Carbon Removal:
Comparing Historical Federal Research Investments with the National Academies' Recommended Future Funding Levels

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AUTHORS

Joseph S. Hezir
Principal, Energy Futures Initiative

Tim Bushman
Senior Analyst, Energy Futures Initiative

Dr. Addison K. Stark
Associate Director for Energy Innovation, Bipartisan Policy Center

Erin Smith
Senior Policy Analyst, Bipartisan Policy Center

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Glossary

Afforestation: Planting forest on lands that were originally grasslands or shrublands.

Bioenergy with carbon capture and storage (BECCS): Energy production using plant biomass to produce electricity, liquid fuels, and/or heat combined with capture and sequestration of any carbon emissions produced when using the bioenergy and any remaining biomass carbon that is not in the liquid fuels.

Biochar: A solid carbon product of biomass thermochemical conversion.

Biofuel: Any fuel derived from biomass (plant or algae material or animal waste) rather than a fuel produced by geological processes, such as fossil fuels like coal, petroleum, or natural gas.

Carbon capture: Capturing carbon emissions from a point source (usually large industrial and power plants), compressing it for transformation, and either storing or using the captured carbon dioxide (CO_2). Not a type of CO_2 removal.

Carbon removal (CDR): Intentional efforts to remove CO_2 from the atmosphere. Also referred to as "carbon dioxide removal."

Carbon mineralization: The acceleration of a naturally occurring process in which CO_2 from the atmosphere reacts with minerals to form solid carbonite minerals, both at the surface (ex situ) where CO_2 in the ambient air is mineralized on exposed rock, and in the subsurface (in situ) where concentrated CO_2 streams are injected into rock where it mineralizes in the pores. Also called "accelerated weathering."

Coastal blue carbon: Land-use management practice that increases the carbon stored in living plants or sediments in coastal ecosystems, such as mangroves, tidal marshlands, seagrass beds, and other tidal wetlands.

Direct air capture (DAC): Chemical processes that capture CO_2 from ambient air and concentrate it so that it can be injected into a storage reservoir.

Geologic Sequestration: Process of injecting CO_2 captured from an industrial or energy-related source into deep subsurface rock formations for long-term storage.

Negative emission technologies (NETs): An approach that removes CO_2 from the atmosphere for sequestration. NETs complement carbon capture and sequestration methods that primarily focus on reducing CO_2 emissions from point sources, such as fossil fuel power plants.

Reforestation: Planting forest on lands that used to be forest but were converted to another use.

Terrestrial carbon removal: Land-use and management practices, such as afforestation/reforestation, changes in forest management, or changes in agricultural practices that enhance soil carbon storage.

Overview

Carbon removal encompasses a suite of land-based and technological approaches to removing already-emitted carbon dioxide (CO_2) from the environment.[a] Carbon removal (CDR) approaches—also referred to as "negative emission technologies"—complement mitigation efforts to protect the environment while opening new opportunities for U.S. businesses in a growing global marketplace as many countries move toward a lower-carbon economy. Several companies around the world have built demonstration facilities for direct air capture, a type of technological carbon removal that involves using machines to remove CO_2 directly from the atmosphere, so it can then be sequestered or converted into commercial products, such as fuels, cement, plastic, and chemicals. In February 2018, Congress expanded tax credits (45Q) for carbon capture projects that broadened eligibility to include direct air capture and is actively examining additional legislative opportunities to complement 45Q and facilitate carbon removal technology advancement.

In October 2018, the National Academies of Sciences, Engineering, and Medicine (NASEM) released a report, *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*, that examined the state of carbon removal technology. The findings built on the recent Intergovernmental Panel on Climate Change's (IPCC) *Special Report: Global Warming of 1.5°C*, which found that all pathways that limit temperature rise to no more than 1.5° Celsius require carbon removal. The NASEM report identified barriers to land-based carbon removal approaches (for example, afforestation/reforestation and bioenergy with carbon capture and storage) at the level needed to achieve global climate targets and concluded that significant federal research investment is necessary across a portfolio of carbon removal approaches. The report recommended specific levels of future funding at key federal science agencies that are necessary to advance six types of carbon removal and enabling technologies (see Appendix A).

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Just as decades of federal research investment drove efficiency and cost improvements for many of the technologies Americans enjoy today—including fuel-efficient vehicles, lithium-ion batteries, and natural gas production—so, too, will it be necessary to advance the next generation of technologies involving carbon removal.

As the global appetite for clean technologies grows, the United States stands at a moment of immense opportunity. The United States has a long history of leveraging its scientific and technological capabilities at national laboratories, universities, and the private sector to pioneer advances in technology that move the economy forward. Just as decades of federal research investment drove efficiency and cost improvements for many of the technologies Americans enjoy today—including fuel-efficient vehicles, lithium-ion batteries, and natural gas production—so, too, will it be necessary to advance the next generation of technologies involving carbon removal. The benefits of developing and exporting these technologies include unlocking new market opportunities for U.S. businesses and spurring spillover benefits in other industries.

[a] The scope of CDR as used in this report is focused on capture from dilute concentrations of CO_2 and excludes carbon capture from concentrated CO_2 emissions at the point of fossil fuel combustion. CDR also excludes research on geoengineering approaches—that is, experimentation that seeks to directly modify the Earth's climate system. The scope does include research on carbon storage and sequestration approaches, which are applicable to carbon captured from both concentrated or dilute sources.

The United States currently does not have a dedicated research program for carbon removal. What little[1] federal research funding that has been spent on carbon removal to date has been patchwork and piecemeal. In order to turn the NASEM research, development, and demonstration (RD&D) future funding recommendations into effective solutions, it is critical to examine the historical baseline of federal carbon removal-related investments to ensure new research investments are targeted, complementary, and effective.

SUMMARY

The objective of this analysis is to review the historical baseline estimates of federal RD&D investment related to carbon removal and assess how they compare with the recommended future funding levels from the 2018 NASEM report. The analysis employed two approaches: (1) a top-down analysis to identify federal agency appropriations accounts and major program elements within those accounts that could support RD&D activities related to carbon removal; and (2) a bottom-up analysis to search a database of historical federal spending to identify specific RD&D projects funded in prior years that may have directly or indirectly supported carbon removal scientific and technical objectives. The historical analysis provides further insight into the federal programs that could form the nucleus of a future carbon removal RD&D program, as well as establishing a baseline level of historical RD&D investments related to carbon removal.

The top-down analysis identified 23 separate appropriations accounts within nine federal departments and agencies that contain program elements with sufficiently broad research program scope that they could encompass RD&D support for carbon removal. These appropriations accounts and program elements present opportunities to add or redirect federal funding to support RD&D projects in support of carbon removal objectives with little or no additional legislative authorization other than direction in appropriations bills.

The bottom-up analysis identified cumulative federal funding totaling $3,717.1 million across 1,409 carbon removal-related RD&D projects over a 27-year period from 1993 to 2019. This historical record is very small relative to the recommended funding levels by NASEM—$8.1 to $10.5 billion—over the next one to two decades. It is especially small given that the research projects identified in the historical baseline primarily targeted other science and technology objectives, and may only tangentially address potential carbon removal applications. For example, the historical data revealed only 15 research projects totaling $10.9 million related to direct air capture technology, with over half devoted to military or space applications.

Ten federal departments and agencies supported the carbon removal-related RD&D projects, with the U.S. Department of Energy (DOE) providing 91 percent of the total funding. (Note: The list of federal departments and agencies coincides with the top-down analysis except for the U.S. Department of Defense, which the bottom-up analysis identified but was not included in the top-down analysis.) Results from the bottom-up analysis were compared with the future funding levels recommended in the 2018 NASEM report (see Figure 1).

KEY FINDINGS

- Federal agencies have historically funded some carbon removal-related RD&D projects in all of the major categories recommended in the NASEM report; however, that funding has been scattered and piecemeal as the United States does not have a dedicated research program for carbon removal.
- Historical funding was concentrated by carbon removal category in carbon sequestration—approximately one-half (49 percent) of estimated federal funding for about 20 percent of the total projects identified in the bottom-up analysis.[b]
- Slightly more than half of the remaining historical funding—$1,879.5 million—was targeted to various forms of terrestrial and biological carbon capture.
- Very little funding was invested historically in other technologically enhanced forms of carbon removal—for example, $10.9 million total (spanning an 11-year period) for direct air capture and $24.7 million total (over a 17-year period) for research on carbon mineralization.

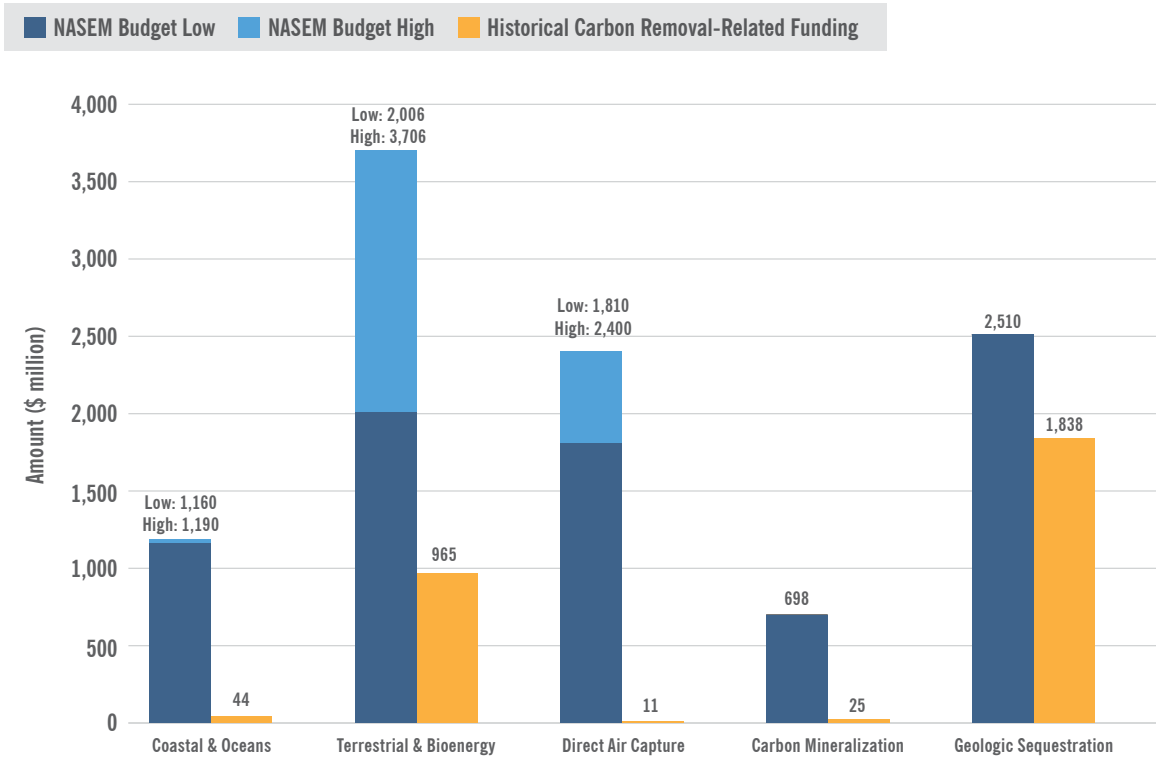
For all categories of carbon removal-related RD&D, the historical baseline investments were significantly lower than the future funding levels recommended in the NASEM report. Figure 1 displays historical RD&D investment levels identified in the analysis along with the NASEM recommended future levels for each major category of carbon removal. Note that these two sets of data are not directly comparable. While the NASEM committee was generally aware of many of the historical carbon removal-related RD&D activities, it did not have detailed available data on historical investment levels, as shown in Figure 1. Consequently, the NASEM report identified recommended future funding levels for various elements of the carbon removal-related RD&D portfolio that are primarily in addition to existing levels, but it did not make any assumptions as to what a future baseline spending level might be in the absence of the report recommendations. Similarly, the fact that this analysis was able to identify in some detail the historical levels of investment in carbon removal-related RD&D should not be viewed as a future budget baseline funding level in the absence of affirmative congressional action on the fiscal year (FY) 2020 (and future) budgets. Nonetheless, comparing the historical levels of investment with recommended future funding levels does illustrate the scale of future funding challenges to the implementation of the NASEM report. The challenges are particularly acute for implementing the NASEM recommendations for RD&D on direct air capture, mineralization, and coastal and oceans carbon removal:

- NASEM-recommended future funding needs for direct air capture are 100 to 200 times the historical baseline level;
- NASEM-recommended future funding needs for carbon mineralization are nearly 30 times the historical baseline level;
- NASEM-recommended future funding needs for coastal and oceans carbon removal-related research are nearly 30 times the historical baseline level; and
- Even in the categories of terrestrial and bioenergy and geologic sequestration, the future funding levels recommended in the NASEM report represent significantly higher future funding levels compared with the historical baseline estimates.

[b] Research on carbon sequestration enables the storage of carbon captured from both concentrated sources (for example, fossil fuel combustion) as well as dilute sources of carbon in the atmosphere.

Figure 1. Historical Investments in Carbon Removal-Related RD&D and Comparison with NASEM-Recommended Future Funding Levels

(in millions of dollars, rounded to the nearest whole number)



Sources: Energy Futures Initiative,[2] Bipartisan Policy Center,[3] National Academies of Sciences, Engineering, and Medicine.[4] Compiled using data from USASpending.gov.[5]

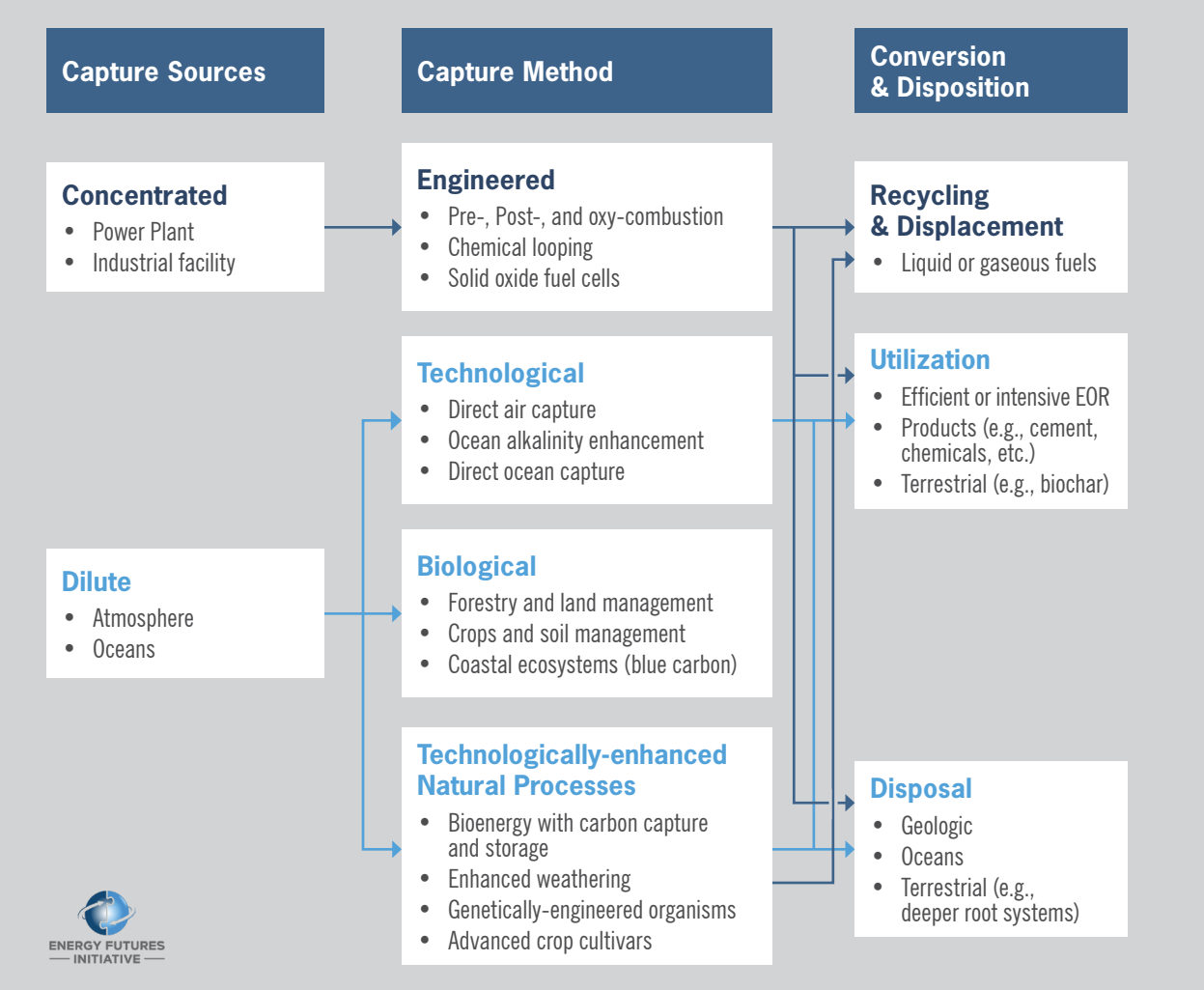
Where applicable, the estimates for the cumulative NASEM budget used both the lower- and upper-bound estimates for funding needs and time durations to arrive at cost ranges. In instances where time durations were listed as greater than or equal to a certain number, the lowest relevant number of years was used.

Background

Despite international commitments to decrease economy-wide greenhouse gas (GHG) emissions and limit an increase in global average surface temperature to no more than 1.5° to 2.0° Celsius,[6] GHG emissions continue to rise. In 2017, energy-related CO_2 emissions grew by 1.4 percent globally,[7] and were expected to increase again in 2018 among the world's advanced economies.[8] The recent uptick in annual GHG emissions, and continued escalation of the cumulative atmospheric stock of CO_2, challenges the mitigation efforts required to reach the global target of net-zero emissions by 2050 to limit warming to 1.5° Celsius or by 2070 to limit warming to 2.0° Celsius.[9]

Given the difficult-to-abate nature of certain economic sectors (for example, heavy industry) and the possible need to compensate for a temperature overshoot, analyses increasingly show that carbon removal will need to serve as a complement to mitigation in order to avoid the worst impacts of climate change. According to the IPCC, carbon removal at the (cumulative) scale of 100 to 1,000 billion tons of CO_2 will be required by the end of the century to limit the increase in warming to no more than 1.5° Celsius.[10] Furthermore, 87 percent of the scenarios from the IPCC's *Fifth Assessment Report*[11] deployed carbon removal during the period 2050 to 2100 to limit warming to no more than 2.0° Celsius.[12] This underscores the need for a broad portfolio of carbon removal approaches that can capture dilute CO_2 emissions from the atmosphere or oceans and facilitate a net reduction in emissions (see Figure 2).

Figure 2. Technical Pathways for Carbon Dioxide Removal



Technical pathways for carbon removal are shown in blue. Note that the determination of whether negative emissions have been achieved is dependent on the capture source, capture method, and the conversion and disposition of the CO_2. For example, if the captured CO_2 is used to make synthetic fuels, then the process is likely to be carbon-neutral, because the embodied CO_2 would ultimately be returned to the atmosphere after combustion. However, applications like these can provide market drivers for carbon removal approaches that achieve negative emissions. CO_2 that is embedded in long-lived products (for example, cement) or stored in various geologic formations (for example, oil and gas reservoirs) would likely result in negative emissions. Where applicable, the determination of net-negative emissions also hinges on the use of clean energy (both electrical and thermal) from a lifecycle analysis standpoint. (Note: EOR is "enhanced oil recovery.")

Sources: Energy Futures Initiative, 2019.[13] Graphics courtesy the Noun Project.[14]

Carbon removal can employ technological, biological, or technologically enhanced natural processes to accomplish negative emissions. Technological approaches include mechanical systems or chemical processes that separate CO_2 from ambient air (primarily a nitrogen and oxygen mixture) or seawater. Although these methods tend to be more costly and require greater RD&D, they carry a lower risk of reversal (or loss) of the captured CO_2. Further, as the NASEM report showed, approaches such as direct air capture and carbon mineralization have nearly unlimited CO_2 removal capacity. Biological approaches, which use natural processes and photosynthesis to capture CO_2, are less costly[c] (and closer to the deployment stage) but carry a higher risk of reversal.[15] However, these land-based approaches face competition for other land uses (for example, food production) that potentially limit their total CO_2 removal capacity, underscoring that a portfolio of approaches is necessary. Technologically enhanced natural processes are a hybrid category that uses a combination of approaches to accomplish carbon removal.

Two previous analyses from the U.S. Government Accountability Office (GAO) have reported on historical federal funding for climate change-related programs. The 2010 GAO report identified $99 million across 43 research activities (FY 2009 to FY 2010) focused on basic science or mitigation strategies (for example, including geologic sequestration).[16] The 2018 GAO report identified 18 programs (out of 533 programs reviewed) across six federal agencies (DOC, DOD, DOE, NASA, NSF, USDA) that were primarily dedicated to addressing climate change. The report also noted that the Office of Management and Budget separately identified $154 billion in federal investments (FY 1993 to 2017) for climate change activities ranging from climate change science, adaptation, clean energy technologies, and international assistance.[17,18]

These prior studies did not single out carbon removal, i.e.—that is, approaches to remove dilute concentrations of CO_2 from the atmosphere or oceans—as a discrete program activity. The objective of this analysis was to review the historical baseline estimates of federal RD&D investment related to carbon removal and assess how they compare with the recommended future funding levels from the 2018 NASEM report *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*.[19] The top-down analysis identified appropriations accounts and program elements that could support carbon removal-related RD&D activities using federal agency budget request documents. The bottom-up analysis provided an estimate of historical carbon removal-related RD&D investments at the project-level using a search of federal grant spending. These analyses are intended to be complementary and provide a more holistic understanding of historical federal investment for carbon removal-related RD&D.

[c] NASEM previously reported that afforestation and reforestation, forest management, agricultural soil management, and bioenergy with carbon capture and storage are ready for deployment at a cost of less than $100 per ton of CO_2 in *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*.

Top-Down Analysis

Top-down, program-level spending for RD&D activities that could support carbon removal was compiled using federal budget request documents for the following nine agencies: Denali Commission (DENALI), U.S. Department of Commerce (DOC), Department of Energy (DOE), U.S. Department of the Interior (DOI), Department of Transportation (DOT), Environmental Protection Agency (EPA), National Aeronautics and Space Administration (NASA), National Science Foundation (NSF), and U.S. Department of Agriculture (USDA). The results of the top-down analysis are presented for FY 2017 to FY 2018.

RESULTS

The top-down analysis identified 23 separate appropriations accounts within nine federal departments and agencies that contain program elements with sufficiently broad research program scope that could encompass RD&D support for carbon removal (see Table 1). These appropriations accounts and program elements present opportunities to add or redirect federal funding to support RD&D projects related to carbon removal objectives with little or no additional legislative authorization other than direction in appropriations bills. The U.S. Department of Defense (DOD) was not included in this analysis. Although DOD-funded RD&D provide important contributions to the knowledge base for carbon removal, the DOD carbon removal-related RD&D activities have national security objectives as their primary purpose.

Table 1. Appropriations for Programs Conducting RD&D with Potential Relevance to Carbon Removal

Department/ Agency/ Organization	Appropriations Account	Program Element	FY 2017 Enacted (millions of dollars)	FY 2018 Estimate (millions of dollars)	Notes
DENALI	DENALI	n/a	32.0	28.0	Provide critical utilities, infrastructure, and economic support throughout Alaska
DOC/National Oceanic and Atmospheric Administration (NOAA)	Operations Research and Facilities	National Ocean Service	n/a	513.9	Observe, measure, assess, and manage coastal, ocean, and marine areas
	Operations Research and Facilities	NOAA	n/a	474.5	Enhance protection of coastal and ocean resources
	Gulf Coast Ecosystem Restoration Science, Observation, Monitoring, and Technology	Gulf Coast Restoration	6.0	6.0	Initiate and sustain an integrative, holistic understanding of the Gulf of Mexico ecosystem
DOE/Advanced Research Projects Agency-Energy (ARPA-E)	ARPA-E	ARPA-E Projects	276.8	274.9	New energy technologies, including new ways to generate, store, and use energy

Department/ Agency/ Organization	Appropriations Account	Program Element	FY 2017 Enacted (millions of dollars)	FY 2018 Estimate (millions of dollars)	Notes
DOE/Office of Energy Efficiency and Renewable Energy (EERE)	EERE	Bioenergy Technologies	205.0	203.6	Research on biomass conversion to bioenergy and bioproducts
DOE/Office of Fossil Energy (FE)	FE Research and Development	Carbon Capture, Utilization, and Storage	196.3	0	Research on pre- and post-combustion capture, compression, and CO_2 utilization
DOE/Office of Science	Office of Science	Basic Energy Sciences	1,871.5	1,858.8	Energy-related research
	Office of Science	Biological and Environmental Research	612.0	607.8	Research on biological, biogeochemical, and physical properties of natural systems
DOI/U.S. Geological Survey (USGS)	Surveys, Investigations, and Research	Core Science Systems: National Cooperative Geologic Mapping Program	24.4	24.2	Research on geological resources
	Surveys, Investigations, and Research	Core Science Systems: National Geospatial Program	67.4	66.9	Geospatial research on topography, natural landscape, and built environment
	Surveys, Investigations, and Research	Energy and Mineral Resources: Mineral Resources Program	48.4	48.0	Research on non-fuel mineral potential, production, consumption, and interaction with the environment
	Surveys, Investigations, and Research	Natural Hazards: Coastal/Marine Hazards and Resources Program	40.5	40.2	Research on the hazard and resource potential of offshore and coastal areas
	Surveys, Investigations, and Research	Land Resources: Land Change Science Program	38.2	37.9	Research support for land-use decisions
	Surveys, Investigations, and Research	Land Resources: National Land Imaging Program	85.8	85.2	Research on changes in landscapes and natural resources

Department/ Agency/ Organization	Appropriations Account	Program Element	FY 2017 Enacted (millions of dollars)	FY 2018 Estimate (millions of dollars)	Notes
DOT/Federal Highway Administration	Federal-Aid Highways (Highway Trust Fund) (Contract Authority)	Research, Technology, and Education Program	218.0	218.0	Construction, maintenance, and preservation of highways, bridges, and tunnels
DOT/Federal Aviation Administration	Research, Engineering, and Development (Airport and Airway Trust Fund)	Reduce Environmental Impact of Aviation	43.0	33.0	Investments in airport and airway systems; research on use of biofuels in aviation
EPA	State- and Tribal-Assistance Grants	Categorical Grant: Underground Injection Control	10.6	10.4	Permitting, oversight, implementation, and outreach related to injection wells
NASA	Deep Space Exploration Systems	Advanced Exploration Systems	97.8	n/a	Includes development of technology options for atmosphere revitalization, such as CO_2 removal and reduction; amine-based CO_2 removal systems as alternate approaches to current zeolite-based sorbent system
	Exploration Research and Technology	CO_2 Conversion Challenge	n/a	n/a	$1 million prize to develop synthesis technologies that convert CO_2 into molecules for bio-manufacturing in space

Department/ Agency/ Organization	Appropriations Account	Program Element	FY 2017 Enacted (millions of dollars)	FY 2018 Estimate (millions of dollars)	Notes
NSF	Research and Related Activities	Biological Sciences: Molecular and Cellular Biosciences	137.0	n/a	Fundamental research on complex living systems
	Research and Related Activities	Biological Sciences: Environmental Biology	145.4	n/a	Research on evolutionary and ecological processes
	Research and Related Activities	Engineering: Chemical, Bioengineering, Environmental, and Transport Systems	183.5	n/a	Support research in chemical engineering, biotechnology, bioengineering, and environmental engineering
	Research and Related Activities	Geosciences: Atmospheric and Geospace Sciences	253.37	n/a	Fundamental research on physical, chemical, and biological processes related to matter between the sun and Earth's surface
	Research and Related Activities	Geosciences: Earth Sciences	179.1	n/a	Research on the structure, composition, and evolution of Earth and Earth materials
	Research and Related Activities	Geosciences: Ocean Sciences	316.7	n/a	Research on all aspects of oceans and ocean basins
	Research and Related Activities	Mathematical and Physical Sciences: Chemistry	246.2	n/a	Research on chemical sciences
	Research and Related Activities	Mathematical and Physical Sciences: Materials Research	314.3	n/a	Research on advancing materials discovery, design, synthesis, and characterization
	Research and Related Activities	Social, Behavioral, and Economic Sciences	97.9	n/a	Research on individual, social, and organizational behavior
USDA/Farm Service Agency	Commodity Credit Corporation Fund	Biomass Crop Assistance Program	5.0	0	Provide assistance to farmers and forest landowners for growing, maintaining, and harvesting biomass
	Reforestation Pilot Program	Reforestation Pilot Program	1.0	1.0	Reforestation efforts

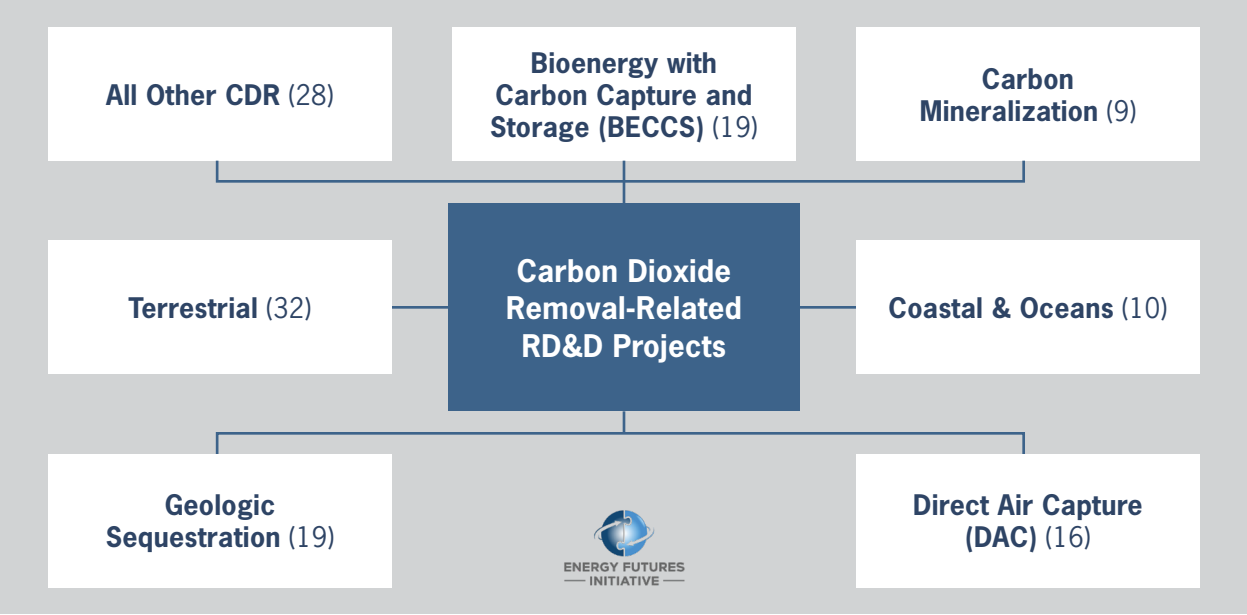
Department/ Agency/ Organization	Appropriations Account	Program Element	FY 2017 Enacted (millions of dollars)	FY 2018 Estimate (millions of dollars)	Notes
USDA/U.S. Forest Service (USFS)	Forest and Rangeland Research	Forest and Rangeland Research	308.0	306.0	Productive and sustainable use of lands; wildfire risk mitigation
USDA/Natural Resources Conservation Service (NRCS)	Private Lands Conservation Operations	Conservation Technical-Assistance Program	759.0	754.0	Conservation practices to improve farm operations and enhance environmental sustainability
	Farm Security and Rural Investment Programs (Mandatory Spending)	Environmental Quality Incentives Program	1,551.0	1,524.0	Key performance measure: soil carbon retained on cropland to improve yields and sequester carbon
	Private Lands Conservation Operations	Soil Surveys	81.0	80.0	Conservation practices to improve farm operations and enhance environmental sustainability
USDA/National Institute of Food and Agriculture	Biomass Research and Development	Biomass Research and Development	3.0	0	Agricultural research, extension, and higher education
USDA/Agricultural Research Service	Salaries and Expenses	Crop Production	226.0	224.0	Animal and crop protection and production; natural resource conservation
USDA/Economic Research Service (ERS)	ERS	n/a	87.0	86.0	Inform decision-making on economic and policy issues related to food and natural resources
USDA/National Agricultural Statistics Service (NASS)	NASS	n/a	171.0	170.0	Provide statistics on agriculture

Sources: Energy Futures Initiative.[20] Compiled using data from DOC,[21] DOE,[22] ,[23] DOI,[24] EPA,[25] NASA,[26] ,[27] NSF,[28] Office of Management and Budget,[29] and USDA.[30]

Bottom-Up Analysis

Bottom-up, project-level searches of federal grant spending for carbon removal-related RD&D was performed February 8 and 9, 2019, using USAspending.gov.[d] Seven categories of carbon removal (CDR), drawn from the NASEM report categories, were used to organize the search results (see Figure 3). The category "All Other CDR" was used as a generic category to capture carbon removal-related projects (for example, CO_2 utilization and conversion) that did not fall into the other six categories. A total of 133 unique search terms (shown in Appendix B) were identified across the seven categories and applied to search through research projects in the database. The list of search terms was deliberately broad in scope to maximize the possibility of capturing all potentially relevant carbon removal-related RD&D. Similarly, other search filters were intentionally broad, including all fiscal years available in the database, multiple award types (block grants, formula grants, project grants, and cooperative agreements), and all federal agencies. The time period included projects from FY 2008 to FY 2019 but returned results from 1993 to 2019 based on the period of performance start dates from the final list of projects that were analyzed.

Figure 3. Number of Search Terms by Category for Historical Federal Investment in Carbon Removal-Related RD&D



Source: Compiled using data from USAspending.gov.[31]

A total of 133 unique search terms were used across seven categories for the bottom-up analysis. The numbers in parentheses indicate the amount of search terms used in each category. *Bioenergy with carbon capture and storage* involves harvesting bioenergy crops or biomass waste products to produce electricity, biofuels, or thermal energy (with capture and storage of the CO_2). *Carbon mineralization* involves reacting CO_2 with rocks or mining wastes for sequestration. *Coastal and oceans* involves sequestering CO_2 in various marine ecosystems. *Direct air capture* involves the separation of CO_2 from ambient air for utilization or sequestration. *Geologic sequestration* involves permanent sub-surface disposal options for CO_2 in locations such as saline formations, oil and gas reservoirs, and un-minable coal seams. *Terrestrial* involves sequestering CO_2 in terrestrial ecosystems through mechanisms such as afforestation, reforestation, and soil management. *All other CDR* was used as a generic category to capture carbon removal-related projects that did not fall into the other six categories, such as CO_2 utilization and conversion.[32]

[d] USAspending.gov is the official source of federal spending data in the United States.

The initial screening yielded a total of 16,529 rows of project-level information. The data were screened according to the following steps: (1) 856 rows were deleted that either had a zero or negative number for the federally obligated amount; (2) 3,938 duplicate projects were removed; (3) 482 rows were deleted to eliminate data from 13 agencies that were deemed to not have relevance for this analysis (the African Development Foundation, the Agency for International Development, the Corporation for National and Community Service, the U.S. Department of Health and Human Services, the U.S. Department of Homeland Security, the U.S. Department of Housing and Urban Development, the U.S. Department of Justice, the U.S. Department of State, the U.S. Department of the Treasury, the Institute of Museum and Library Services, the Inter-American Foundation, the National Endowment for the Arts, and the National Endowment for the Humanities). Note that in instances where there were more than one performer for the same project, each performer is included in the analysis since each had a unique project identification number. Following these steps, there were a total of 11,253 rows of project-level information.

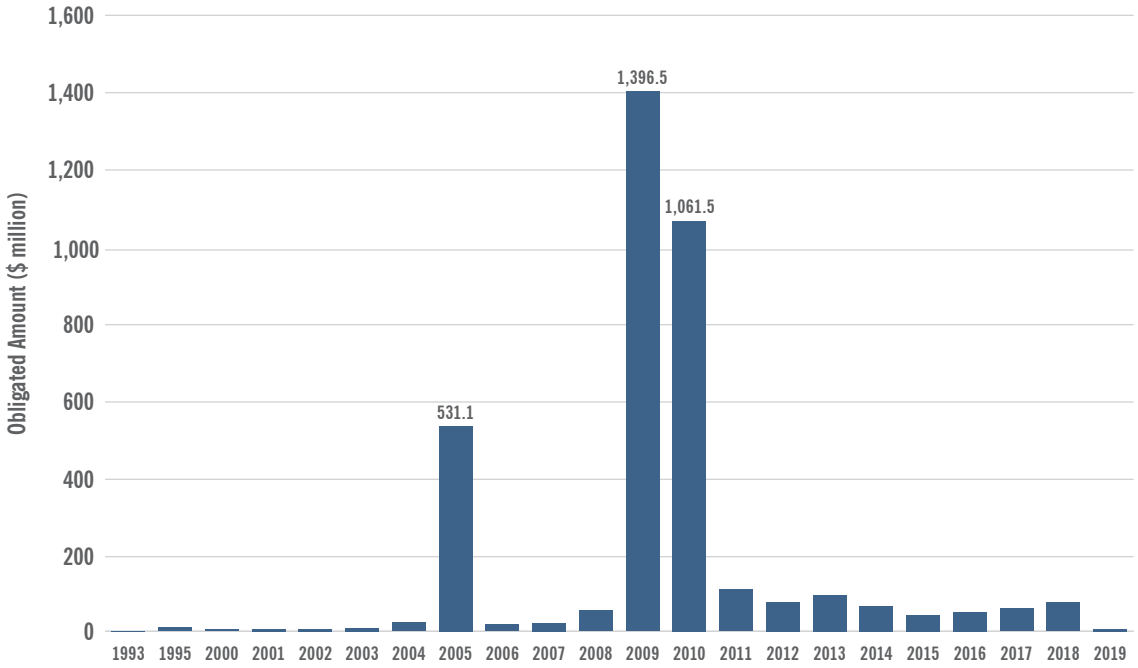
The projects were then assessed for their degree of relevance to carbon removal-related RD&D funding based on expert judgment, which resulted in the sample of projects that were included in the analysis. The results of the bottom-up analysis represented the time period from 1993 to 2019. Since the time of the screening (February 8 and 9, 2019), there was at least one federally funded RD&D project related to direct air capture, which was announced on February 21, 2019.[33] In view of its relevance to the objective of this analysis, this project was added to the final set of projects and included in the results.

RESULTS

There were 1,409 carbon removal-related RD&D projects identified in the analysis that had a total historical investment of $3,717.1 million from 1993 to 2019 (based on the period of performance start dates) (see Figure 4). The funding spike in 2005 was largely driven by DOE funding for geologic sequestration, which coincided with the Regional Carbon Sequestration Partnerships Initiative.[34] The major funding spikes in 2009 and 2010 coincided with the American Recovery and Reinvestment Act of 2009.

Figure 4. Historical Federal Investment for All Carbon Removal-Related RD&D Projects by Year

(1,409 projects; $3,717.1 million in total funding)

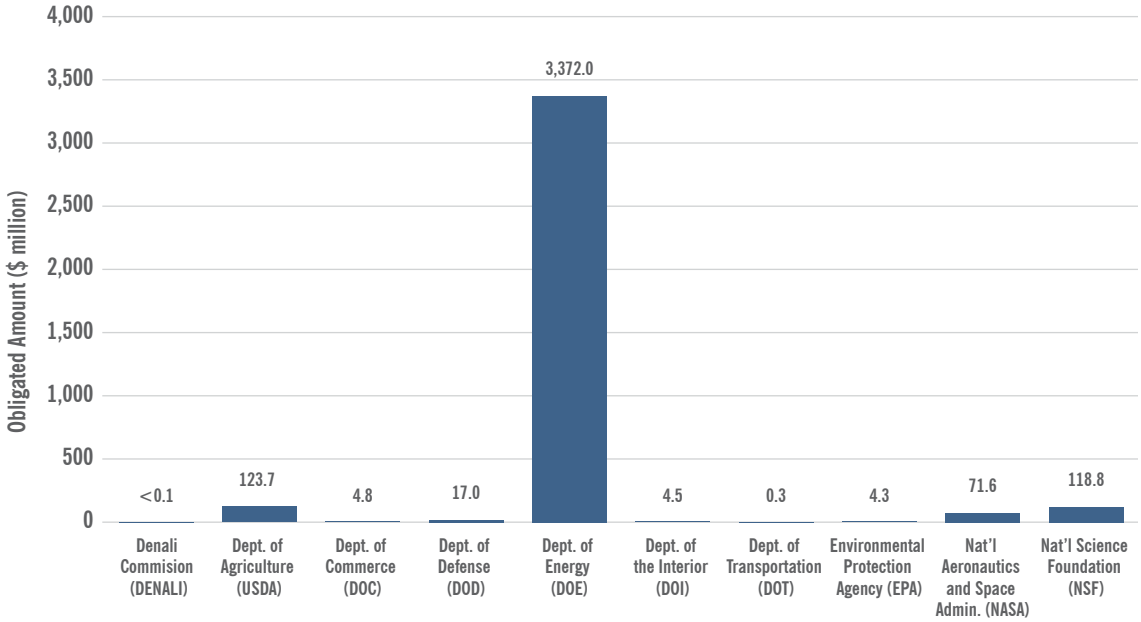


Sources: Energy Futures Initiative, 2019.[35] Compiled using data from USAspending.gov.[36]

There were 10 agencies that obligated funding for these projects, of which 91 percent came from DOE (see Figure 5). Three-fourths of the historical funding was invested in two carbon removal categories—geologic sequestration (49 percent) and terrestrial and bioenergy (26 percent) RD&D projects. Several carbon removal categories identified in the NASEM report as important priority areas received very little historical investment; for example, historical investment in coastal and oceans carbon removal-related research comprised about 1 percent of the total, and carbon mineralization and direct air capture were each less than 1 percent (see Figure 6).

Figure 5. Historical Federal Investment for All Carbon Removal-Related RD&D Projects by Agency

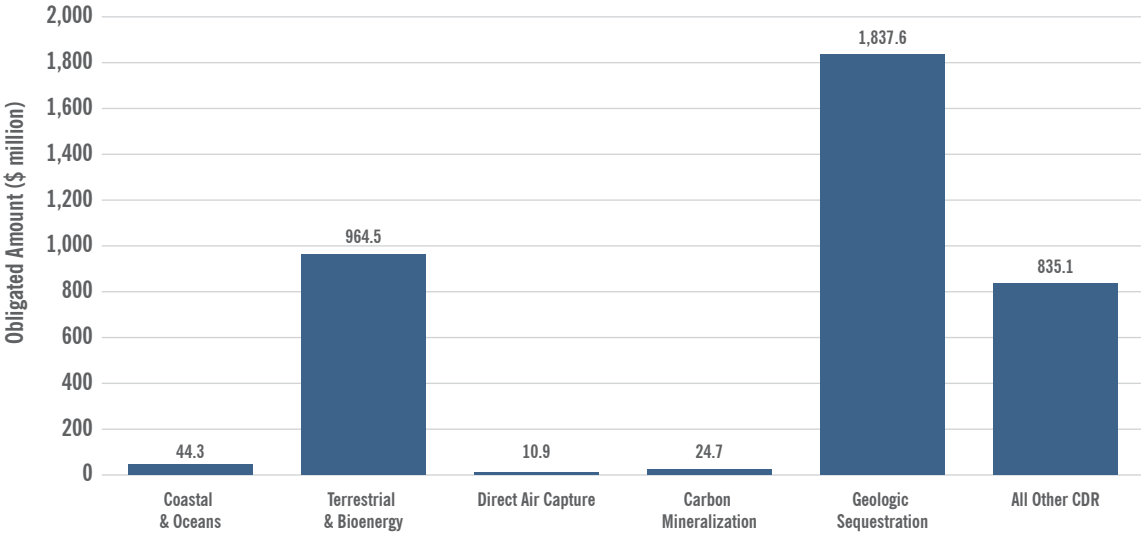
(1,409 projects; $3,717.1 million in total funding)



Sources: Energy Futures Initiative, 2019.[37] Compiled using data from USAspending.gov.[38]

Figure 6. Historical Federal Investment for All Carbon Removal-Related RD&D Projects by Category

(1,409 projects; $3,717.1 million in total funding)



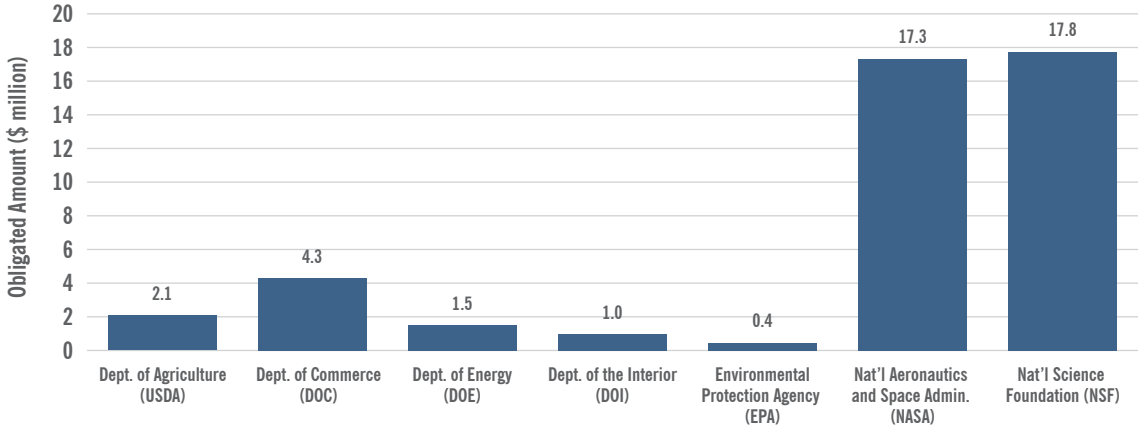
Sources: Energy Futures Initiative, 2019.[39] Compiled using data from USAspending.gov.[40]

Coastal and Oceans

Historical federal investment for carbon removal-related coastal and oceans activities amounted to $44.3 million across 115 RD&D projects from 2005 to 2018, which was 1 percent of the total historical funding for carbon removal-related RD&D projects identified in the analysis. The majority of federal funding came from NSF (40 percent) and NASA (39 percent), followed by DOC (10 percent), USDA (5 percent), DOE (3 percent), DOI (2 percent), and EPA (1 percent), respectively (see Figure 7). Compared with the estimated cumulative NASEM budget for coastal and oceans, this amounts to 4 percent of the recommended future funding level.

Figure 7. Historical Federal Investment for Carbon Removal-Related Coastal and Oceans RD&D Projects, 2005-2018

(115 projects; $44.3 million in total funding)



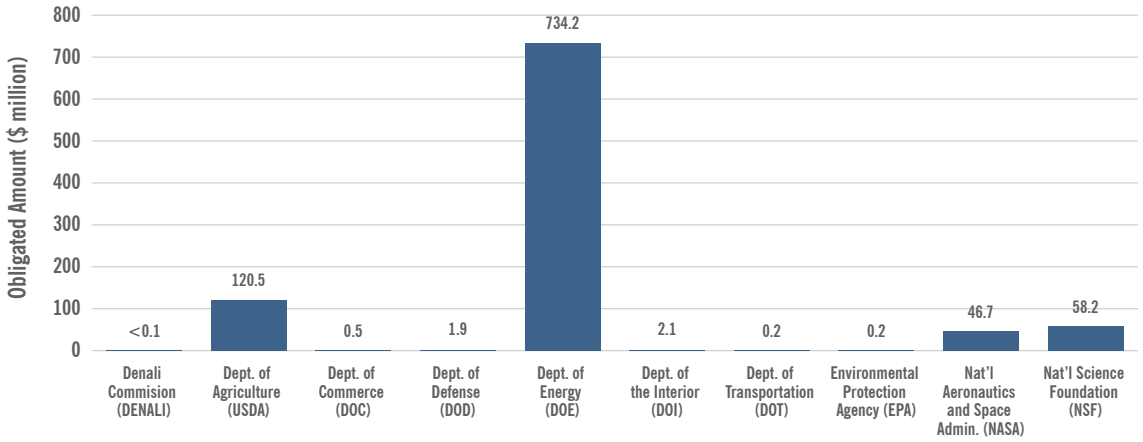
Sources: Energy Futures Initiative, 2019.[41] Compiled using data from USAspending.gov.[42]

Terrestrial and Bioenergy

Historical federal investment for carbon removal-related terrestrial and bioenergy activities amounted to $964.5 million across 763 RD&D projects from 1993 to 2019, which was 26 percent of the total historical funding for carbon removal-related RD&D projects identified in the analysis. The majority of federal funding came from DOE (76 percent), followed by USDA (12 percent), NSF (6 percent), NASA (5 percent), DOI (less than 1 percent), DOD (less than 1 percent), DOC (less than 1 percent), DOT (less than 1 percent), EPA (less than 1 percent), and DENALI (less than 1 percent), respectively (see Figure 8). Compared with the estimated cumulative NASEM budget for terrestrial and bioenergy, this amounts to 34 percent of the recommended future funding level.

Figure 8. Historical Federal Investment for Carbon Removal-Related Terrestrial and Bioenergy RD&D Projects, 1993-2019

(763 projects; $964.5 million in total funding)



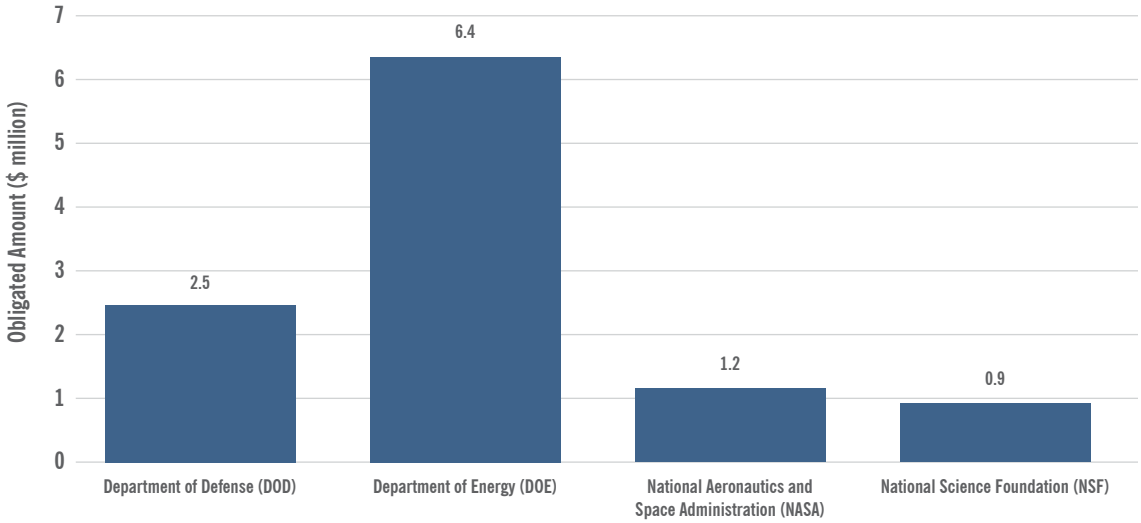
Sources: Energy Futures Initiative, 2019.[43] Compiled using data from USAspending.gov.[44]

Direct Air Capture

Historical federal investment for carbon removal-related direct air capture activities amounted to $10.9 million across 15 RD&D projects from 2009 to 2019, which was less than 1 percent of the total historical funding for carbon removal-related RD&D projects identified in the analysis. The majority of federal funding came from DOE (58 percent), followed by DOD (23 percent), NASA (11 percent), and NSF (8 percent), respectively (see Figure 9 and Table 2). Compared with the estimated cumulative NASEM budget for direct air capture, this amounts to less than 1 percent of the recommended future funding level.

Figure 9. Historical Federal Investment for Carbon Removal-Related Direct Air Capture RD&D Projects, 2009-2019

(15 projects; $10.9 million in total funding)



Sources: Energy Futures Initiative, 2019.[45] Compiled using data from USAspending.gov[46] and Arizona State University.[47]

Table 2. Historical Federal Investment for Carbon Removal-Related Direct Air Capture RD&D Projects, 2009-2019

Agency	Project Name	Performance Start Date	Federal Funding (millions of dollars)
DOD	Fundamental Assessment of Supported Amine Adsorbents for CO_2 Extraction from Ambient Air	2014	0.29
	Amine-Tethered Porous Materials for CO_2 Capture from Air	2014	0.15
	Polyamine-Tethered Porous Materials for CO_2 Capture from Air	2013	0.15
	An Investigation into the Use of Concentrating Monoliths to Remove CO_2 from Underwater Breathing Apparatuses	2013	0.95
	CO_2 Scrubbing Systems Using Seawater for Shallow-Water Combat Submersible	2010	0.93
DOE	Mining Air for Fuels and Fine Chemicals	2019	1.50
	Direct Air Capture of CO_2 and Delivery to Photobioreactors for Algae Biofuel Production	2018	1.65
	Atmospheric CO_2 Capture and Membrane Delivery	2015	1.0
	A Compact Integrated System for Air Capture of Atmospheric CO_2	2010	1.70
	Novel Nanosorbents for Air CO_2 Capture	2010	0.20
	High-Performance Sorbents for CO_2 Capture from Air	2009	0.30
NASA	International Space Station Air Revitalization System that Currently Removes CO_2 from the Station Using Adsorbent Beds	2016	0.75
	Lower the CO_2 Concentration in Space Cabin	2010	0.09
	Rapid CO_2 Capture	2009	0.32
NSF	A Novel Route to an Important Monomer, 2,5 Furandicarboxylic Acid, Using CO_2 Captured from Air	2014	0.91
Total			10.89

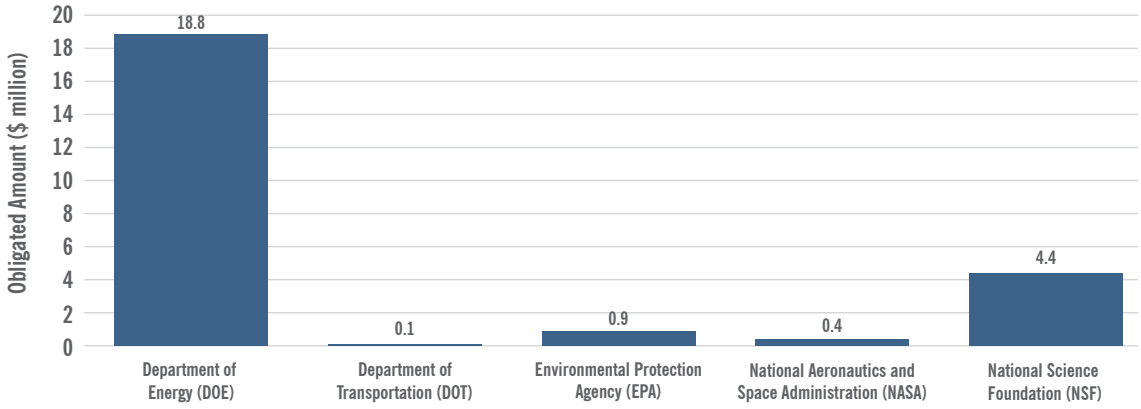
Note: Federal funding for the project "Mining Air for Fuels and Fine Chemicals" was announced on February 21, 2019, and was not captured during the performance of the bottom-up analysis. However, the project is included in the overall analysis.
Sources: Energy Futures Initiative, 2019.[48] Compiled using data from USAspending.gov[49] and Arizona State University.[50]

Carbon Mineralization

Historical federal investment for carbon removal-related carbon mineralization activities amounted to $24.7 million across 39 RD&D projects from 2002 to 2018, which was less than 1 percent of the total historical funding for carbon removal-related RD&D projects identified in the analysis. The majority of federal funding came from DOE (76 percent), followed by NSF (18 percent), EPA (4 percent), NASA (2 percent), and DOT (less than 1 percent), respectively (see Figure 10). Compared with the estimated cumulative NASEM budget for carbon mineralization, this amounts to 4 percent of the recommended future funding level.

Figure 10. Historical Federal Investment for Carbon Removal-Related Carbon Mineralization RD&D Projects, 2002-2018

(39 projects; $24.7 million in total funding)



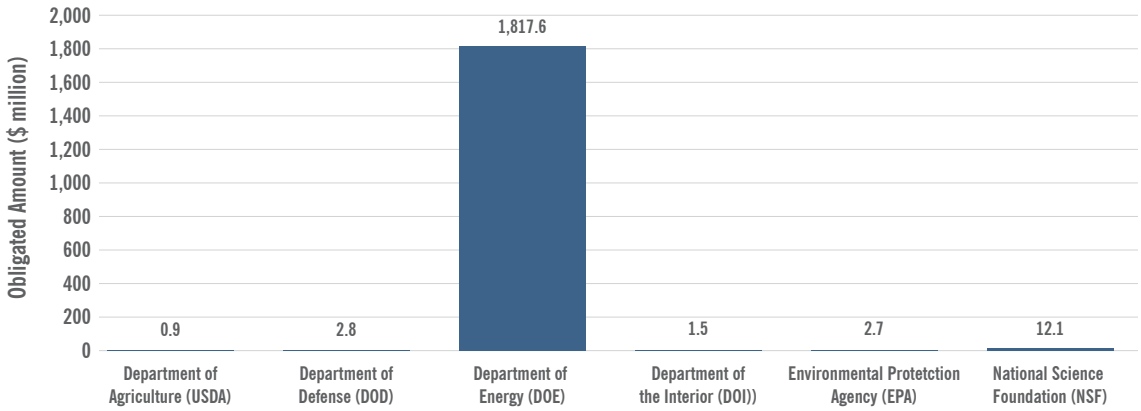
Sources: Energy Futures Initiative, 2019.[51] Compiled using data from USAspending.gov.[52]

Geologic Sequestration

Historical federal investment for carbon removal-related geologic sequestration activities amounted to $1,837.6 million across 288 RD&D projects from 2000 to 2018, which was 49 percent of the total historical funding for carbon removal-related RD&D projects identified in the analysis. The majority of federal funding came from DOE (99 percent), followed by NSF (less than 1 percent), DOD (less than 1 percent), EPA (less than 1 percent), DOI (less than 1 percent), and USDA (less than 1 percent), respectively (see Figure 11). Compared with the estimated cumulative NASEM budget for geologic sequestration, this amounts to 73 percent of the recommended future funding level.

Figure 11. Historical Federal Investment for Carbon Removal-Related Geologic Sequestration RD&D Projects, 2000-2018

(288 projects; $1,837.6 million in total funding)



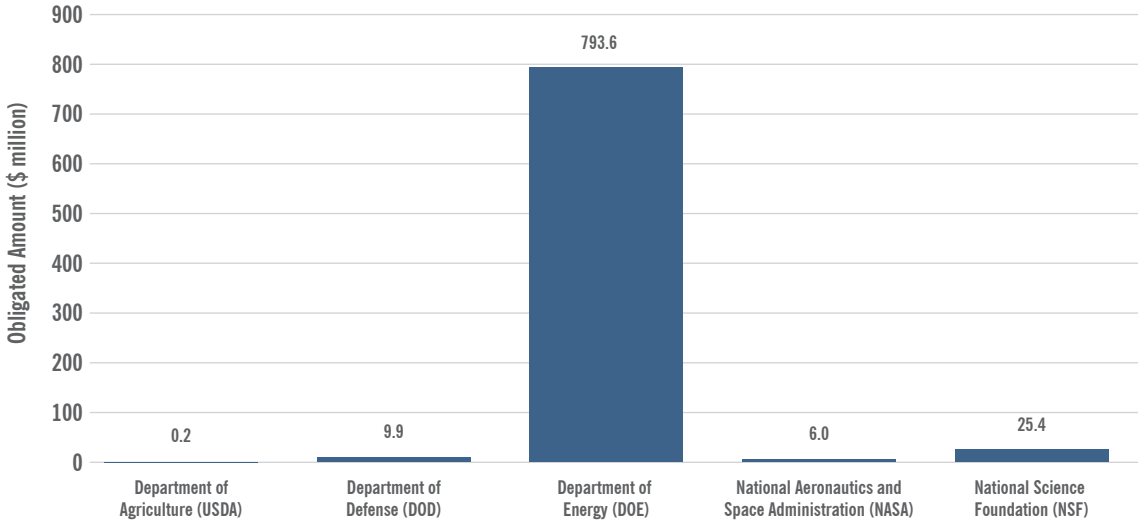
Sources: Energy Futures Initiative, 2019.[53] Compiled using data from USAspending.gov.[54]

All Other Carbon Removal

Historical federal investment for all other carbon removal-related activities amounted to $835.1 million across 189 RD&D projects from 2004 to 2019, which was 22 percent of the total funding for historical carbon removal-related RD&D projects identified in the analysis. The majority of federal funding came from DOE (95 percent), followed by NSF (3 percent), DOD (1 percent), NASA (less than 1 percent), and USDA (less than 1 percent), respectively (see Figure 12).

Figure 12. Historical Federal Investment for All Other Carbon Removal-Related RD&D Projects, 2004-2019

(189 projects; $835.1 million in total funding)



Sources: Energy Futures Initiative, 2019.[55] Compiled using data from USAspending.gov.[56]

Comparison of Historical Investment for Carbon Removal-Related RD&D with Recommended Future Funding Levels

The results from the bottom-up analysis were compared with the funding levels recommended in the 2018 NASEM report[57] (see Table 3). Although federal agencies have historically funded carbon removal-related RD&D projects in all of the major categories recommended in the NASEM report, the funding has been scattered and piecemeal as the United States does not have a dedicated research program for carbon removal. By carbon removal category, approximately one-half (49 percent) of historical federal investment went to geologic sequestration projects (even though geologic sequestration projects only accounted for 20 percent of the total projects identified in the bottom-up analysis), followed by terrestrial and bioenergy (26 percent), all other CDR (22 percent), coastal and oceans (1 percent), and carbon mineralization and direct air capture (both less than 1 percent).

Cumulative estimates for historical carbon removal-related RD&D investments were considerably lower than the NASEM-recommended future funding levels across each carbon removal category: coastal and oceans (4 percent of recommended funding level); terrestrial and bioenergy (34 percent of recommended funding level); direct air capture (less than 1 percent of recommended funding level); carbon mineralization (4 percent of recommended funding level); geologic sequestration (73 percent of recommended funding level). Direct air capture had the lowest estimated cumulative carbon removal-related funding level across all carbon removal categories and also the shortest time period for project performance.

Table 3. Historical Federal Investments in Carbon Removal-Related RD&D and Comparison with NASEM-Recommended Future Funding Levels

Carbon Removal Category	Estimated Cumulative NASEM Future Budget Recommendation (millions of dollars)	Estimated Cumulative Historical Carbon Removal-Related Investments (millions of dollars)
Coastal and Oceans	**1,160.0–1,190.0** (5–20 years)	**44.3** (14 years; 2005–2018)
Terrestrial and Bioenergy	**2,006.4–3,706.0** (3–20 years)	**964.5** (27 years; 1993–2019)
Direct Air Capture	**1,810.0–2,400.0** (10 years)	**10.9** (11 years; 2009–2019)
Carbon Mineralization	**697.5** (5–10 years)	**24.7** (17 years; 2002–2018)
Geologic Sequestration	**2,510.0** (10 years)	**1,837.6** (19 years; 2000–2018)
All Other CDR	**n/a**	**835.1** (16 years; 2004–2019)
Total	**8,183.9–10,503.5** (3–20 years)	**3,717.1** (27 years; 1993–2019)

Sources: Energy Futures Initiative, 2019.[58] Compiled using data from BPC,[59] NASEM,[60] and USAspending.gov.[61]

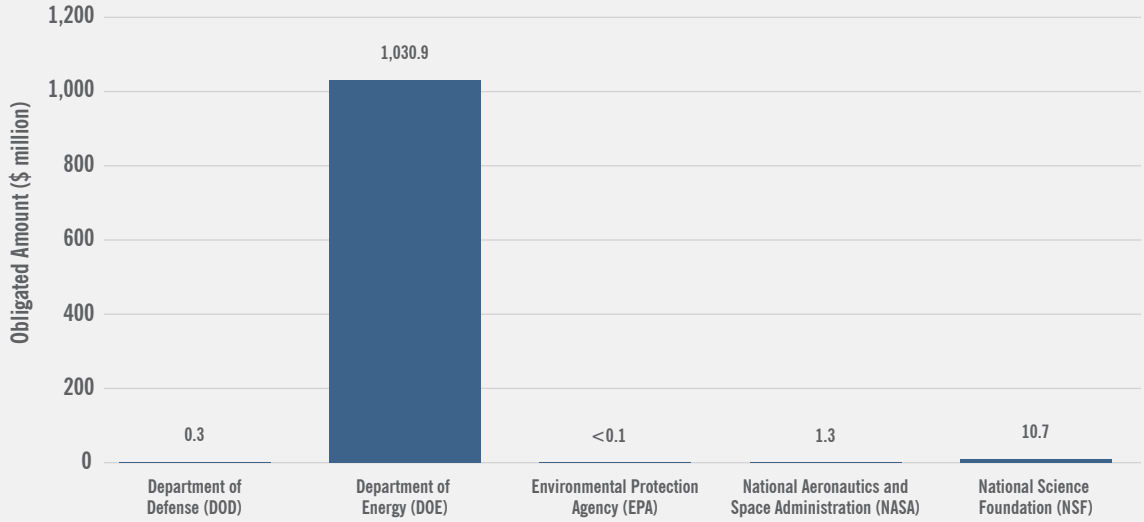
The estimated cumulative NASEM budget totaled $8,183.9 million to $10,503.5 million, with budget line items spanning three to 20 years. The estimated cumulative historical carbon removal-related investment totaled $3,717.1 million (including the "all other CDR" category) and spanned 27 years. Where applicable, the estimates for the cumulative NASEM budget used both the lower- and upper-bound estimates for funding needs and time durations to arrive at cost ranges. In instances where time durations were listed as greater than or equal to a certain number, the lowest relevant number of years was used.

Historical Federal Investment in Carbon Capture from Concentrated Sources

Although not included in the scope of this analysis, RD&D for carbon capture from concentrated sources could also offer opportunities to advance the technological readiness of bioenergy with carbon capture and storage and direct air capture, which both rely on similar mechanisms to capture carbon dioxide. There were 240 projects (approximately $1,043.1 million in funding) identified for carbon capture RD&D projects from 2000 to 2018. Nearly all of the federal investment came from DOE (99 percent), with marginal amounts from NSF, NASA, DOD, and EPA, respectively (see Figure 13). The majority (55 percent) of the total funding occurred with project start dates in 2010 ($578.5 million), coinciding with American Recovery and Reinvestment Act. In general, these projects spanned numerous capture methods (such as pre-combustion, post-combustion, and chemical looping) and sought to improve the performance of capture mechanisms (such as sorbents and solvents).

Figure 13. Historical Federal Investment for Carbon Capture RD&D Projects, 2000-2018

(240 projects; $1,043.1 million total funding)



Sources: Energy Futures Initiative, 2019.[62] Compiled using data from USAspending.gov.[63]

Limitations and Uncertainties

The principal uncertainty that affected the results was cases of limited or incomplete project descriptions from which to make a definitive judgment as to the degree of relevance to carbon removal. Furthermore, the final set of projects excluded a number of projects that appeared to be outside the scope of the analysis. The projects included in the analysis were limited to the following four funding instruments: block grants, formula grants, project grants, and cooperative agreements. Contracts were not included in the analysis because they could be considered outside the scope of RD&D. Finally, federal funding for agency intramural RD&D (including DOE national laboratory RD&D) is not included in the USAspending.gov database and thus was not a part of the analysis. Nonetheless, these results offer a robust, initial guidepost for better understanding proposed and actual spending related to carbon removal, and how this spending compares with the recommendations in the NASEM study.

Appendix A

Table 4. Breakdown of NASEM Research Agenda for Carbon Removal by Stage of Research

Carbon Removal Type	Stage of Research	Specific Research Needs	Annual Funding Needs	Cumulative Funding Needs (millions of dollars)	Potential Federal Agencies and Research Partners
Coastal Blue Carbon	Basic Research	Fate of carbon and selection of plants in coastal ecosystems	$6M/yr for 5–10 yrs	$30–60	NSF, DOE, EPA, NASA, NOAA, USFS/USDA, and the U.S. Army Corps of Engineers
	Development	Map/monitor coastal wetlands and establish a national coastal wetland data center	$4M/yr for 20 yrs	$80	
	Demonstration/ Deployment	Establish and operate a network of research sites for experimental work	$40M/yr for 20 yrs	$1,000	
		Demonstration projects and field experiment network	$10M/yr for 20 yrs		
	Deployment	Research on incentives and barriers	$5M/yr for 10 yrs	$50	
			Total	**$1,160–1,190**	
Terrestrial (Agricultural Soils)	Basic Research	Develop new crop varieties	$40–$50M/yr for 20 yrs	$830–1,050	USDA, NSF, DOE, and land-grant universities
		Research on soil decomposition at depth	$3–$4M/yr for 5 yrs		
		Biochar studies	$3M/yr for 5-10 yrs		
	Development, Measurement, and Monitoring	Monitoring system on existing USDA National Resource Inventory locations	$5M/yr ongoing	$100–125	
		Data platform to quantify agricultural soil carbon removal	$5M/yr for 5 yrs		
	Demonstration	Experimental network improving soil processes, 10-15 sites at $600K/yr each	$6–$9M/yr for ≥12 yrs	$72–108	
	Deployment	Scale up agricultural sequestering activities	$2M/yr for 3 yrs	$6	
			Total Agricultural (cumulative)	**$1,008–1,289**	

Carbon Removal Type	Stage of Research	Specific Research Needs	Annual Funding Needs	Cumulative Funding Needs (millions of dollars)	Potential Federal Agencies and Research Partners
Terrestrial (Afforestation/ Reforestation/ Forest Management)	Basic Research	Landfill design to minimize wood decomposition; assessment of emissions balance, cost, and land requirements for consuming wood products	$2.4M/yr for 3 yrs	$7.2	USFS has main responsibility in partnership with USDA, NSF, and EPA
	Development, Measurement, and Monitoring	Monitor forest carbon stock enhancement projects	$5M/yr for ≥3 yrs	$15	
	Demonstration	Forest demonstration projects	$4.5M/yr for 3 yrs	$13.5	
	Deployment	Research on incentives and reducing the use of biomass for fuel	$2M/yr for 3 yrs	$6	
			Total Forest (cumulative)	**$41.7**	
			Terrestrial Total	**$1,049.7–1,330.7**	
Bioenergy with Carbon Capture and Storage (BECCS)	Cross-cutting Activities	Lifecycle analysis and integrated assessment modeling to understand land constraints	$3.7–$14M/yr for 10 yrs	$37–140	USDA, DOE, NSF, EPA, and the National Laboratories
	Biomass-to-Power with Carbon Capture	Biomass supply and logistics	$53–$122.6M/yr for 5 yrs	$493.7–1,180.3	
		High-efficiency biomass power	$39–$93.5M/yr for 10 yrs		
	Biomass-to-Fuel with Biochar	Biochar permanence in soil and impact on crop productivity, and conversion pathways profitable for fuel production	$39.4–$102.5M/yr for 10 yrs	$384–995	
	Biomass-to-Fuel with Carbon Capture	Carbon-negative pathways, 7-10 projects per year at $0.2 to $1 million/project	$4.2–$6M/yr for 10 yrs	$42–60	
			Total	**$956.7–2,375.3**	
Direct Air Capture (DAC)	Basic and Applied Research	Design and test materials and component designs with many $1 million efforts	$20–$30M/yr for 10 yrs	$230–350	DOE's Office of Fossil Energy and the National Energy Technology Laboratory, with cooperation from researchers and industry
		Establish evaluation for performance	$3–$5M/yr for 10 yrs		
	Development	Scale up materials and components for pilot scale	$13–$25M/yr for 10 yrs	$130–250	
	Demonstration	Establish a National DAC Test Center	$30–$60M/yr for 10 yrs	$300–600	
		Build and test $20 million/project pilots			
	Deployment	Scale to >10,000 tons CO_2/yr removed at $100 million/project	$115–$120M/yr for 10 yrs	$1,150–1,200	
			Total	**$1,810–2,400**	

Carbon Removal Type	Stage of Research	Specific Research Needs	Annual Funding Needs	Cumulative Funding Needs (millions of dollars)	Potential Federal Agencies and Research Partners
Carbon Mineralization	Basic Research	Kinetics of carbon capture by minerals	$5.5M/yr for 10 yrs	$452.5	DOE's Basic Energy Sciences and the Office of Fossil Energy, NSF, USGS, and universities
		Rock mechanics, numerical modeling, and field studies	$17M/yr for 10 yrs		
		Mapping of reactive mineral deposits (scoping for pilots)	$7.5M/yr for 5 yrs		
		Develop a resource database for carbon mineralization	$2M/yr for 5 yrs		
		Reactive mineral additions to soils	$3M/yr for 10 yrs		
		Environmental impacts of mineral additions to ecosystems	$10M/yr for 10 yrs		
		Socioenvironmental impacts of expanded extraction industry	$5M/yr for 10 yrs		
	Pilot Studies	Medium-scale injection of CO_2 in peridotite rock	$10M/yr for 10 yrs	$245	
		Medium-scale injection of CO_2 in a basalt formation	$10M/yr for 10 yrs		
		Surficial (ex situ) carbon removal pilot studies	$3.5M/yr for 10 yrs		
		Mine tailings and industrial wastes	$1M/yr for 10 yrs		
			Total	**$697.5**	
Secure Geologic Storage	Basic Research and Development	Reduce risks of induced seismicity	$50M/yr for 10 yrs	$850	DOE, NSF, EPA, USGS, and the Bureau of Land Management
		Improve secondary trapping prediction and methods	$25M/yr for 10 yrs		
		Improve simulation models for performance prediction	$10M/yr for 10 yrs		
	Development/ Demonstration	Improve site characterization and selection	$45M/yr for 10 yrs	$1,450	
		Improve and lower cost for monitoring and verification	$50M/yr for 10 yrs		
		Co-optimize CO_2 with enhanced oil recovery and sequestration	$50M/yr for 10 yrs		
	Deployment	Assess and manage risk of CO_2 leakage	$20M/yr for 10 yrs	$210	
		Research on best practices and public engagement	$1M/yr for 10 yrs		
			Total	**$2,510**	
			Grand Total	**$8,183.9–10,503.5**	

Source: Bipartisan Policy Center.[64]

Appendix B

Table 5. Unique Search Terms by Category for Historical Federal Investment in Carbon Removal-Related RD&D

Carbon Removal Category							
No.	**BECCS**	**Carbon Mineralization**	**Coastal and Oceans**	**Direct Air Capture**	**Geologic Sequestration**	**Terrestrial**	**All Other CDR**
1	Biochar	Accelerated weathering	Aquaculture	Absorption	CO_2 enhanced oil recovery	Afforestation	Activated carbon
2	Bioenergy crops	Basaltic lava	Blue carbon	Adsorption	CO_2 injection	Agricultural management	CO_2
3	Biofuel	Carbon mineralization	Coastal ecosystem	Amine	CO_2 sequestration	Agricultural residue	CO_2 conversion
4	Biomass carbon	Enhanced weathering	Coastal restoration	Carbon capture	CO_2 storage	Algae	CO_2 removal
5	Biomass conversion	Mantle peridotite	Coastal wetlands	CO_2 capture	Carbon sequestration	Biologic sequestration	CO_2 utilization
6	Biomass harvesting	Mine tailings	Direct ocean capture	CO_2 separation	Carbon storage	Biological sequestration	Carbon fiber
7	Biomass with carbon capture	Mineralization kinetics	Mangrove restoration	Chemical looping	CO_2 enhanced oil recovery	Carbon farming	Carbon flux
8	CRISPR	Reactive minerals	Ocean capture	CO_2 capture	CO_2 injection	Carbon fixation	Carbon intensification
9	Crop cultivars	Ultramafic	Ocean fertilization	CO_2 separation	CO_2 sequestration	Carbon microbial	Carbon management
10	Feedstock		Phytoplankton	Direct air capture	CO_2 storage	Compost	Carbon nanotubes
11	Fermentation			Flue gas	CO_2-EOR	Cover crop	Carbon negative
12	Gasification			Oxy-combustion	Geologic storage	Crop rotation	Carbon neutral
13	Miscanthus			Post-combustion	Monitoring reporting verification sequestration	Double cropping	Carbon removal
14	Photosynthesis			Pre-combustion	Offshore storage	Ecosystem restoration	Carbon stock
15	Plant breeding			Solvent	Saline aquifer	Engineered crops	Carbon stocks

Carbon Removal Category							
No.	**BECCS**	**Carbon Mineralization**	**Coastal and Oceans**	**Direct Air Capture**	**Geologic Sequestration**	**Terrestrial**	**All Other CDR**
16	Plant genomics			Sorbent	Sequestration	Forest management	Carbon tech
17	Selective breeding				Sequestration characterization	Forest residue	Carbonaceous
18	Switchgrass				Sequestration seismic	Forest restoration	Carbonate
19	Thermochemical				Storage characterization	Forest stock	Carbonation
20						Forestry management	CO_2
21						Macroalgae	CO_2 conversion
22						Microalgae	CO_2 polymers
23						Microbial engineering	CO_2 removal
24						Pyrolysis	CO_2 utilization
25						Reforestation	Fischer-Tropsch
26						Root system	Lifecycle analysis
27						Soil amendment	Negative emissions
28						Soil biota	Synthetic fuels
29						Soil carbon	
30						Soil management	
31						Terrestrial uptake	
32						Tree cultivars	

Source: Energy Futures Initiative, 2019. Researchers used a total of 133 unique search terms across seven categories for the bottom-analysis.[65]

Endnotes

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