		
8.11 Large-scale demonstration projects	N/A	N/A	Central funding pool to cost-share demonstration projects competitively across all technology areas.	TBD	TBD	$0	$10	$15	$50	$100	$175	$275	$350	$400	$400	$400	$2,000	$1,263-1,313
8.10 Sub-total, Large-Scale Demonstration Projects						$0	$10	$15	$50	$100	$175	$275	$350	$400	$400	$400	$2,000	
TOTAL, Large-Scale Demonstration Projects						$0	$10	$15	$50	$100	$175	$275	$350	$400	$400	$400	$2,000	$1,263-1,313
OVERALL TOTAL						$325	$651	$883	$1,046	$1,195	$4,100	$1,372	$1,404	$1,371	$1,258	$1,195	$10,700	$7,232-9,446

References

- NAS2018a: Negative Emissions Technologies and Reliable Sequestration: A Research Agenda (2018)[1]
- NAS2018b: Gaseous Carbon Waste Streams Utilization: Status and Research Needs (2018)[2]
- GESAMP: High Level Review of a Wide Range of Proposed Marine Geoengineering Techniques (2019)[3]
- ICEF: Direct Air Capture of Carbon Dioxide: ICEF Roadmap 2018 (Chapter 5)[4]

Acronyms and Abbreviations

1. Department of Commerce (DOC)
    a. National Oceanic and Atmospheric Administration (NOAA)
        i. Fisheries (Fisheries)
        ii. Oceanic and Atmospheric Research (OAR)
    b. National Institute of Standards and Technology (NIST)
2. Department of Defense (DOD)
    a. U.S. Army Corps of Engineers (USACE)
    b. Army Research Laboratory (ARL)
    c. Naval Research Laboratory (NRL)
3. Department of Energy (DOE)
    a. Advanced Research Projects Agency-Energy (ARPA-E)
    b. Office of Energy Efficiency and Renewable Energy (EERE)
        i. Advanced Manufacturing Office (AMO)
        ii. Bioenergy Technologies Office (BETO)
        iii. Building Technologies Office (BTO)
    c. Office of Fossil Energy (FE)
    d. Office of Science (SC)
        i. Basic Energy Sciences (BES)
        ii. Biological and Environmental Research (BER)
4. Department of the Interior (DOI)
    a. U.S. Geological Survey (USGS)
5. Department of Transportation (DOT)
    a. Federal Highway Administration (FHWA)
6. Environmental Protection Agency (EPA)
    a. Office of Research and Development (ORD)

7. National Aeronautics and Space Administration (NASA)
    a. Earth Sciences Division (ESD)
8. National Science Foundation (NSF)
    a. Directorate for Biological Sciences (BIO)
    b. Directorate for Engineering (ENG)
    c. Directorate for Geosciences (GEO)
    d. Directorate for Mathematical and Physical Sciences (MPS)
    e. Directorate for Social, Behavioral, and Economic Sciences (SBE)
    f. Division of Social and Economic Sciences (SES)
9. United States Department of Agriculture (USDA)
    a. Agriculture Advanced Research and Development Authority (AGARDA)
    b. Agricultural Research Service (ARS)
    c. National Institute of Food and Agriculture (NIFA)
    d. Natural Resources Conservation Service (NRCS)
    e. U.S. Forest Service (USFS)

[1] https://www.nap.edu/catalog/25259/negative-emissions-technologies-and-reliable-sequestration-a-research-agenda
[2] https://www.nap.edu/catalog/25232/gaseous-carbon-waste-streams-utilization-status-and-research-needs
[3] http://www.gesamp.org/publications/high-level-review-of-a-wide-range-of-proposed-marine-geoengineering-techniques
[4] https://www.icef-forum.org/pdf2018/roadmap/ICEF2018_DAC_Roadmap_20181210.pdf