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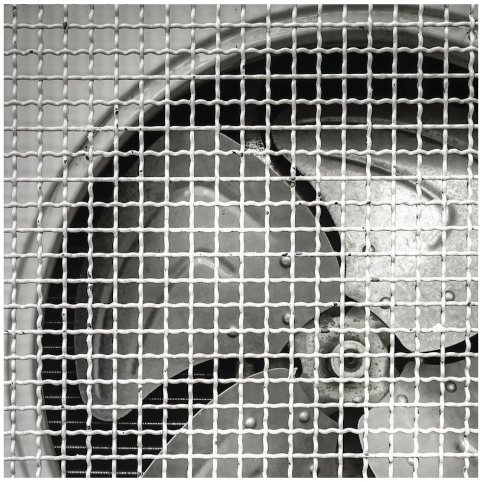

Clearing the Air

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

--SUMMARY REPORT--

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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Project Team

Chairman

Ernest J. Moniz – Founder and CEO

Project Director

Joseph S. Hezir – Principal

Project Lead

Colin McCormick – Consultant

Contributing Authors

Tim Bushman – Senior Analyst

Sam Savitz – Analyst

Additional Contributors

Alex Breckel – Associate Director of Strategic Research

Anne Canavati – Analyst

David Ellis – Director of Strategic Communications

Melanie Kenderdine – Principal

Alex Kizer – Director of Strategic Research

Natalie Volk – Communications & Business Development Associate

Technical Reviewers

EFI would like to thank the following individuals for their technical review of all or portions of the report.

Julio Friedmann – Columbia University and EFI Distinguished Associate

Michael Knotek – EFI Distinguished Associate

Ari Patrinos – Consultant

Dan Sanchez – University of California-Berkeley

Deborah Stine – Consultant

Siobhan A. (Sasha) Wilson – University of Alberta

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.

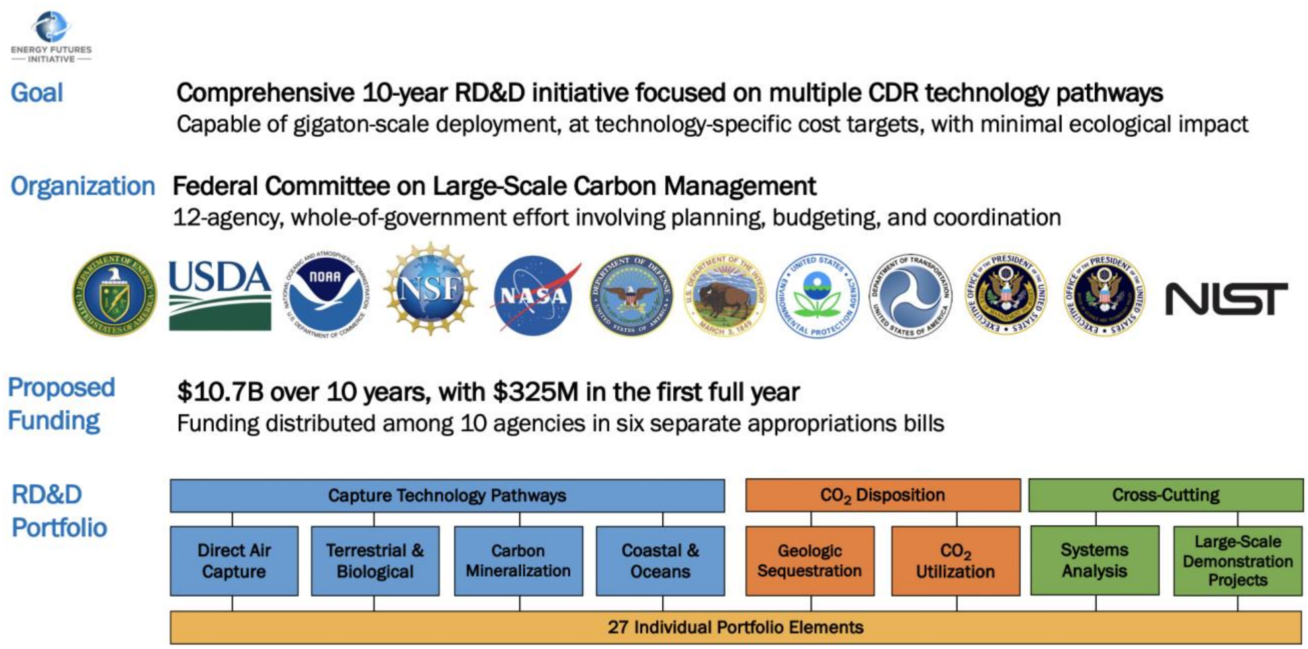
Concerns about the inadequacy of collective emissions mitigation efforts, a growing body of scientific evidence, and current emissions trajectories are reflected in the actions of many foreign governments, including many U.S. states and cities, in their movement towards “net-zero” emissions targets to 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.

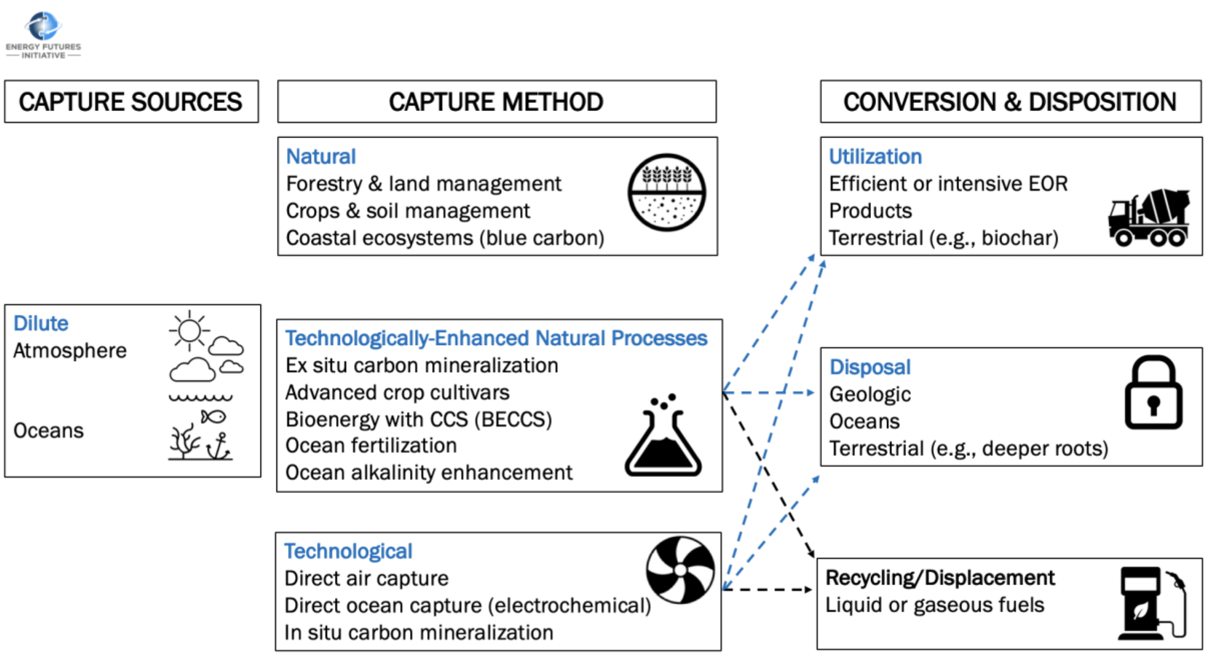
- Clearly defined technology-specific cost objectives and commercial application potential;
- Carefully defined research protocols to fully address and promote collateral environmental and resource benefits and minimize any adverse environmental impacts;
- A logical and transparent initiative structure, 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.

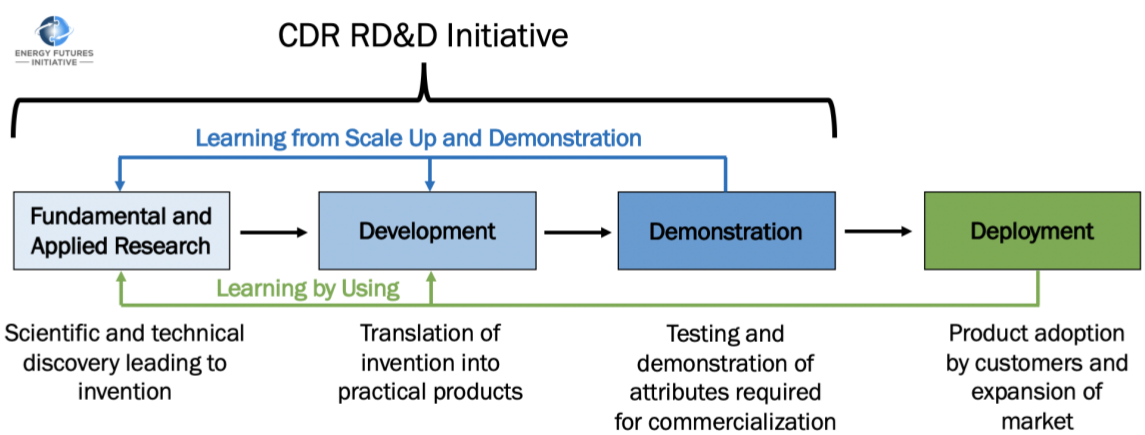
It is extremely important to note that CDR is distinct from geoengineering; the former involves the management of GHG emissions to address climate change, while the latter involves techniques that modify climate such as the management of solar radiation, but do not affect CO_2 fluxes or atmospheric concentrations.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

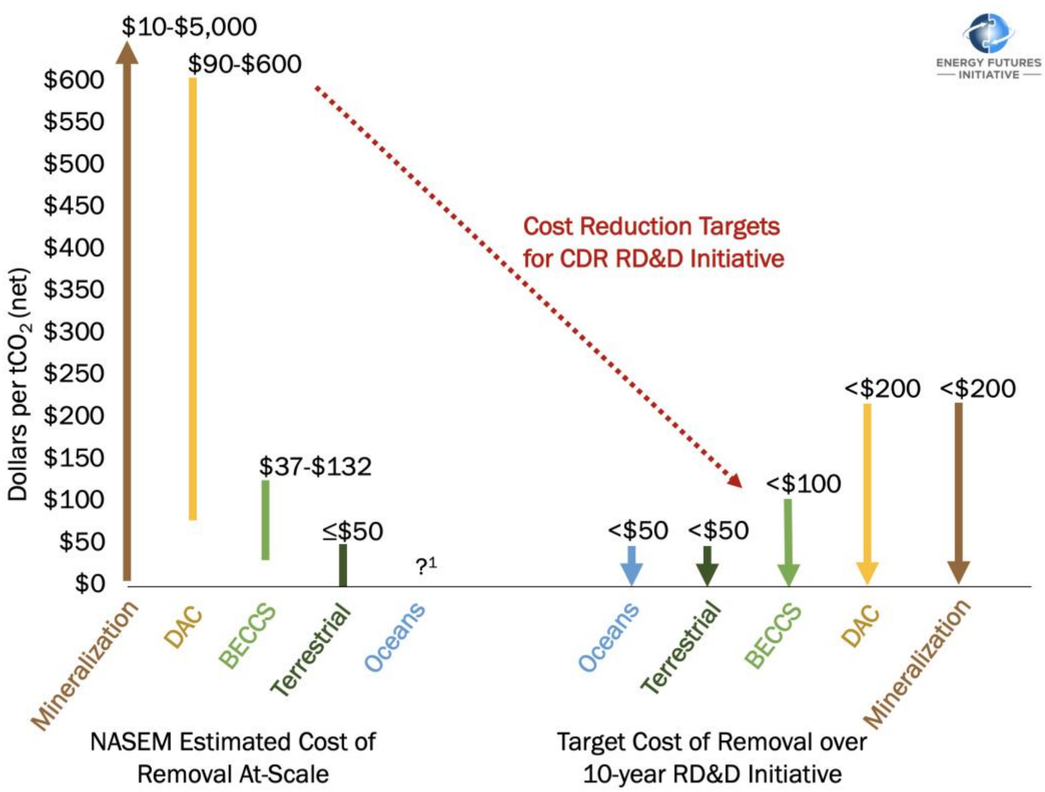
The core objectives supporting this RD&D initiative fall into two categories: potential for scale and technology cost. These categories follow from the considerations of the need for CDR in climate strategy. In order to have a material impact on climate outcomes, technological pathways for CDR must achieve 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



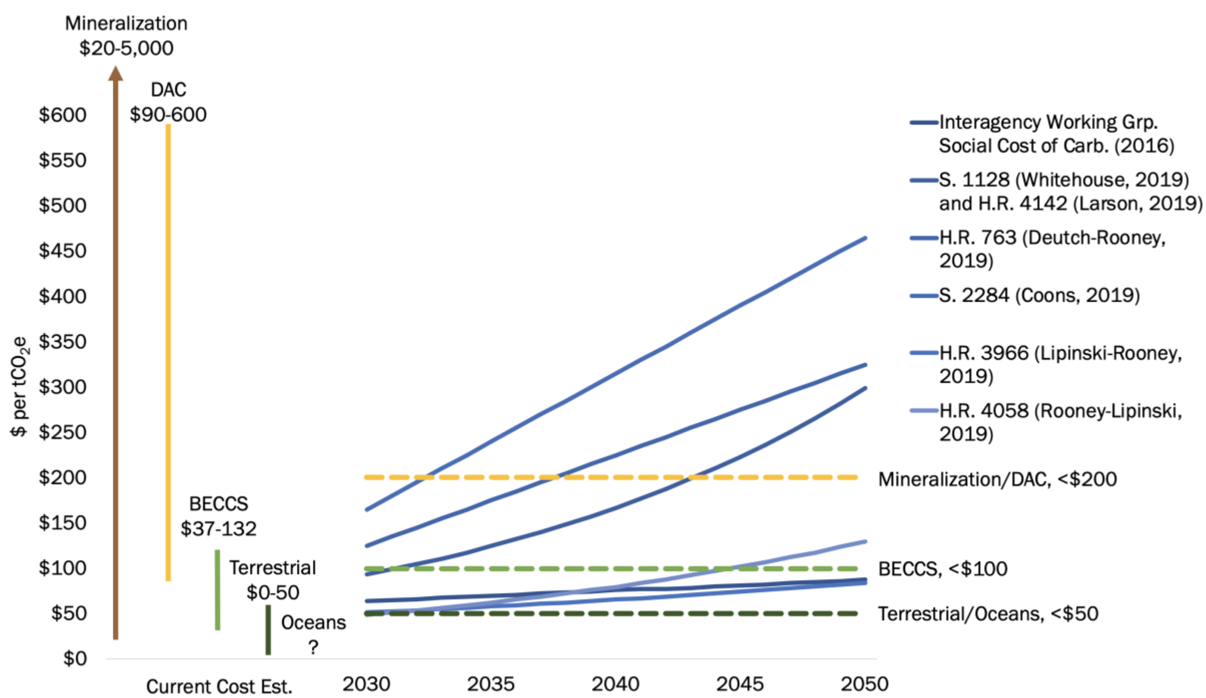
The CDR RD&D initiative cost targets are technology-specific given the high degree of cost uncertainties for various CDR capture technology pathways. [1]Cost estimates were available for blue carbon but not for other oceans-related CDR pathways. Source: EFI, 2019. Compiled using data from the National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

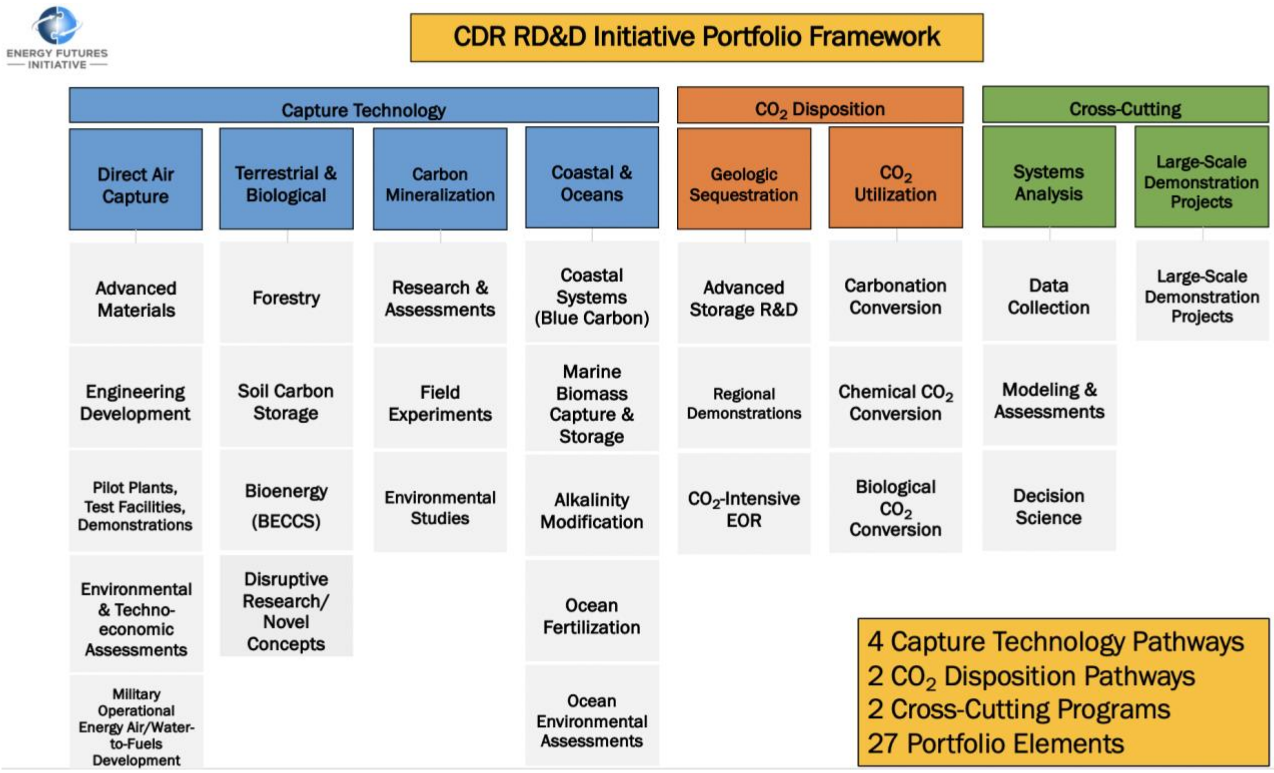
The proposed technological CDR RD&D portfolio framework consists of:

- 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.

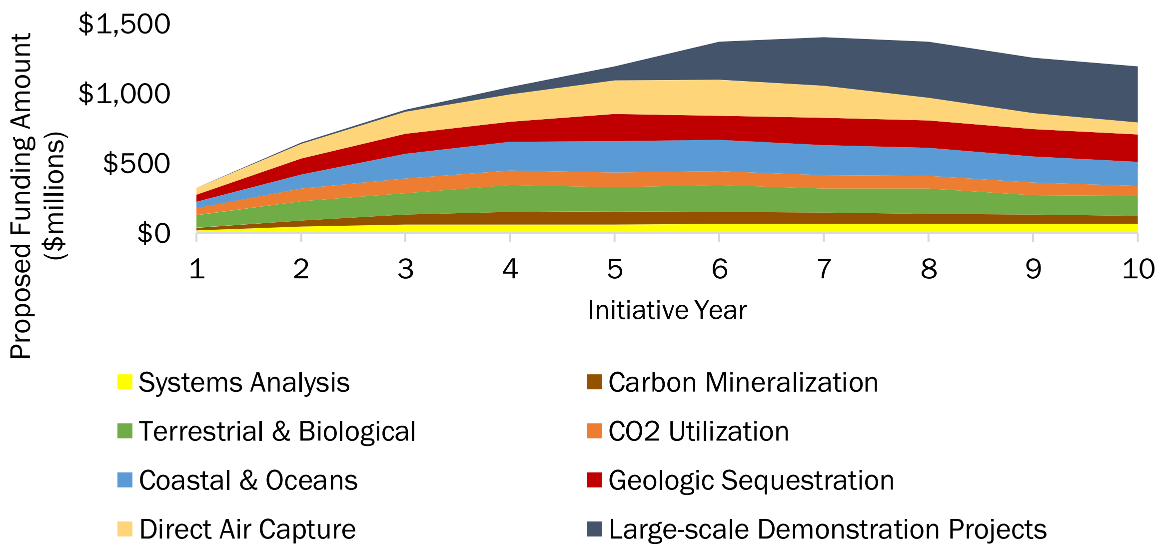
Recommended Budget Planning Estimates

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

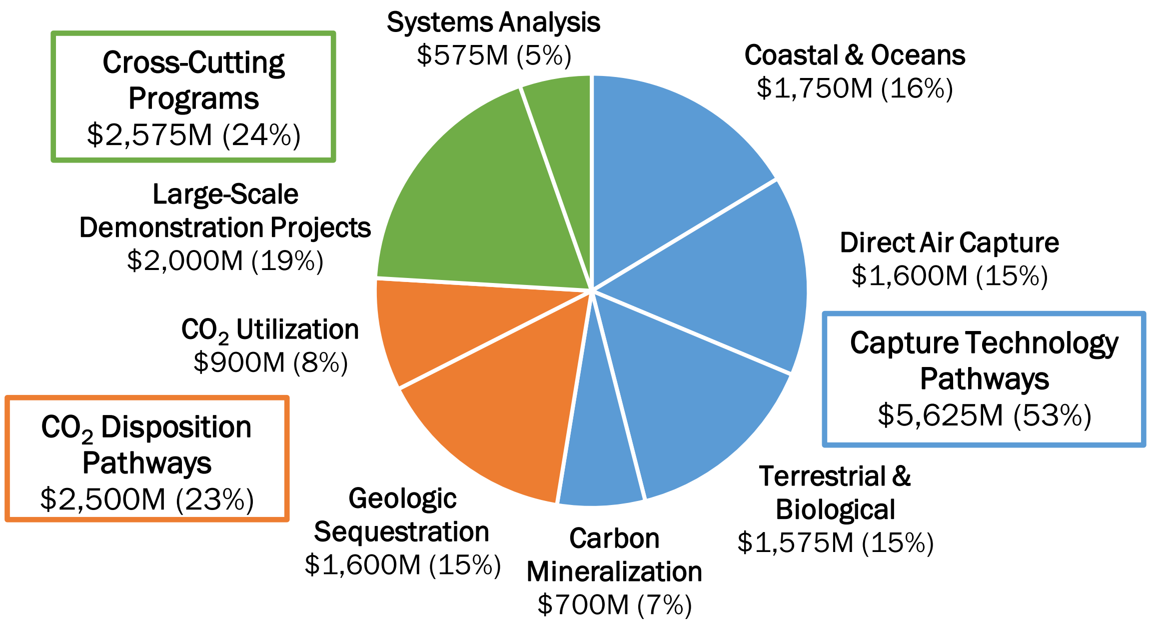


Proposed funding ramps to $325 million in Year 1 and peaks at $1,404 million in Year 7. Source: EFI, 2019.

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.

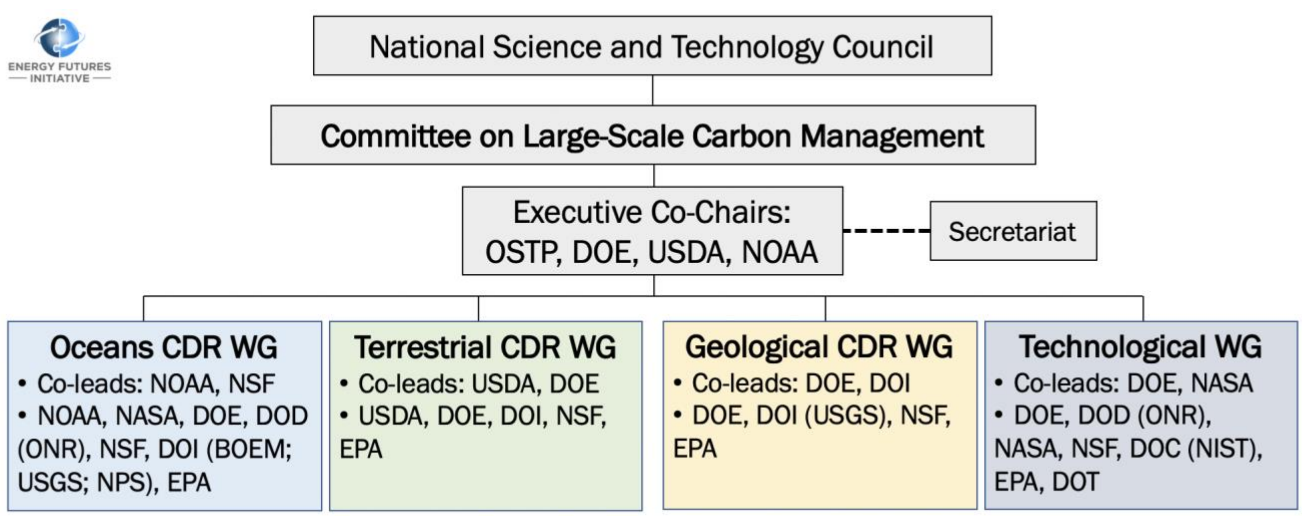
[a] A previous analysis identified a baseline of nine federal agencies that historically supported RD&D activities related to CDR, which could help provide a framework for a federal CDR RD&D initiative. Individual RD&D projects related to CDR were funded in 23 separate appropriations accounts contained 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
9 https://www.nap.edu/catalog/25259/negative-emissions-technologies-and-reliable-sequestration-a-research-agenda
10 https://www.nap.edu/catalog/25259/negative-emissions-technologies-and-reliable-sequestration-a-research-agenda
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/