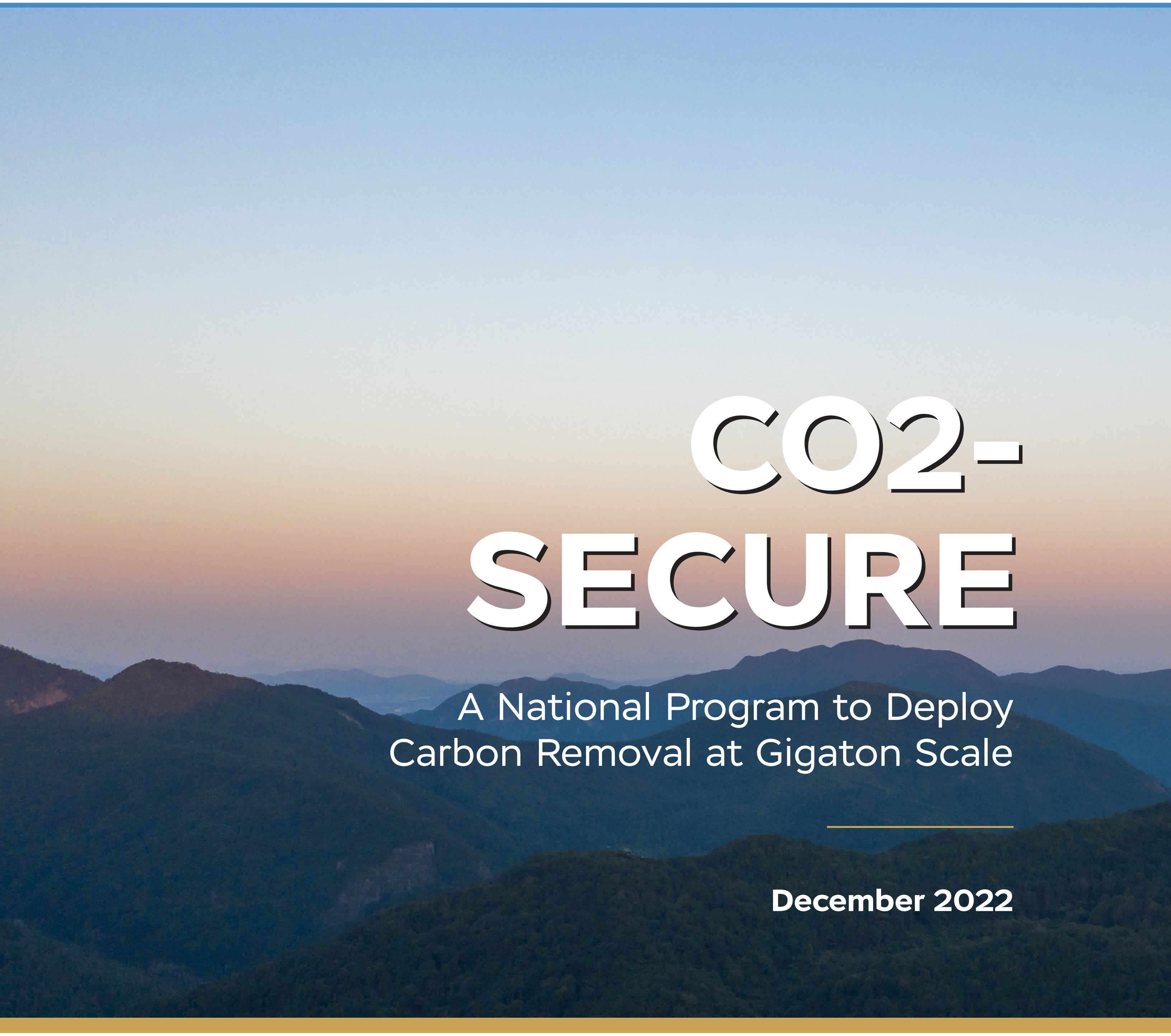


CO2-SECURE

A National Program to Deploy Carbon Removal at Gigaton Scale

December 2022

ENERGY FUTURES INITIATIVE

About the
ENERGY FUTURES INITIATIVE

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

CONTRIBUTORS

President & CEO, Energy Futures Initiative
Ernest J. Moniz

Project Executive
Joseph S. Hezir

Project Leads
Tim Steeves
Sam F. Savitz

Contributing Authors
Ansh Nasta
Richard W. Westerdale II

Additional Contributors
David Ellis
Alicia Moulton
Jaycee Scanlon
Sonia Velazquez

Layout and Design
Nola Shelton

Copyediting and Review
Jane Hirt
Joe Gray

This report was supported by a grant from the Linden Trust for Conservation.

Citation: Energy Futures Initiative. "CO2-Secure: A National Program to Deploy Carbon Removal at Gigaton Scale," December 2022.

Cover photo by Xu Wu

energyfuturesinitiative.org

TABLE OF CONTENTS

SUMMARY

This report outlines a proposed new initiative for climate remediation through large-scale deployment of carbon removal, contributing to U.S. net-zero greenhouse gas (GHG) emissions by midcentury and ultimately to net-negative emissions. The goal of this proposed new initiative, CO2-Secure, would be to achieve carbon removal on a billion-ton scale by midcentury, well beyond implementation of current policies and programs for carbon dioxide removal.

> **The goal of this proposed new initiative, CO2-Secure, would be to achieve carbon removal on a billion-ton scale by midcentury. . . .**

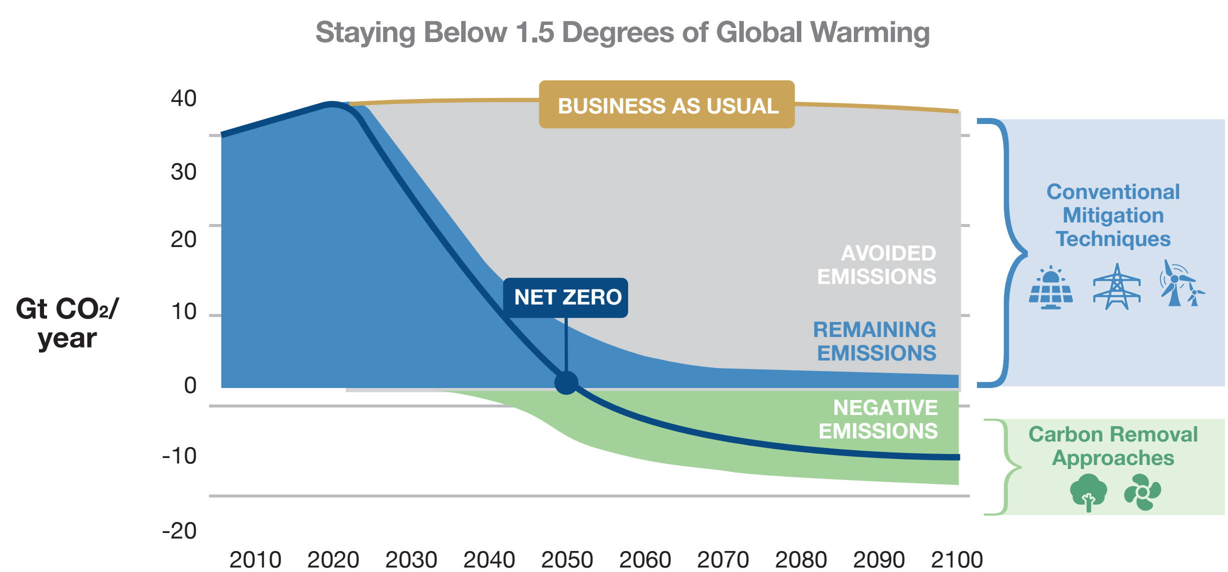
Implementation of carbon dioxide removal (CDR) on a gigaton (Gt) scale poses new challenges in managing hundreds if not thousands of long-term carbon removal agreements of varying size, location, and technology. Managing a program of this scale and complexity while providing a stable oversight environment for decades will, in turn, require new institutional arrangements. The proposal entails establishment of a new government corporation, the National Carbon Removal Authority, with the mission, authority, and funding to secure carbon dioxide removal through a variety of acquisition methods. The initiative is proposed for initiation in 2035, as a follow-on to current proposed legislation—including the Federal Carbon Dioxide Removal Leadership Act and the purchasing pilot program in the Carbon Removal and Emissions Storage Technologies (CREST) Act—that would establish a precursor pilot program in the U.S. Department of Energy (DOE).

Motivation For This Study

There are abundant signs of climate change: increased number of severe weather events with larger geographic scopes, changes in temperature and precipitation beyond the bounds of normal historical variation, and threats to both natural ecosystems and human life, health, and well-being. These impacts are consistent with the ever-increasing capability of climate modeling studies, which have refined our ability to project climate change with temporal and spatial granularity.

The most recent international scientific assessments from the United Nations' Intergovernmental Panel on Climate Change (IPCC)—the gold standard for climate modeling—point to a need to limit the rise in global temperature to 1.5 degrees Celsius (or less) above pre-industrial levels. This temperature threshold allows the planet to stave off some of the most severe adverse future impacts of climate change.[1] Achieving this goal will require global carbon dioxide (CO_2) emissions to reach net zero (i.e., more carbon removed by human action than emitted) by midcentury.[2] Long-term stabilization of the climate eventually will require net-negative emissions across all greenhouse gases (GHGs)—reversing climate change will require drawing down emissions already in the atmosphere and oceans.[3] These projections are illustrated in Figure 1, based on various modeling scenarios developed by IPCC.

Figure 1 | The Need for Gigaton-Scale CDR to Meet Science-Based Climate Goals



Source: Adapted from IPCC 2018. World Resources Institute.

Meeting the 1.5-degree target—or, in fact, the 2-degree target set by the Paris Agreement—will require both rapid reductions in GHG emissions and CDR. All scenarios in IPCC's latest report that met these targets required CDR, which can accelerate the pace of decarbonization, compensate for emissions from hard-to-abate sectors (e.g., agriculture, heavy industry), and facilitate reaching net-negative emissions.[4] The median estimate scenarios meeting these targets was 6 Gt/yr of negative emissions in 2050 (a combination of natural, technological, and hybrid CDR methods).[5] Some estimates for CDR requirements are even higher: A report from the National Academies of Sciences, Engineering, and Medicine (NASEM) estimated that around 10 Gt/yr would be needed by 2050 and 20 Gt/yr by 2100.[6] If the pace of GHG emissions reductions is slower than these scenarios project, more rapid CDR deployment would be needed in order to correct for overshooting the 1.5-degree target.

> **A Princeton University study, for instance, found that up to 2 Gt per year of technological and hybrid CDR could be necessary by 2050 to reach the Biden administration's long-term goal of net-zero GHG emissions.**

CDR, however, must be coupled with emissions reductions. Even with 6 Gt/yr of CDR, around 40 Gt/yr of additional CO_2 emissions reductions (below current levels) would be needed to achieve net zero by 2050—not to mention reductions of other GHGs, such as methane.[7]

The magnitude of the global CDR challenge is huge. The 6 Gt/yr target would be equivalent to about 13 percent of current global CO_2 emissions. Reaching 20 Gt/yr toward the end of the century, as NASEM estimates, is equivalent to current annual consumption of all oil and gas products—a trillion-dollar industry.[8] This comparison provides some perspective on the ultimate scale needed for CDR investment. CDR of this magnitude is achievable, however, with technologies that already are being explored. Between 9 and 28 Gt/yr of CDR—or even more with faster technological maturation—could feasibly be deployed at a cost below $100 per ton.[9,10]

The United States will need to be responsible for a large share of the global CDR effort; CDR can play an important role in the U.S. commitment to achieving net-zero emissions by midcentury. A Princeton University study, for instance, found that up to 2 Gt per year of technological and hybrid CDR could be necessary by 2050 to reach the Biden administration's long-term goal of net-zero GHG emissions.[11,12] A study by the Rhodium Group estimated the need for 1 to 2 Gt/yr to reach a highly ambitious goal of net zero by 2045, and 185 to 750 Mt/yr of CDR by midcentury to meet a more modest target of an 83 percent net emissions reduction.[13]

As on the global scale, CDR does not eliminate the need for rapid emissions reductions. Even in Rhodium Group's high-CDR scenario, 4.5 Gt/yr of GHG emissions reductions are still necessary to achieve net zero.

CDR deployment in the United States serves the dual purpose of contributing to global emissions goals and spearheading the CDR innovation push. There is an opportunity for the United States to lead the way toward drawing down historical emissions, especially considering that the United States accounts for about 25 percent of past human-caused emissions of CO_2.[14]

Rapidly Expanding CDR Landscape

Carbon dioxide removal is a relatively new element of climate policy that has rapidly gained attention, as these actions show:

- In 2016, the DOE Secretary of Energy Advisory Board issued the first technical assessment report on CDR.
- In 2018, the National Academy of Sciences issued a major study of technological CDR options.[a]
- In 2018, Congress enacted the Bipartisan Budget Act, expanding the Section 45Q tax credit for carbon sequestration to include carbon oxides captured from ambient air to be eligible for the credit.
- In 2019, as part of appropriations for fiscal year 2020, Congress specifically allocated funding for research, development, and demonstration (RD&D) of CDR generally, and to direct air capture technology in particular.
- In 2020, Congress enacted the Energy Act of 2020 that authorized a comprehensive CDR RD&D program, including the establishment of an interagency coordination committee housed in DOE.
- In the 2021 Bipartisan Infrastructure Law (BIL), Congress appropriated $3.5 billion to establish four direct air capture regional hubs.
- In the 2022 Inflation Reduction Act (IRA), Congress extended, expanded, and increased the tax credits for carbon sequestration.

The increasing recognition of the need for CDR, combined with the enactment of RD&D funding and other financial incentives, has spawned an explosion of activity and innovation in CDR technologies with a primary focus on direct air capture (DAC).

- DAC companies such as Climeworks, Global Thermostat, CarbonCapture, and Carbon Engineering have entered bilateral deals to implement the first round of commercial-scale CDR projects:
  - Climeworks operates a 4 kiloton (Kt)/yr facility in Iceland and has broken ground on its second CDR project, a 36 Kt/yr project also in Iceland. It has raised a total investment of $787 million through September 2022.
  - Global Thermostat has announced plans for a 100 Kt/yr facility built in collaboration with DOE.
  - CarbonCapture recently announced Project Bison in Wyoming that aims to be the largest DAC plant in the world, opening in 2024 with plans to reach 5 Mt/yr by 2030.
  - Carbon Engineering recently announced plans for the Brown Pelican project in West Texas, with plans to begin operations in late 2024 at a capacity of 0.5 Mt/yr, and the capability to scale up to 1 Mt/yr.
- Several major private sector entities, ranging from Panera to Microsoft, have announced voluntary corporate goals to achieve net-negative GHG emissions, requiring the

a Working from the National Academy study, the Energy Futures Initiative (EFI) issued a major study in 2019, *Clearing the Air*, recommending a 10-year, $10.7 billion, government-wide CDR RD&D initiative across 10 departments and agencies. EFI followed up with four technology-specific CDR reports, including three "Frontiers of CDR" papers that examined areas of future research in CDR (land-based solutions, ocean CDR, and mineralization) and *Surveying the BECCS Landscape*, a deep dive into the current state of the bioenergy with carbon capture and storage (BECCS) policy and research environment. This report represents a continuation of EFI's series of reports on CDR and the broader carbon management space.

need for CDR projects as part of their decarbonization portfolios:

- The First Movers Coalition, a collective of more than 50 companies, is funding decarbonization initiatives, including CDR. As part of this group, Alphabet, Microsoft, and Salesforce collectively pledged $500 million to invest in carbon removal by 2030.
- The Frontier Fund, formed by Alphabet, Stripe, and Shopify, has established a target to raise $925 million by 2030 to invest in CDR purchases and technological demonstration and development projects.

- The Musk Foundation launched a four-year, $100 million prize program for advanced CDR concepts. Currently, 15 teams have been selected to receive milestone grants of $1 million each as they further refine their proposed technological concepts. The four final winning companies will share the remaining $80 million prize money. One of these companies, Verdox, has raised $150 million in venture capital since its inception.[15]
- The Carbon Business Council reports more than 60 startup members.[16] In 2021, Pitchbook reported on venture capital investment in nearly 20 companies in DAC and bioenergy with carbon capture and storage (BECCS).[17] A recent report from Pitchbook identified three additional companies that have received seed capital investment.[18]

> **Scaling CDR from tens of megatons per year to a level of a gigaton per year requires expansion of numerous orders of magnitude.**

Need for Direct Federal Investment in CDR

Current and planned CDR activities will enable deployment to transition from the kiloton (Kt) to megaton (Mt) scale. Current federal policies—tax credits, prizes, and cost-shared hubs—provide a base of financial incentives, but these incentives are limited in both timing and scale. In short, successful implementation of current announced plans would result in a CDR industry on the order of several tens of megatons per year within a decade. Those plans are:

- The four planned DAC hubs, if fully realized, could account for 4 Mt/yr of CDR in the early 2030s.
- The proposed Frontier Fund alone could support additional CO_2 removal of up to about 6 Mt/yr by 2030.
- Project Bison and Project Pelican, with expansions, could achieve 6 Mt/yr of CDR.

Scaling CDR from tens of megatons per year to a level of a gigaton per year requires expansion of numerous orders of magnitude. Extension of current federal tax incentives beyond FY 2032 will incent voluntary private sector investments, and, when combined with additional corporate voluntary commitments, substantial additional CDR is attainable. There is no assurance, however, that voluntary action can be implemented at the scale needed to achieve gigaton scale removal.

Direct Federal Investment in CDR as a Public Good

The need for assured large-scale CDR deployment has prompted consideration of the concept of direct federal investment in CDR. The policy rationale is based on the principle that climate remediation through large-scale deployment of CDR is a public good that merits public sector investment not unlike other government investments in preserving other natural resources on land and in the marine environment. The benefits of a public good, such as climate remediation, affect everyone with no one's benefit diminished by benefits enjoyed by others. The benefits of a public good cannot readily be monetized in a manner that can be appropriable to individual buyers.

Implementation of a large-scale program of direct federal investment in CDR is analogous to the role played by the U.S. Environmental Protection Agency (EPA) Superfund program that remediates hazardous waste sites where the responsible party no longer exists or is incapable of assuming responsibility. Similarly, in the case of atmospheric and marine CDR, the liability for historical CO_2 emissions can be apportioned readily to responsible parties.

Congressional climate policy leaders have made initial proposals to implement pilot programs for direct investment in CDR. In the spring of 2022, members in both houses of Congress introduced draft legislation, the Federal Carbon Dioxide Removal Leadership Act, to establish a foundational DOE-based CDR direct investment program. This bill authorizes DOE to undertake a 10-year CDR purchase program, beginning with the removal of 50,000 tons/yr of CO_2 in 2024, rising to a level of 10 million tons (or 10 megatons) per year by 2035. Another bill, the proposed Carbon Removal and Emissions Storage Act (CREST), promotes a similar approach but at a more modest scale—a competitive purchasing pilot program authorized at a total of $230 million over five years.[19] These proposals represent a first step forward in codifying the policy principle of federal direct investment in CDR, and in practice can serve as an important learning step for the much larger effort ultimately needed to meet science-based climate policy goals.

> **The CO2-Secure initiative would expand on the emerging concept of direct federal investment in CDR as a public good.**

The Proposed CO2-Secure Concept

The CO2-Secure initiative would expand on the emerging concept of direct federal investment in CDR as a public good. The goal of CO2-Secure is to implement a program of direct federal investment in CO_2 removal from the atmosphere and the oceans at gigaton scale by midcentury. The program represents the next step in scaling from current kiloton-scale pilot plants, through the megaton-scale projects in response to current government and private sector initiatives, through the proposed pilot federal purchasing programs that can serve as important precursor efforts, to eventual large-scale deployment reaching gigaton scale.

Implementation of a CDR investment program at gigaton scale would be a daunting task. It would require deployment of hundreds if not thousands of individual CDR projects of all sizes and technological approaches across the United

States. Management of the carbon removed by these projects would require an extensive monitoring program lasting for decades or more. The cost of the program would run into the hundreds of billions of dollars over its lifetime. Design and implementation of such a program requires thoughtful consideration of business models, environmental oversight, and sound financial management.

The bulk of this report provides an in-depth analysis of what form a large-scale direct federal CDR investment program should take. The main elements of the CO2-Secure framework can be summarized as follows:

Mission and goal: The program must have a clear mission, flexible authorities, defined schedule, and adequate funding. The report recommends that Congress establish an explicit goal to achieve gigaton-scale carbon removal by midcentury in order to provide a clear national path forward to guide entrepreneurs, investors, and planners, with phased implementation.

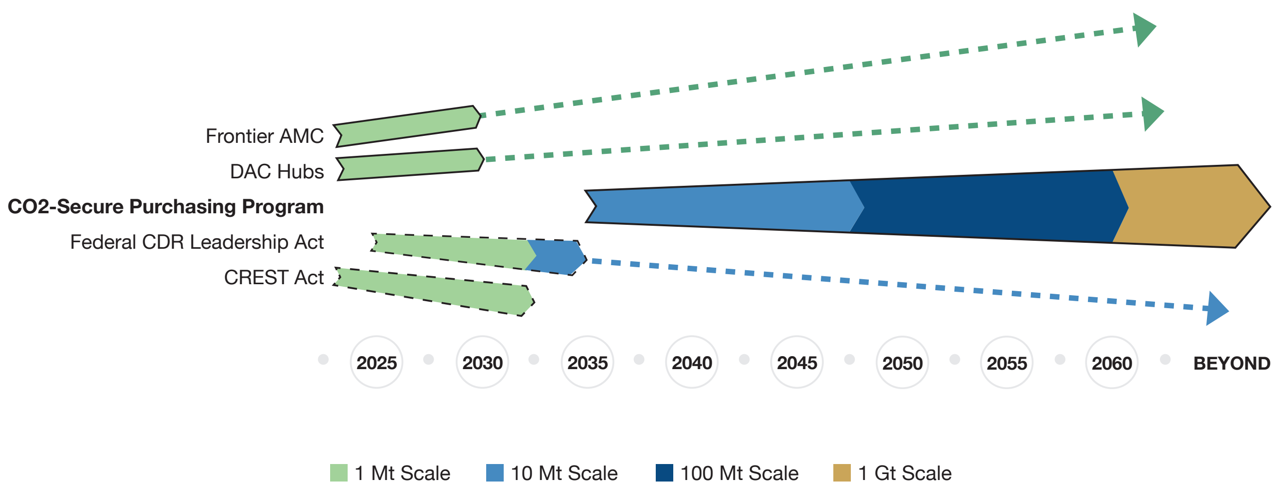
Implementation mechanisms: The program design should encompass a range of government mechanisms to secure large-scale CDR, ranging from purchasing CDR services provided by the private sector to establishing a government-owned and operated CDR program. There are a number of issues to be considered in these various investment models, including contractual terms and conditions, risk sharing, liability management, and funding. Based on a review of past and current government programs that provide helpful analogs, this report recommends that government efforts be focused on, but not limited to, the purchase of CDR services from the private sector.

Organization and management: Recognizing the variety of technologies and diverse geographical circumstances, the report recommends that the scale and pace of the program will require the establishment of a federal organization dedicated to this purpose. While it could be assigned to DOE, the experience with other large-scale, quasi-government, quasi-business ventures suggest that forming a sole-purpose government organization, such as the proposed National Carbon Removal Authority, with expert senior leadership and flexible operational practices, offers the potential to achieve the most effective and efficient program implementation.

Schedule: The CO2-Secure initiative would be planned for initiation at the end of the current available federal incentives and would benefit from enactment of a precursor pilot-scale program such as in the proposed Federal Carbon Dioxide Removal Leadership Act or the CREST Act. Assuming enactment of the necessary authorizing legislation by the end of the decade, the new organization could be established and begin operation as other initiatives end, allowing a continuity of support ideal for market growth. This timeline would allow for learning to take place from the initial CDR deployments initiated through voluntary private sector measures with support from current federal incentives, initial implementation of the proposed regional DAC hubs, and enactment and implementation of a precursor purchase demonstration program that could be housed in DOE and modeled after the Federal Carbon Dioxide Removal Leadership Act or CREST Act. This report outlines a possible implementation scenario in which the initial project investments from CO2-Secure become operational by 2035. The timing of progression is illustrated in Figure 2.

Funding: The initial phase would be authorized for a 10-year period, a typical timeframe for congressional authorizations and federal budget scoring. The initial 10-year window will provide sufficient time for the CO2-Secure initiative to gain experience with large-scale implementation

Figure 2 | Increasing CDR Scale Needed Over Time



of alternative business models and innovation opportunities. In order to provide funding certainty, the initial 10-year funding would be provided as a lump sum direct spending authority totaling $33 billion, with the intent that Congress would reauthorize funding for subsequent years based on this experience, and also taking into account climate science assessments at that time.

Feasibility: The proposed framework for the CO2-Secure initiative embodies a number of characteristics that are not only necessary for effective implementation but also attractive to broad-based support, including that:

- It builds upon DOE precursor pilot programs in current legislative proposals.
- It is additive to current law, policies, programs, and incentives for voluntary actions, separate and independent from any new proposals for mandated GHG emissions reductions or carbon pricing.
- It has a flexible program design, with multiple forms of public-private partnerships and multiple acquisition methods, and is technologically neutral and technology inclusive if performance criteria are met.
- It has strong monitoring, reporting, and verification (MRV) and permanence requirements backed by a long-term, advance-funded program to manage liability.
- It involves regional implementation with benefits of job creation, workforce development, and community benefits.
- It addresses social, environmental, and community concerns.
- It is resilient to short-term volatility in the political environment, providing the program stability to enable the long-term purchase commitments needed by CDR projects.

A summary of the framework elements of the proposed CO2-Secure concept is provided on the following page.

FRAMEWORK ELEMENTS OF THE CO2-SECURE INITIATIVE

Concept

- Federal government direct investment in gigaton-scale CO_2 removal from atmosphere and oceans

Deployment Assumptions

- Goal of achieving annual removals at gigaton scale by 2060; interim milestones of 30 megaton (Mt)/yr in 2040 and 200 Mt/yr in 2050
- Initiation by 2035, following implementation of Bipartisan Infrastructure Law, Inflation Reduction Act, and proposed precursor U.S. Department of Energy (DOE) pilot purchasing program modeled after the Federal Carbon Dioxide Removal Leadership Act, Carbon Removal and Emissions Storage Technologies (CREST) Act, or similar legislation
- Deployment initially of 500 Mt/yr, ramping at a rate of 20 percent compounded annually

Organization and Management

- Wholly owned government corporation—National Carbon Removal Authority (NCRA)
- Board of directors with seven members—heads of the U.S. Department of the Treasury, DOE, and U.S. Environmental Protection Agency, plus four public members appointed by the president with Senate confirmation; members on staggered terms; president designates public member as chair
- CEO appointed by the board, with full executive powers

Financing

- Direct spending authority, authorized for first 10 years ($33.2B)
- Financial transactions on-budget, but not subject to annual appropriations

Program Implementation Authorities

- Eligibility of CDR projects determined based on performance criteria that are technologically neutral
- Authority to enter into multiple forms of public-private partnerships, including:
  - Contract for CDR capture and storage services
  - Acquisition of captured carbon for government-owned, contractor-operated transport and storage facilities
  - Complete end-to-end government-owned, contractor-operated (GOCO) implementation
- Multiple acquisition approaches: tenders, auctions, requests for proposal (RFPs), set-asides
- Financial management, personnel, and procurement authorities typical of other government corporations

Liability

- NCRA holds liability for leakage of carbon that is owned and stored in government-owned facilities.
- Private entities hold liability for carbon stored in nongovernment-owned facilities (regardless of title) for a period of 20-25 years after completion of injection, with subsequent transfer of liability to NCRA.
- NCRA establishes dedicated fund to mitigate leakage in cases of government liability, either to correct leakage or acquire offsets. Leakage mitigation insurance could be offered to private entities to cover their liability.

Benefits

- Pursue climate remediation through gigaton-scale carbon removal
- Imbue CDR with the financial value commensurate with its climate benefits
- Incentivize CDR developers and innovators by establishing market pull (i.e., firm demand signal for carbon removal services)
- Facilitate optionality in carbon removal approaches through performance-based technology-neutral standards
- Manage long-term liability risk of carbon storage safely and effectively
- Promote program effectiveness and efficiency through business-like organization and management structure
- Facilitate new opportunities for job creation and community benefit

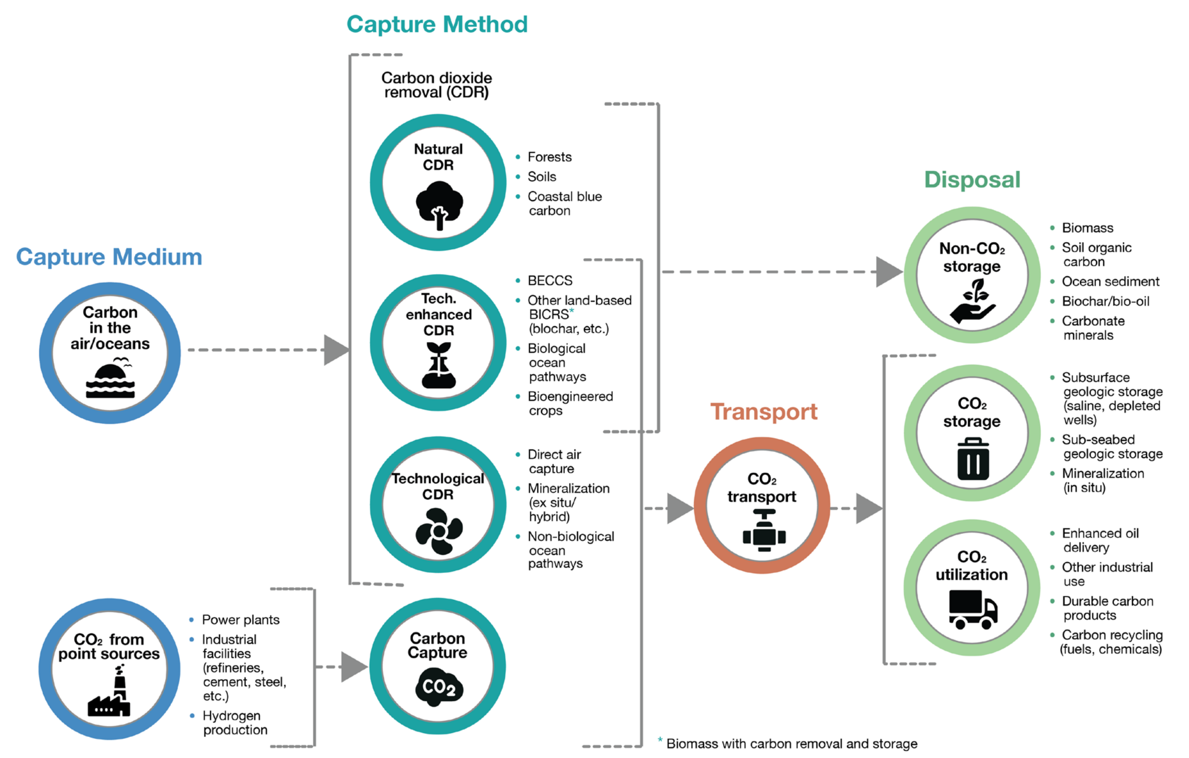
INTRODUCTION

This paper outlines design options for a new initiative, CO2-Secure. The CO2-Secure initiative is intended to clearly and unambiguously build toward gigaton-scale carbon dioxide removal (CDR) (Box 1) in the United States. It builds upon current programs and proposed legislation to link current efforts to what will be required in the next several decades. CO2-Secure is based on the premise that carbon removal is a public good and that removing carbon from the environment benefits all without limitation to any individual. Securing the public good benefits of CDR requires harnessing the investment power of the federal government to expand CDR deployment on a predictable path to gigaton-scale deployment by midcentury. The organizational, management, and funding mechanisms to implement this initiative draw from analogies with long-standing federal government precedents for large-scale investment programs. This paper discusses a range of options for how such a program could be designed and implemented.

Box 1. What Is CDR?

Carbon dioxide removal (CDR) is a form of environmental remediation by removing carbon dioxide (CO_2) from the ambient air and oceans. CDR consists of a suite of approaches (Figure 3), including natural pathways, such as reforestation or agricultural soil management; technological pathways, such as direct air capture (DAC) using chemical solvents or sorbents; and technologically enhanced or hybrid pathways, such as bioenergy with carbon capture and storage (BECCS). These pathways also require some form of carbon disposition: geologic storage (e.g., storage in oil reservoirs, underground saline formations, or surface or subsurface mineral deposits), or storage as living or nonliving biomass, or utilization for industrial processes (e.g., synthetic fuel production) or in useful products (e.g., cement). CDR removes carbon from the environment resulting from past emissions. It is distinct from carbon capture technologies that reduce current emissions from point sources such as power plants and industrial facilities, though there are technological overlaps, and carbon capture can be paired with many of the same methods of disposition. CDR includes pathways across the spectrum of technological readiness, from natural methods that have been used for thousands of years to new technologies still in the research and development stage.

Figure 3 | Overview of Large-Scale Carbon Management Technologies



THE CARBON REMOVAL IMPERATIVE

In the past several decades, the U.S. government, the U.S. public, and the international community have recognized the emerging effects of climate change, recognized the necessity of decarbonization, and taken steps to begin this process and prepare for the long-term effects of a changing climate. As part of this movement, CDR is experiencing unprecedented levels of attention and public funding (Box 2). This elevated interest is because CDR is both the best option for near-term decarbonization of many sectors and the only approach that has the potential to reverse the damage done by centuries of unfettered CO_2 emissions.

Current policies and programs are necessary and encouraging, but their primary objective is to accelerate innovation and demonstration projects, and though they do address scalability, they do not reach the scale necessary to achieve the above goals. Unlike quantum computing or medical innovation, there are no market forces that will create the massive CDR industry that the United States and the world needs.

The first steps toward a program like CO2-Secure have been proposed in Congress, in the Federal Carbon Removal Leadership Act and the purchasing pilot program in the Carbon Removal and Emissions Storage (CREST) Act. The Federal Carbon Dioxide Removal Leadership Act would assign the U.S. Department of Energy (DOE) responsibility to initiate a CO_2 purchase program, beginning at a rate of 50,000 tons/yr in 2024 and increasing to a level of 10 megatons (Mt)/yr in 2035. The CREST Act would authorize a competitive purchasing pilot program in DOE with a funding authorization totaling $230 million over five years. If passed, this legislation could provide the proving ground for transitioning to the much larger scale CO2-Secure initiative.

The CO2-Secure initiative would rapidly scale beyond the Leadership Act program, building to gigaton (Gt) scale CDR in several decades. A gigaton-scale CDR industry is needed to provide a meaningful contribution to climate remediation, and direct federal investment in CDR should be considered as an investment in a public good that the government has the obligation to take on.

Gigaton-Scale CDR is Necessary to Meet Climate Policy Targets

The Intergovernmental Panel on Climate Change's (IPCC) report *Climate Change 2022: Mitigation of Climate Change*—part of a series of reports that comprise its *Sixth Assessment Report (AR6)*—reiterates previous evidence about the necessity of CDR to global decarbonization. The report emphasized that CDR supports three main scientific and policy objectives:

- Accelerating near-term emissions reductions
- Compensating for emissions from hard-to-decarbonize sectors
- Reaching net-negative emissions eventually to stabilize and remediate the climate[20]

In IPCC's modeling, every "illustrative mitigation pathway" that limited global warming to 1.5 or 2 degrees Celsius required significant levels of CDR deployment globally. The median estimates of global CDR in 2050 from all sources (natural, technological, and hybrid[b]) is 6 Gt/yr.[21] The IPCC report documents the need for CDR at a gigaton scale by midcentury to meet these objectives.[22]

b The split between natural CDR and hybrid/technological CDR is roughly 3 Gt/yr each, in the cited median scenario.

It is important to highlight that these goals supplement rather than replace the urgent need for rapid emissions reductions. In the median IPCC scenario with 6 Gt/yr of CDR at midcentury, 40 Gt/yr of current CO_2 equivalent emissions today need to be eliminated.[23]

The United States will need to be responsible for a large share of the global CDR effort, as it will be a crucial component of the U.S. commitment to net-zero emissions by midcentury. Princeton University's *Net-Zero America* study, for instance, found that up to 2.3 Gt/yr of technological and hybrid CDR could be necessary by 2050 to reach the Biden administration's long-term goal of net-zero greenhouse gas (GHG) emissions.[24,25] A study by the Rhodium Group estimated the need for 1 Gt/yr to 2 Gt/yr to reach a highly ambitious goal of net zero by 2045, and 185 Mt/yr to 750 Mt/yr of CDR by midcentury to meet a more realistic target of 83 percent net emissions reduction.[26] By comparison, a report from the National Academies of Science, Engineering and Medicine (NASEM) estimated a potential level of up to 10 Gt/yr by midcentury and 20 Gt/yr by the end of the century.[27,28] Moving beyond midcentury, even larger U.S. CDR will be needed as part of its contribution to meeting global emissions goals, especially considering that the United States accounts for about 25 percent of the historical anthropogenic emissions of CO_2 to the atmosphere.

A Portfolio of Pathways Can Reach Gigaton-Scale CDR

There is a broad portfolio of approaches to CDR, at various levels of technological maturity, that have the potential to achieve carbon removal at gigaton scale. Many natural CDR pathways have been fully demonstrated and are currently being widely deployed. Technological CDR options are at all stages of the innovation spectrum: Bioenergy with carbon capture and storage (BECCS) has been implemented commercially in the ethanol industry, first-generation direct air capture (DAC) systems are in early commercialization, and many other options are in the research, development, and demonstration (RD&D) pipeline.

A main CDR innovation objective is to reduce the cost of removal. NASEM found that CDR could reach gigatons of deployment in the United States at a cost of under $100 per ton, but that reaching that scale and cost would involve substantial federal investment in innovation.[29] In 2019, the Energy Futures Initiative (EFI) published a study providing a detailed road map for a comprehensive 10-year, $11 billion federal interagency RD&D program to reach this goal. EFI subsequently issued a series of follow-up reports, describing in greater detail the RD&D opportunities and challenges for specific CDR pathways: ocean CDR, technologically enhanced land-based CDR, carbon mineralization, and BECCS.

The core impediment to reaching gigaton-scale CDR is that despite its importance to decarbonization goals, developing an industry of that scale cannot easily be accomplished by market forces. In contrast to other low-carbon technologies, such as clean energy systems, CDR has no immediate economic value: Its benefit is its impact on the climate, which is not valued by current markets.[c] Rather than reducing emissions from existing industries and systems, CDR requires generating new economic activity on a massive scale.

c CDR pathways do have tangential economic benefits, including the sale of removed carbon, and co-benefits such as ecosystem restoration or improved economic productivity.

Box 2. Major Current Federal and State CDR Programs

Federal programs and policies devoted specifically to CDR are very new: The phrases “direct air capture” and “carbon removal” did not appear in federal statute until 2018 and 2019 respectively.[30,31,32] Selected current policies impacting CDR deployment are discussed below.

Section 45Q tax credit. The Carbon Oxide Sequestration tax credit, referred to as the 45Q credit, provides an incentive for every ton of CO_2 that is geologically stored, injected for purposes of enhanced oil recovery (EOR), or used in various forms in commercial products. The credit applies to some forms of CDR and point-source capture from power plants or industrial facilities. The U.S. Treasury Department (Treasury) estimates that $460 million in credits were used in 2021, and that the credit will cost an average of $2 billion annually over the next 10 years.[33]

The 45Q credit is an important incentive to deployment of CDR technologies that require some form of geologic disposal of the captured CO_2, such as DAC and bioenergy with carbon capture and storage (BECCS). The Inflation Reduction Act (IRA) extended the availability of the credit for projects commencing construction through the end of 2032 and established a separate structure for DAC projects, reducing the threshold for eligibility to 1 Kt CO_2/yr with a base credit of $36/ton for geologic storage, increasing to $180/ton if prevailing wage and apprenticeship requirements are met. The act also allows the credit to be taken in the form of direct pay for the initial five-year project operating period. Use of the credit is based on voluntary action; the Joint Committee on Taxation (JCT) estimated that utilization of the credit would cost the Treasury $3.2 billion over a 10-year period.[34]

CDR RD&D program. The Consolidated Appropriations Act, 2021 (passed in 2020) contained several provisions related to CDR (and carbon management more broadly).[35] Among these was the establishment of a carbon removal RD&D program within what is now the U.S. Department of Energy (DOE) Office of Fossil Energy and Carbon Management (FECM). The authorizing language includes several CDR pathways across the spectrum of natural and technological options and directs FECM to coordinate RD&D with the U.S. Department of Agriculture (USDA) and other DOE offices. The legislation also directs DOE to fund one or more DAC test centers and encourages DOE to support DAC pilot and demonstration projects.

CDR RD&D at DOE received $104 million in appropriations in fiscal year (FY) 2022—$49 million for the FECM program and $55 million for other DOE offices—of which $75 million was earmarked for DAC.[36] If this program grows by an order of magnitude, it has the potential to develop next-generation technologies that could reach gigaton potential beyond 2030, as well as provide enabling research on issues like life cycle analysis (LCA) that could help with near-term deployment.

Direct air capture prizes. The Consolidated Appropriations Act, 2021 also created DAC prize competitions at both DOE and the U.S. Environmental Protection Agency (EPA).[37] The EPA competition was authorized for $35 million, while the DOE program was bifurcated into a precommercial prize ($15 million) and a commercial prize ($100 million). Both DOE programs were appropriated the full amounts under the Bipartisan Infrastructure Law (BIL), officially the Infrastructure Investment and Jobs Act (IIJA).[38] The EPA and precommercial DOE program operate like traditional prize competitions, rewarding innovativeness and providing support for novel DAC demonstrations. The DOE commercial prize, on the other hand, functions more like a deployment-oriented procurement program or subsidy, funding any facility (up to a price cap of $180 per ton) that captures at least 50 kilotons (Kt) annually.

Direct air capture hubs. The BIL provided additional support for carbon management, including appropriations for several of the previously authorized programs and new funding for DAC hubs.[39] DOE was authorized and appropriated a total of $3.5 billion to fund four hubs, each with a long-term potential to remove 1 Mt CO_2 annually. Like the commercial prize, the DAC hubs program is oriented more toward deployment, including the creation of enabling infrastructure for DAC.

State policy. State policies also can have an impact on CDR deployment. State climate plans have begun to incorporate CDR. New York's Climate Leadership and Community Protection Act, for example, permits up to 15 percent of the state's emissions to be reduced through offsets or removals.[40] Cap-and-trade policies in California and the Northeast—the Regional Greenhouse Gas Initiative (RGGI)—permit forest carbon projects as an eligible category of offsets.[41]

A major incentive for CDR deployment at present is California's Low Carbon Fuel Standard (LCFS), a program designed to reduce the emissions intensity of transportation fuels sold in the state. The LCFS (which has been joined by parallel policies in Oregon and Washington state) incentivizes production of low-carbon bioenergy, including via BECCS, and allows DAC projects to generate credits in the program.[42,43] Unlike most credit-generating pathways under the LCFS, which require the sale of fuel into the California market to be eligible for credits, DAC projects can be located anywhere in the world.

Current CDR Efforts—Public and Private—Are Insufficient for Gigaton-Scale Deployment

There are three market forces currently driving the growing carbon removal industry: market-driven demand for CDR-derived CO_2 for products or industrial use (e.g., EOR, cement, etc.), acquisition of CDR services in voluntary offset markets, and voluntary CDR project funding in response to government regulatory or financial incentives.

Existing demand for **CO_2 for commercial products and industrial processes** is currently met mostly through the supply of naturally occurring CO_2 in the subsurface. The supply cost from natural sources is typically much less than $100 per ton, and the overall market worldwide is less than half a gigaton annually, which means CDR-derived CO_2 cannot currently compete absent policy intervention in the form of mandates or subsidies. Furthermore, even if it were to do so, the current market is only a small fraction of the needed demand for CDR.

The private sector is investing in **CDR as a complementary measure to meet voluntary commitments to reduce net greenhouse gas emissions**, even in the absence of government mandates or subsidies. These efforts are being driven by commitments by some firms to move toward net-zero GHG emissions within their scope of operations. Several private firms have been evaluating CDR project investment opportunities directly, but the growing number of companies with net-zero commitments is giving rise to third-party investors in CDR services. For example, the Frontier Fund, formed by Stripe, Alphabet, Shopify, Meta, and McKinsey, is raising $925 million to invest in CDR projects and sell the carbon credits to other entities seeking to reduce their carbon footprint. While much of this activity has been focused on natural CDR solutions, such as forestry, there is growing interest in acquiring CDR from technological approaches such as DAC.

Government regulation and financial incentives can spur additional private-sector investment in CDR. There are an increasing number of federal and state programs that incentivize CDR (Box 2), including RD&D funding, deployment grants, tax credits, credit support, and regulatory incentives. Box 2 provides a short description of the major policy and financial incentives currently available to support deployment of technological and hybrid CDR approaches.

Table 1 | Cumulative CDR Through 2050 Based on Announced U.S. Projects

Program	CDR Attainable	Description
Announced CDR Projects	130 Mt	Comprising Project Bison and Project Brown Pelican, the removals through 2050 of the two announced projects have been estimated.
DAC Prize Competition	0.5 Mt	Assumes that the full $180/ton value of the commercial prize will be claimed by all users, up to $100 million program budget.
DAC Hubs	80 Mt	The Infrastructure Investment and Jobs Act (known as the Bipartisan Infrastructure Law) authorizes a program of four DAC hubs, each with the capacity to remove 1 megaton per year. Assuming they reach this output by 2030, this value represents their total removals through 2050.
Frontier Fund	Between 1.9 Mt and 4.6 Mt total	With $925 million committed to fund the best possible technologies for long-term CDR scaling, assuming a low price of $200/ton and a high price of $500/ton, a range of removed carbon is estimated.
TOTAL	**~ 210 Mt**	**Cumulative removals through 2050**

While all of these are important to CDR deployment, they are insufficient to reach gigaton-scale deployment on the timescale necessary to achieve net-zero targets. There are several limitations at play. In all cases, the size of the current incentive falls well short of needed levels to reach gigaton scale. As shown in Table 1, current federal incentives programs could support CDR at a scale of 10 megatons to 15 megatons or so. Also, these incentives are capped either in total dollar volume or are time limited. Finally, the incentives rely upon voluntary action—they encourage but do not require investments in CDR—making any future projection of scale subject to large uncertainty. Government incentives may not guarantee additionality if the private firm plans to undertake the CDR investment regardless.

Climate Remediation Is a Public Good

The effects of CO_2 emissions to the atmosphere and oceans can linger for centuries. Emissions going back to the early days of the Industrial Revolution are contributing to climate change today. Public policy measures such as mandates, taxes, or financial incentives can directly impact the rate of new emissions. These measures also can indirectly impact the removal of accumulated carbon through offset credits. However these measures, as described above, cannot reach the scale required to avert the most serious adverse impacts of climate change, nor should they be relied upon as alternatives to reducing new CO_2 emissions where such reductions can be achieved through technologically feasible and cost-effective means.

Box 3. The EPA Superfund: Environmental Remediation as an Investment in a Public Good

The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), aka "Superfund," is an Environmental Protection Agency (EPA) program that combines the long-standing environmental principle of "polluter pays" with the use of taxpayer investments in environmental remediation as a public good.

Established in 1980, the program is responsible for remediation of hazardous waste sites of all sizes and composition. The program has authority to compel the responsible party to perform remediation work (the polluter pays). The program also may directly undertake site cleanups utilizing the Superfund (a trust fund funded through a combination of targeted and General Fund tax revenues), recognizing that environmental remediation is a public good in instances where the responsible party cannot be identified or no longer exists. The investment in environmental remediation is significant. Over the past decade, the U.S. government has invested $10.4 billion in hazardous waste remediation.[44] The principle of addressing hazardous waste remediation as a public good is analogous to the objective of CO2-Secure.

Removing legacy CO_2 from the atmosphere and the oceans will benefit future generations by averting to some degree the adverse impacts of climate change that would otherwise occur. Climate remediation is like other forms of environmental remediation that deal with legacy issues. The EPA Superfund program, for example, provides for the environmental remediation of hazardous waste disposal sites where the responsible party may no longer exist, or cannot be legally determined, or where the responsible party is unable to assume responsibility for cleanup. (The characteristics of the Superfund program are described further in Box 3). Removal of carbon from the atmosphere and oceans represents a similar challenge.

The challenge of removing residual carbon from the environment can be resolved only by treating it as a public good of such importance that it is a federal government responsibility. In economics, a "public good" is defined as something that provides utility and is "non-excludable" (i.e., its consumption cannot be restricted) and "non-rivalrous" (i.e., one person's consumption does not impact others' ability to consume it).[45] These criteria distinguish public goods from other types of goods (private, club, and common pool goods). Categories of public goods include security and safety (e.g., national defense, fire protection), science and information (e.g., open data, scientific discoveries), public health, and environmental protection.

All of the aforementioned public goods have been adopted as federal responsibilities in some form or another. Indeed, the federal government is constitutionally mandated to provide some public goods, such as national defense, the U.S. census, and standards for weights and measures. But the federal government also has frequently taken on subsequent public good responsibilities. One such example is the assumption of control over lighthouses by the federal government in the early days following establishment of the United States (Box 4).

Box 4. Lighthouses and the Evolution of Public Good Responsibilities

The federal government has a broad array of responsibilities for environmental public goods—clean air, waste remediation, a livable climate (itself a recently established federal responsibility)—and public infrastructure, public parks, and recreation areas.

Lighthouses are an archetypal example of public good infrastructure that evolved from an ad hoc system of private sector initiatives into a comprehensive national program that became a federal government responsibility.

Shortly after the ratification of the Constitution, one of the first acts of the new U.S. Congress was to nationalize the former colonies' 12 existing lighthouses and make construction and operation of lighthouses a federal responsibility.

Where lighthouses were previously controlled by state and local governments (and funded by fees on ships using the port), Congress decided that safe navigation of U.S. shores and ports was a public good needed to support all forms of commerce and trade that should be underwritten by the federal government. The "justification" for federal involvement has shifted over time, with control over lighthouses oscillating between civilian and military control.

The CO2-Secure Concept

CO2-Secure is a form of environmental remediation to the global climate. The concept is based on the premise that carbon removal is a public good, requiring the investment power of the federal government to expand CDR deployment on a predictable path to gigaton-scale deployment by midcentury. CO2-Secure relies on direct action by the federal government to purchase carbon removal as either a good or service, or through public infrastructure. This concept is an expansion of the idea of using public procurement power to purchase CDR, which has been proposed by other researchers and advocates.[46,47]

CO2-Secure is a federal direct investment program, where the government would pay for the entire cost (subject to restrictions such as price caps) of carbon removal. The reliance on the government's purchasing power distinguishes it from the federal government's current policy tools for supporting climate and clean energy technologies. Nor would CO2-Secure operate as a mandate or regulation, requiring action of private actors; the responsibility for meeting program targets would fall to the government. The value produced (namely the climate remediation benefit of carbon removed from the environment) would accrue to all taxpayers.

Creating large, firm demand for CDR by positioning the federal government as a buyer of CDR goods and services would provide financial certainty to developers of CDR and CO_2 transport and storage (T&S) infrastructure and create a market pull that would spur innovation and cost declines. The design framework for CO2-Secure also could facilitate resolution of issues around GHG accounting and long-term liability for carbon storage, safeguard against unintended environmental and social consequences, and maximize job creation and other co-benefits.

The scale-up of CO2-Secure also could expand the infrastructure needed to support broader adoption of point source carbon capture and storage of CO_2 emissions from industry and the power sector.

CO2-SECURE PROGRAM FRAMEWORK

The following sections outline programmatic design considerations for the CO2-Secure concept, addressing the following questions:

- What should be the size and scope of the CO2-Secure program?
- Which CDR activities should be eligible for participation in CO2-Secure?
- How would the program operate?
- How should CO2-Secure be organized and managed?
- What will CO2-Secure cost?
- How should CO2-Secure be funded?

Targets, Scope, and Eligibility

Current federal CDR programs are focused on continuing innovation and early commercial deployment of CDR through voluntary private sector action. The federal government provides annual funding for CDR research, development, and demonstration (RD&D) programs, and Congress has enacted incentives, available over the course of this decade, to encourage private investment in commercial CDR deployment.

The proposed Federal CDR Leadership Act and purchasing pilot program in the Carbon Removal and Emissions Storage Technologies

(CREST) Act would create the initial step toward a large-scale CDR deployment program with the eventual goal of climate remediation. The proposed design of the CO2-Secure initiative assumes that something like the currently proposed legislation is enacted and implemented through 2034. CO2-Secure is then started in 2035 with the goal to ramp up CDR capacity to the gigaton (Gt) scale by midcentury. The proposed mid-2030s start date would allow for the compilation of a robust experience base consisting of:

- Experience from private sector CDR investments to meet voluntary commitments and aided by current federal financial incentives programs
- Benefits of innovation arising from current and planned CDR RD&D programs
- Learnings from the proposed precursor federal acquisition efforts such as the Federal Carbon Dioxide Removal Leadership Act or CREST Act

Achieving gigaton-scale operation by midcentury would enable CO2-Secure to make a material contribution to U.S. and global net-zero goals and begin to bend the emissions curve toward net-negative emissions needed for climate remediation. Scaling the program around these two parameters requires rapid growth—a compound annual growth rate of about 20 percent. The program pacing also should provide flexibility for adjustment based on the evolving state of climate science and other changing circumstances.

The scope of CDR approaches supported by CO2-Secure is based on a pathway-agnostic and technology-agnostic approach. No single pathway will likely be sufficient to meet global CDR needs, and different pathways have their own strengths and weaknesses with no single "winner." Furthermore, diversifying the program could reduce costs, support innovation across a wide range of technologies, and allow new concepts to integrate into the program as they advance. Instead, the CO2-Secure concept should govern program eligibility on a set of performance-based criteria. Those criteria would include verifiable removal, scalability, additionality, and permanence.

Verifiable removal. The carbon removal benefits of projects supported by CO2-Secure should be verifiable and transparent. CDR technologies may not always produce net-negative emissions over their life cycle, depending on resource inputs, system configurations, etc. CO2-Secure will need to adopt procedures and guidelines to confirm the size and accuracy of the carbon removal, including standardized, technology-specific accounting frameworks for participating projects; monitoring, reporting and verification (MRV) requirements for storage, including possible third-party verification; and sanctions for projects that fail to deliver promised amounts of removal and storage. These requirements will need to be applied to all steps in the CDR life cycle.

Scalability. For CO2-Secure to reach gigaton scale, the individual CDR pathways supported by the program will need to be readily replicable on a large scale in order to contribute meaningfully to meeting national targets. This criterion would emphasize pathways and technologies such as direct air capture (DAC) while allowing flexibility to incorporate other pathways, such as coastal blue carbon, that have less total deployment potential. In addition, while CO2-Secure funding will need to focus on those pathways that most quickly scale the program, there may be opportunities to support innovative, smaller-scale applications as part of the portfolio through a limited funding set-aside (e.g., 10 percent). This option would be in keeping with the design of current programs, such as the DAC prize competitions.

It is important for CO2-Secure to not only focus on the pathways and technologies that can be replicated at large scale, but also to support individual projects that can be deployed as large-scale projects. To illustrate the importance of this criteria, consider that 1,000 individual projects each at megaton scale (larger than any currently deployed DAC or bioenergy with carbon capture and storage [BECCS] installation) would be needed to meet the program's overall target of 1 Gt.

Additionality. Carbon removed through CO2-Secure should be additive to CDR removal that is credited under other CDR incentives. Additionality of the removed carbon from this proposed program is the concept that the removal of the carbon from the atmosphere would only have occurred due to the activity of the purchase program alone. Additionality is essential to ensure that overall removal targets are achieved. This suggests that CDR measures that are eligible for assistance through CO2-Secure financial support should not be "stacked" with other CDR financial incentives; otherwise, a potential duplication of credited removals would result. Further safeguards may be required to account for duplication that might result from interaction with policies that might indirectly support CDR, such as the federal Renewable Fuel Standard or CO_2 infrastructure financing support.

Permanence. Carbon removed by CDR should be permanently separated from the atmospheric carbon cycle. While the assessment of permanence should address the entire life cycle of the capture and disposition process, the main element is to ensure that the method of disposition—whether utilization or storage—can meet a reasonableness standard for preventing the re-release of the CO_2 back into the environment. Permanence can be established through a combination of upfront geological assessment combined with a program of long-term modeling. Geological analysis and modeling can project geologic conditions over periods of 1,000 years or more. MRV requirements extended for 100 years and backed by liability insurance (as described in a later section) can provide certainty for a 100-year period and can help validate the longer-term modeling projections.

Environmental impact. The acquisition of CDR also will need to prevent other environmental impacts. CDR is intended to address a global environmental issue (the concentration of CO_2 in the atmosphere), but CDR project architectures and infrastructure can have other effects on the local environment. CDR projects require resource inputs including energy, land, water, chemicals, and minerals that differ among projects and pathways. They have the potential to substantially impact their surrounding air, water, and natural ecosystems. For example: BECCS projects need land, water, and fertilizer to cultivate biomass; DAC requires a substantial amount of energy to process large amounts of ambient air and to separate the captured CO_2 from the sorbent; mineralization often requires mining or reactive rocks.[48]

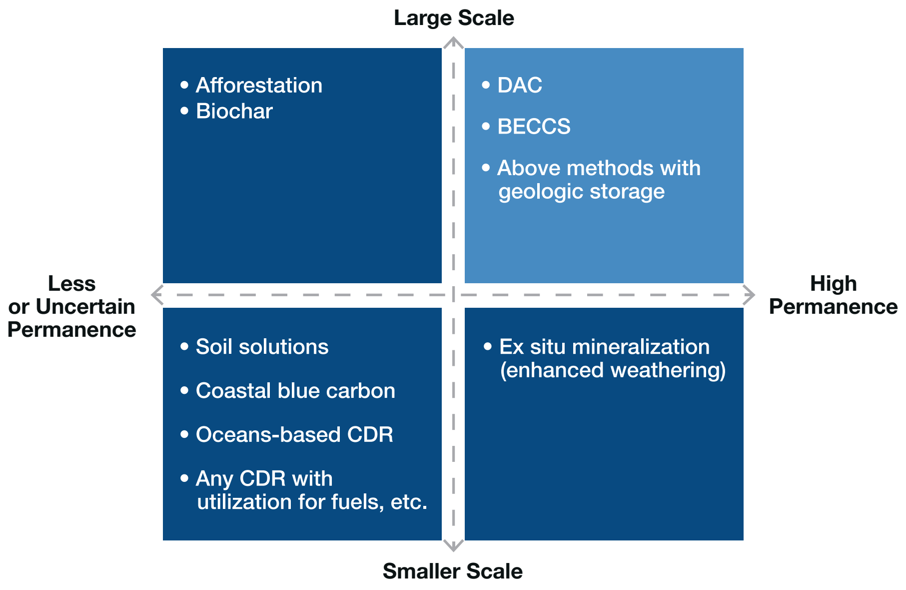
CO2-Secure acquisition plans for goods and services will need to incorporate specific environmental criteria for eligible CDR technologies. In addition to standing environmental regulatory requirements applicable to similar types of technologies and projects, CO2-Secure could establish additional environmental incentives that could be tailored to CDR pathways and technology. For example, DAC projects could be incentivized to use low or emissions-free electricity to be eligible for the program. BECCS projects could incorporate an environmental assessment of the land use change caused by the undertaking. CO2-Secure also could prioritize projects that bring positive economic benefits, such as BECCS projects coupled with forestation or carbon-storing soil management.

Social equity. A gigaton-scale CDR industry will have numerous large-scale projects located in different communities across the country. These projects will affect the local environment (as discussed above), require new large-scale physical infrastructures, and will alter the social and economic landscape in the surrounding communities through jobs and economic development. The CO2-Secure eligibility criteria should ensure that the benefits of these projects are equitably distributed and that the burdens do not fall disproportionately on vulnerable populations. Achieving such equity will require careful attention to project and site selection, as well as a focus on ensuring early input and collaboration with local communities. This goal is especially important considering recent cases of opposition to CDR or related technologies (e.g., carbon capture, utilization and storage [CCUS], bioenergy), often as a result of the perception that these technologies provide a license to continue burning fossil fuels or extend the life of emitting infrastructure.

Workforce and community benefits. Construction of new CDR infrastructure will create opportunities for new well-paying, high-skilled jobs. The Inflation Reduction Act, for example, mandated prevailing wages—set by the secretary of labor—for the construction and renovation of 45Q-eligible carbon capture and storage infrastructure.[49] Such mandates could be incorporated into the eligibility criteria for CDR projects. Workforce development programs, such as apprenticeship and visa worker protection incentives, could further increase the socioeconomic benefits of the CO2-Secure program at the community level. Training programs sponsored by labor unions also could provide substantial contributions to workforce development and associated community benefits.

Figure 4 illustrates how two of these eligibility criteria—namely scale and permanence—could be applied to individual CDR pathways. The figure shows that technologies such as DAC and BECCS already have the potential to support both criteria. Natural CDR pathways, such as afforestation, have the potential for scalability but are more challenging in regard to permanence and verifiability. Mineralization has the potential for permanence, but its ability to scale is very uncertain. Other CDR pathways—such as coastal, ocean, and soil CDR, or many forms of carbon utilization—have a number of unknowns and uncertainties that would need to be further evaluated if they are to become major elements of the CO2-Secure portfolio.

Figure 4 | Eligibility Criteria



Box 5. The Role of BECCS in Integrated Assessment Modeling

Bioenergy with carbon capture and storage (BECCS) is the dominant technological CDR method in multiple IPCC modeling scenarios, and the only modeled option reaching gigaton scale.[50] It can achieve more than a quarter of its contribution at a cost of less than \$100/tCO_2 but is estimated to require a median 119 million hectares of land in 2100 by the IPCC.[51,52]

BECCS has a distinct advantage over other technological and hybrid CDR methods. It can produce—rather than consume—energy while removing CO_2 at relatively low cost. BECCS deployment at gigaton scale, however, could pose other challenges such as feedstock availability and land use change.

Estimates for the United States suggest the potential for a large-scale BECCS industry without adversely affecting biomass feedstock availability. On the global level, however, the IPCC AR6 report highlights issues regarding the demand on land and water and associated sustainability at the scale of BECCS deployment assumed in the modeling.[53]

Public-Private Collaboration Models

The large-scale investment that underlies the CO2-Secure concept necessitates consideration of the nature of the public-private partnerships (PPP) required for implementation. At present, most if not all infrastructure for technological and hybrid CDR—including CO_2 transport and storage (T&S) infrastructure—is being developed by private companies.

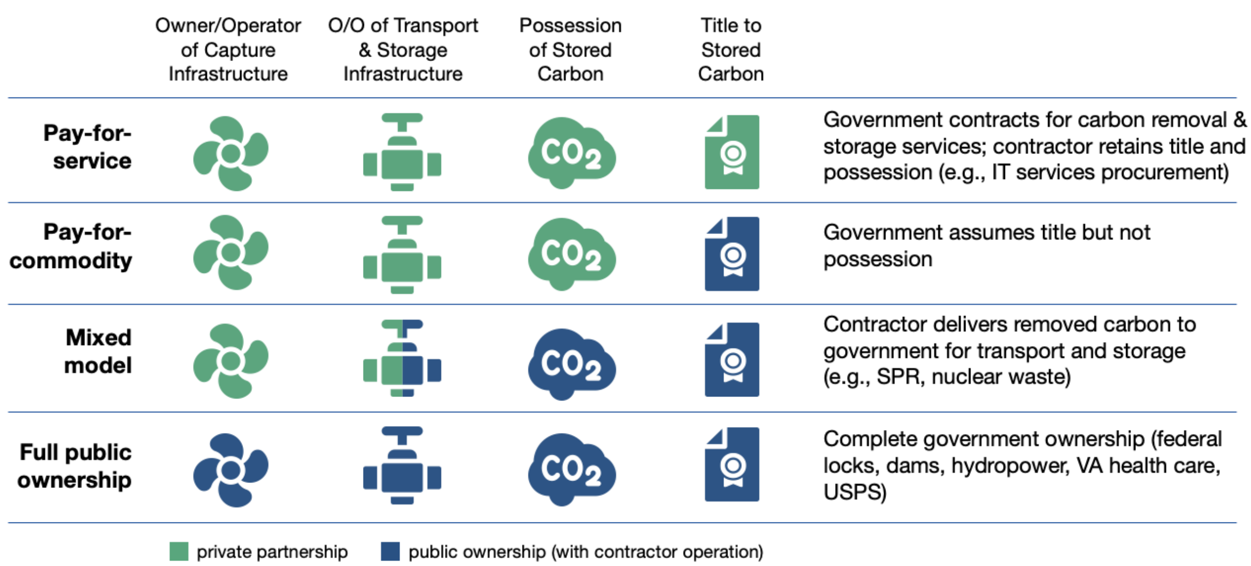
The CO2-Secure initiative could be implemented under a range of PPP arrangements. The government could implement CO2-Secure through purchases of CDR services that would be provided by private-sector partners. Alternatively, the CO2-Secure program could procure captured CO_2 as a good, with the private sector acting as a contractor to the government. The range of PPP models encompasses not only ownership and possession of removed CO_2, but also ownership of the infrastructure needed for removal, transportation, and storage of the carbon. Figure 5 illustrates a range of options for PPP arrangements in ascending order of government involvement.

Pay-for-service. Under a pay-for-service model, all components of a CDR project—removal infrastructure, T&S infrastructure, possession of and title to stored carbon—would remain privately owned. The government would contract with those private owners for carbon removal and storage services. This model would resemble how the government contracts with other service providers that do not deliver a physical good, such as contracts for IT services. The pay-for-service model underlies recent legislative proposals in Congress and New York state (see Box 6).

Pay-for-commodity. Under this model, all infrastructure still would be privately owned, but the government would assume title to—though not physical possession of—the carbon once it is captured and stored. This model mirrors how the government sets up power purchase agreements, such as contracts for renewable power where the government takes and consumes the commodity (as well as takes the carbon-free attributes in the form of renewable energy certificates).[54] The advantage of this model is that it relies upon the effectiveness and efficiency of the private sector to implement the program, while transferring the ownership of the commodity and associated liability to the government in order to reduce the risk to the private sector, which could incentivize greater participation in the program. (Mechanisms for sharing liability risk are discussed in more detail in a later section on liability.)

Mixed model. Various combinations of public and private ownership are possible, but one mixed model of note involves government ownership of T&S infrastructure as well as ownership of the commodity. Under this scenario, the contracted removal entity would deliver CO_2 to government-owned pipelines for transport and storage. This model would resemble government stockpiles—such as the Strategic Petroleum Reserve (SPR)—or waste disposal programs—such as local municipal waste services or federal radioactive waste management programs. Government ownership of important CDR physical assets could reduce financing costs through the application of Treasury borrowing. There also could be benefits in terms of siting and permitting of new infrastructure if the CO2-Secure program (rather than a private entity) was the permittee and it was vested with eminent domain authority. Government ownership and control of the T&S infrastructure also could facilitate efforts by the government to provide shared infrastructure for other technologies (i.e., point-source carbon capture storage [CCS]). There are tradeoffs, however, with public ownership of large infrastructure, including greater political visibility and higher construction costs associated with government contracting.

Figure 5 | Options for Public-Private Divisions of Ownership, Responsibility, and Operation



Box 6. Proposed State and Federal Legislation: The New York Carbon Dioxide Removal Leadership Act, the Federal Carbon Dioxide Removal Leadership Act of 2022, and the Carbon Removal and Emissions Storage Technology Act of 2022

Examples of proposed legislation to enact a pay-for-services carbon removal program have been proposed in New York state and in the U.S. Congress.

The New York State Assembly Bill A08597 proposed the creation of a CDR purchase program to enable the state to reduce its GHG emissions by 15 percent (relative to 1990 levels) by 2050.[55] The aim of this bill is to help New York achieve its 85 percent emissions reduction goal; stimulate technical advancements in CDR; and establish the state as a hub for a future CDR industry. The program would be funded through tax revenues from aviation gasoline. A reverse auction would be conducted every year from 2025 to 2050 to select suitable CDR projects. The maximum cost of procurement would be $350/tCO_2$ in 2025 and would be reduced by 5 percent each year. The CDR project would have to start and be completed within 10 years from the date of the contract. The captured CO_2 would have to be stored for at least 100 years. The Department of Environmental Conservation would evaluate all submitted bids using a scorecard consisting of various criteria, such as price per ton, location, and scale.

The Federal Carbon Dioxide Removal Leadership Act of 2022 outlines the establishment and operation of a program within the U.S. Department of Energy (DOE) to remove carbon dioxide.[56] The bill mandates 50 Kt/yr for 2024 and 2025 (price capped at $550 a ton) and increases this amount at a specified rate annually to reach a level totaling 10 Mt/yr in 2035 (with a cap on price reduced progressively to $150/ton) and continue at that rate every year thereafter. The program has a mandate to prioritize smaller projects, as well as projects with co-benefits for the environment and community. The program also includes provisions to prevent double counting and requires that CDR for a given year be completely sequestered within three years from the year in which it was counted as being removed.

The Carbon Removal and Emissions Storage Technologies Act of 2022 (CREST Act) authorizes a broad suite of CDR R&D programs and, in addition, authorizes a DOE pilot program for procurement of carbon removal services. The bill establishes detailed procedures for a competitive process of reverse auctions. The reverse auction process is structured into two tiers, one for long-term carbon storage permanence (greater than 1,000 years) and another for medium-term permanence (between 100 and 1,000 years). Bids are solicited and awarded on the basis of lowest cost of carbon removal, up to a price cap set by DOE. The bill authorizes a total of $230 million for purchases over a five-year period. Based on the pricing assumptions in this study, the pilot program could result in about 0.9 Mt of CO_2 removals.

Full public ownership. Rather than owning just T&S infrastructure, the government also could own and control its own carbon removal infrastructure (e.g., DAC and BECCS plants). Owning this infrastructure would put carbon removal in the same category as federal hydropower infrastructure (dams, locks, etc.), the Veterans Health Administration, or the Postal Service. Public ownership of removal infrastructure could have some of the same trade-offs of owning only the T&S infrastructure; it also could bring additional social and economic advantages such as giving communities a greater degree of involvement in decision-making and benefits.[57] Public ownership need not be limited to the federal government; state, tribal, and local governments also could assume an ownership role in CDR or storage development. Nor would government ownership necessarily obviate the need for private contractors; government-owned, contractor-operated (GOCO) facilities already are used at the federal level for research and manufacturing (e.g., federally funded R&D centers, nuclear weapons manufacturing, Army ammunition plants).

> **A program design for CO2-Secure that focuses the government's role as a purchaser of CDR services may in fact offer the most efficient and rapid mode of implementation.**

There are advantages and challenges with each PPP model. A program design for CO2-Secure that focuses the government's role as a

Box 7. Title and Liability with Other Forms of Disposition

The design of the CO2-Secure program would have to account for the fact that title to stored carbon, MRV, and long-term liability could look very different for CDR projects that dispose of carbon through means other than saline formation geologic storage. Utilization for enhanced oil recovery (EOR), storage in reactive minerals (in situ mineralization), and storage in sub-seabed geologic formations have many similarities to geologic storage but would have their own considerations in terms of MRV and liability.

A larger program design question surrounds storage or utilization methods that securely dispose of carbon in products, which could be impractical to monitor and assign liability for. Similar concerns would apply for CDR methods that do not produce gaseous CO_2 (e.g., ex situ mineralization).

One option would be for the program's administrating entity to evaluate these methods and determine that the likelihood of reversal is low enough that post-conversion monitoring or liability would not be necessary. Pathways such as conversion to plastics, injection into concrete, and ex situ mineralization in mine tailings might meet this threshold.

purchaser of CDR services may in fact offer the most efficient and rapid mode of implementation. It also could lessen the likelihood that other policy and political factors would shape program implementation decisions. The models, however, are not mutually exclusive, and multiple models could be incorporated into the final program design for CO2-Secure. A mixed-model program would need to set constraints on the use of the public ownership model in order to avoid unnecessary competition with the pay for goods-and-services models.

Contracts and Award Mechanisms

The CO2-Secure initiative could be implemented through one or more of the well-established federal government contracting mechanisms that are compatible with the various models of public-private partnerships (PPPs) described earlier. Federal agencies engage in different types of contracts depending on a variety of factors such as price or quantity certainty, time of need, complexity and urgency of requirements, contractor experience, profit incentives, and liability.[58] Price-setting is an important element of contract structure, with the two principal price-setting approaches, fixed-price contracts and cost-plus-fee contracts. CO2-Secure could have broad authority to implement one or more fixed price contracting mechanisms as well as authority to issue requests for proposals (RFPs) that could encompass both price and non-price selection criteria.

Fixed-price contracting mechanisms. Fixed-price contracts are contracts with either a firm price or a base price with a set formula that allows for automatic adjustments.[59] They are used for acquiring commercially available goods and services that have ample competition and where bidders can accurately estimate costs.

These contracts could be awarded either on a competitive basis through a reverse auction or through a tender.

- A **reverse auction** is the most common process for awarding fixed-price contracts. Reverse auctions involve vendors bidding against each other for the price at which they are willing to sell a good or a service.[60] Federal agencies use reverse auctions to obtain products at a lower cost and reduce administrative efforts.[61] Reverse auctions are effective "when requirements are steady and relatively simple and might otherwise be acquired through low price technically acceptable" criteria. They are mostly used to acquire products commercially available from multiple sources.[62]

  A reverse auction for acquiring CDR services could have multiple designs. The federal government could require vendors to bid the lowest price they are willing to accept to remove and sequester a fixed quantity of carbon dioxide—a conventional reverse auction. The government alternatively could require vendors to bid the highest volume of carbon dioxide they are willing and able to remove and sequester at a fixed price. A third approach could involve a combination of the two above approaches, whereby potential contractors bid for both the price per metric ton and the quantity of carbon dioxide removed and sequestered.

- A **tender** is another approach to securing fixed-price contracts. The tender is essentially an offer to acquire private sector carbon removal services at a price set by the government in the tender offer. The tender could set limits on quantity, either on a contract specific basis or an overall cap on the tender or both.

The federal government has successfully used prize competitions to encourage innovation in various technologies as well as crowdsource ideas to solve problems.

- Another variant on the fixed-price contract process is a **prize**. The federal government has successfully used prize competitions to encourage innovation in various technologies as well as crowdsource ideas to solve problems. DOE started the L-Prize to spur the development of efficient LED lightbulbs to replace conventional lightbulbs.[63] Prize competitions have several advantages that help them supplement other award methods:[64] They enable the federal government to shift the risk burden onto the participants, they mobilize private sector investment, and the government pays only for success. Prize competitions, however, have traditionally dealt with a smaller sum of money when compared to the amount needed for CDR. The total prize money awarded by all federal competitions was $37 million in 2018.[65] The Energy Act of 2020 authorized two separate prize programs for DAC—a commercial DAC prize and a pre-commercial DAC prize. Both programs were subsequently funded in the Bipartisan Infrastructure Law. The prize concept, however, is more suited to innovation challenges rather than large-scale deployment.

Flexible contracting mechanisms. CO2-Secure also could implement more flexible contracting approaches through an RFP process. The RFP could include evaluation criteria that encompass a variety of price and non-price factors. Price criteria, for example, could allow for cost-plus-fee proposals. Non-price criteria could allow for flexibility on factors such as CDR pathway, technology, size, and environmental impacts. Each of these factors, along with price, would be weighted in the overall assessment of proposals, and the contracting entity could then select the proposal that offers the best value. The use of RFPs allows greater flexibility in program design, for example, by including smaller size projects or encouraging greater regional variation. In short, it would allow CO2-Secure to advance multiple policy goals when lowest price is not the sole criterion for selection. Nonetheless, the RFP process should lead to a firm fixed-price contract that best meets the full range of criteria identified in the RFP.

Relationship between contract structures and PPP models. CO2-Secure could be implemented through either the fixed-price or competitive but more flexible RFP approaches. If early commercialization efforts in this decade are successful, they may establish a sufficient data base for CO2-Secure to begin implementation of a pay-for-services model in 2035 through competitive fixed-price methods, either a reverse auction or a tender. If there remain large uncertainties in cost (and implementation schedule) for CDR projects, CO2-Secure could initially rely on the RFP process to provide more flexibility to account for cost and other uncertainties. Over time, a pay-for-services model will need to increasingly rely upon fixed-price contracts that could be awarded through both reverse auctions and tenders.

For PPPs that involve a larger public sector role, such as CO2-Secure purchasing and taking title to removed carbon for storage utilizing either privately owned or government-owned transportation and storage infrastructure, the fixed-price contracting model also may be applicable. However, fixed-price contracts are typically less likely to be employed with government ownership of infrastructure. Instead, the government is more likely to engage in cost-plus-fee (either fixed fee or award fee) for acquisition of infrastructure. Cost-reimbursement contracts provide greater assurance to contractors to recover incurred costs as long as the costs are within the established guidelines in the contract.[66] These contracts are used when it is not possible for either the federal agencies or the contractors to accurately estimate costs. Other contract types are variations of these two contracts and are spread throughout a spectrum.

Long-Term Liability Management

The carbon removed from the environment by the CO2-Secure initiative is most likely to be stored in subsurface geologic formations. Some quantities also may be mineralized at the surface or used in products and processes where it will not be re-released into the environment, but the capacity of these options appears likely to fall short of that needed to support a gigaton-scale removal program. Ocean and terrestrial/biological sources of storage also may be feasible if they can satisfy the permanence requirement.

> **Because of the extent of characterization, depleted oil and gas reservoirs offer a potentially attractive resource for carbon storage.**

The United States has immense potential geologic storage capacity, enough to store all of the country's legacy emissions many times over (somewhere between 2,000 Gt to 15,000 Gt).[67] To date, the focus of underground injection activities has been oil- and gas-related, where there has been substantial economic motivation to carefully characterize the relevant subsurface. Because of the extent of characterization, depleted oil and gas reservoirs offer a potentially attractive resource for carbon storage. There has been increasing federal RD&D investment in carbon storage in saline aquifers and other non-oil and gas subsurface geological-fossil fuel formations through the DOE CarbonSAFE and Regional Carbon Sequestration Partnership programs, but commercial application has been limited to date.

Underground injection of all materials, including CO_2, is currently regulated by the U.S. Environmental Protection Agency (EPA) under the Safe Drinking Water Act. EPA can delegate this responsibility to states and tribes that apply for "primacy." Currently several states or tribes oversee permitting and regulation within their borders, including Wyoming and North Dakota, which have primacy over all of their underground injection control (UIC) permitting.[68]

UIC regulation under the Safe Water Drinking Act is statutorily focused on protecting underground sources of drinking water (USDWs). Although this objective is immensely important and a risk factor for an underground CO_2 storage project, the risk of leakage of stored carbon back into the atmosphere is not a statutory consideration in this permitting. The monitoring, reporting, and verification (MRV) requirements in UIC permits will shed light on potential leakage issues but may require augmentation to fully satisfy the CO2-Secure requirements for permanence or verifiability. The necessity of permanent storage means that risk evaluation must be examined in timeframes of decades and centuries, commensurate with science-based climate objectives, which may differ from the regulatory requirements for evaluation of USDW impacts.

Long-term liability is a potential challenge for CO_2 storage. Although leakage rates are very low, CO_2 storage sites will require monitoring over very long periods of time. As a result, obtaining insurance may be challenging, and CO_2 leakage issues may arise decades after it has been injected, when the party that injected it may have ceased to exist. This scenario has been an issue, for example, with the disposal of hazardous wastes, where the parties responsible for generating, transporting, and disposing of the hazardous materials may no longer exist. It was this problem that led to the establishment of the EPA Superfund program, another federal environmental remediation program addressing a problem that has evolved into a public good.

So, how best to manage liability for the risk of CO_2 leakage over the longer term? There are three major approaches to long-term liability management models for CO_2 storage that could be considered: private, public, and a hybrid of the two.

In the private model, the company that injects the CO_2 would own the CO_2 and be liable for it. The company would be responsible over decades or

Box 8. Private Insurance

Insurers facilitate projects by mitigating defined project risks. The traditional scope of risk insurance consists of property and casualty insurance. Property insurance covers risk to physical assets due to natural risks (e.g., flood, windstorm, hail, earthquake), fire, and various human-caused events. Casualty insurance typically covers various forms of liability protection including product liability and professional liability. In addition, specialty forms of insurance can be provided for events such as project performance guarantees or coverage against specialized events.

Insurance coverage for liability for potential CO_2 leakage or other environmental impacts could in concept be underwritten in commercial insurance policies. To do so, however, the industry would require better information on the potential frequency and severity of CO_2 leakage. While the risk appears to be very low, the period of insurance coverage introduces major uncertainty and thus difficulty in pricing. As noted in a recent insurance industry white paper, "Private insurers are not willing to take very long duration tail risks due to uncertainties in loss prediction."[69] It is reported that one large insurer, Zurich Insurance, has indicated that it would offer liability insurance for point source CCS projects in the United States, but there is very little public information on the product.[70]

A hybrid approach to liability management, in which the federal government would assume liability after a fixed period of time (e.g., 20 to 25 years) would eliminate the long duration tail risk for private insurance and enable providers to offer liability insurance coverage for the initial storage period. As more experience is gained with subsurface CO_2 management, the period of coverage of private insurance could be extended.

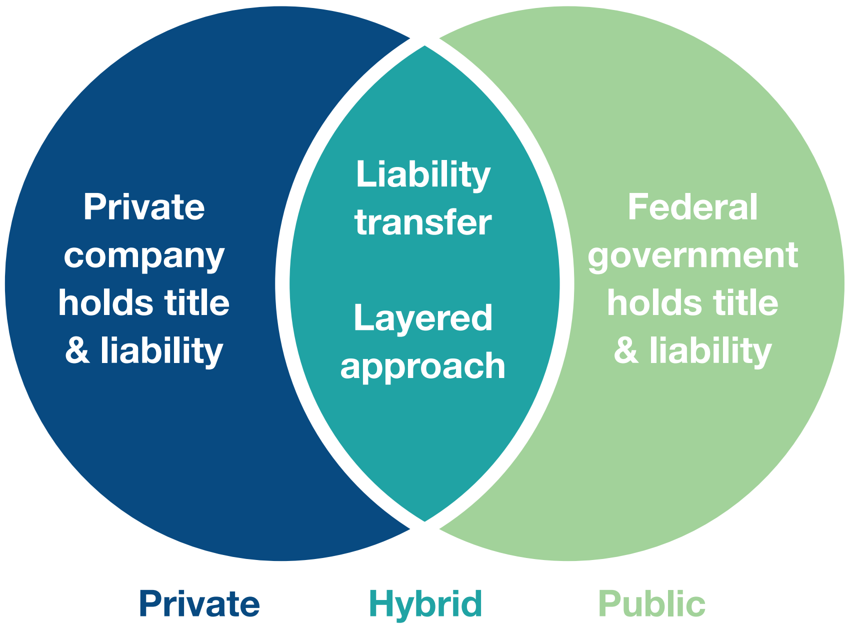
even centuries for ensuring that the CO_2 does not leak. In the event of a leak, the company would need either to fix the cause of the leak and replace the CO_2; pay a penalty; and/or pay for estimated climate damage. A private long-term liability model may not be practical given that private insurers may not be willing to provide insurance coverage over such long timeframes. Or they may do so only at a substantial premium to account for the uncertainty that in turn would be challenging to price into a private sector offering for CDR services (Box 8). Consequently, assigning full liability to the private sector party could discourage participation in the CO2-Secure program.

An alternative would be for this liability to be assumed by the CO2-Secure program. A governmental institution would have the long-term staying power to monitor and respond to any leakage issues that might arise over a period of decades or more. It also could establish a durable funding mechanism for addressing leakage. Assumption of liability could be shared between the government and private sector in a variety of ways (Figure 6).

A hybrid approach could involve the private entity being liable for a certain number of years, followed by a transfer of the liability to the CO2-Secure program. Several states have adopted hybrid programs to assume liability for CO_2 leakage as a means of risk sharing to facilitate private sector projects for carbon capture from industrial and power sector point-source emissions. These hybrid concepts could be extended to CDR projects as well.

The "layered approach" is a variation of the hybrid liability model, in which the costs for an incident is borne by the private operator, up to a certain dollar amount. After that limit is reached, additional costs are borne by a combination of a pool of private operators and by the government. Both the hybrid and the layered approaches encourage responsible operator behavior: They assign operators with limited, prescribed, and bounded liability while transferring to the government longer-term liability management responsibilities.[71] Current examples of hybrid and layered approaches can be found in Box 9.

Figure 6 | Liability for Stored CO_2



Assuming that CO2-Secure adopted hybrid liability management, the cost of assuming liability after an initial post-injection period

Box 9. CO_2 Storage Liability Provisions in Existing Policies and Programs

Section 45Q tax credit. The Section 45Q tax credit has MRV requirements specified by Subpart RR of EPA's Greenhouse Gas Reporting Program (GHGRP).[72] The party that owns and operates the geologic storage site is liable for three years from the date that the tax credit was last claimed or from the date that the well is closed, whichever is earlier.

EPA's Underground Injection Control (UIC) program. EPA's UIC program requires 50 years of post-injection site care (PISC) for CO_2 sequestered in Class VI wells.[73] Storage in Class II wells also requires a PISC plan, but the plan duration varies by state.

California Low Carbon Fuel Standard (LCFS). California's LCFS program requires 100 years of PISC for CO_2 storage.[74] A portion of LCFS credits accrued from CCS—determined by the risk level of the site—are paid into a buffer account managed by the California Air Resources Board (CARB). The title to and liability for the sequestered CO_2 is held by the responsible party: They are not transferred to the state.

Other state policies. Several states, such as Louisiana, Montana, North Dakota, West Virginia, and Texas, have provisions to transfer the title and liability to the state. The transfer may occur immediately or after a set period of years (e.g., 10 years in West Virginia) of storage.[75] These states, along with Wyoming and Kansas, require permittees to pay into funds that cover permitting, MRV, and PISC costs for the state.

would need to be incorporated into the business and financial structure of the program. The assumption of liability could be accomplished by establishing a dedicated fund to pay for the cost of replacing CO_2 that has been found to be leaking, as well as pay for any direct damages (other than climate) that might have been caused by the leaks. The cost for this fund would be reflected in the upfront cost of acquisition of the carbon removal goods or services.

The cost of a centralized liability management program can be estimated based on projected leakage rates. For example, liability can be estimated for an overall leakage rate of 1 percent, with the leakage being replaced with additional captured carbon. A phased-in CO2-Secure program to reach 1 Gt/yr capture by midcentury could cumulatively remove and store nearly 17 Gt of CO_2 by 2060. If the overall leakage rate was 1 percent, the replacement target would be 170 Mt. If the replacement CO_2 is obtained from industrial CO_2 sources, such as ethanol-CCS plants, the cost of the replacement would be about $5.4 billion.[d] If the replacement CO_2 is obtained from CDR projects, the cost of the buffer could be as high as $12 billion. The liability cost could be incorporated into the CO2-Secure cost model. Alternatively, the liability cost could be addressed through in-kind contributions. For example, CO_2 service providers could be required to "buffer" the amount of CO_2 provided to the CO2-Secure program by 1 percent on an unreimbursed basis. In all cases, the replacement CO_2 would need to be subject to the same eligibility criteria, such as additionality as the original captured quantities.

d This estimate is based on an assumed CCS price of $32/t.

Several other considerations would need to be part of any liability management plan. MRV requirements beyond those provided in UIC permits may be required to address issues such as expanded scope and duration of monitoring, additional reporting, and possible third-party verification. Policies and procedures also may be needed to administer liability transfer between parties if a hybrid liability management plan is adopted. For example, subsurface ownership laws vary by state (in some states, pore space rights are assigned identically to mineral rights). Finally, tortious liability (i.e., liability for harming another party) could be a serious concern if CO_2 leaks in large amounts and causes damages to the local environment in addition to climate damage.

Regionality

The implementation of the CO2-Secure initiative could vary substantially by region, and the program implementation plan could incorporate flexibility measures to accommodate regional considerations.

Regions with abundant biomass resources may be better suited to BECCS deployment, whereas areas with available low- or zero-carbon electricity may be ideal for DAC projects. Given the nascency of nationwide carbon transport infrastructure, near-term CDR projects co-located with already surveyed geologic storage sites will be best suited to scale rapidly and cost-effectively. In the long term, CDR projects that don't have access to nearby geologic storage may be located near future CCS hubs connected to regional CO_2 transport and storage infrastructure.

Broad-based regional interest in CDR could lead to the creation of CDR hubs. The CO2-Secure program could seek to foster creation of regional networks of CDR participants akin to its network of Regional Carbon Sequestration Partnerships (RCSPs).[76] CO2-Secure could lead efforts to identify regions that are ideal for CDR, similarly to how the Bureau of Ocean Energy Management (BOEM) has been identifying resource areas for offshore wind. BECCS projects that produce hydrogen may be located near hydrogen hubs; CDR technologies that have synergies with existing industries or with point source CCS in a region may be better suited to that region.

Public ownership models for CDR projects could vary by region. For example, privately owned BECCS projects may be more favorable in the Southeast where there is an established forestry industry on privately owned forests. Publicly owned BECCS projects may be more practical in the U.S. Forest Service portfolio of federal forest lands, which are predominately in Western states.

The most likely approach for CO2-Secure to address regionality would be through regionally tailored RFPs. For example, targeted RFPs could be developed to address the various examples cited here. Regional variation in terms and conditions also may be appropriate in some circumstances.

Licensing and Permitting

Infrastructure to support CDR varies by the technology involved. DAC, BECCS, and other CDR technologies that capture CO_2 in a concentrated stream will require some form of transportation as well as a secure storage or utilization facility. Permitting and constructing this new storage and transport infrastructure—whether privately or publicly owned—at a rate commensurate with the scaling of the CDR could be a challenge without allocating the proper resources. EPA permitting of carbon storage wells has been criticized for its sluggish pace and unclear guidelines; most projects in development have been located in states that have been granted UIC primacy and fund their own permitting offices.

> **Improved federal, state, and local governmental licensing and permitting processes will be essential to facilitate CDR deployment at a gigaton scale.**

Improved federal, state, and local governmental licensing and permitting processes will be essential to facilitate CDR deployment at a gigaton scale. This effort will require additional resources for EPA and state permitting offices. Permitting requirements could be more sharply defined and procedures safely streamlined as more experience is gained from the operation of early CDR projects. In cases where storage is proposed for siting on federal land, the leasing timeline and process for these locations could be integrated concurrently with other federal, state, and local permitting programs.

ORGANIZATION, MANAGEMENT, AND FUNDING

The large scale and long time frame for the CO2-Secure initiative requires an effective, efficient, and durable organization and management structure. The financing requirements will be substantial and will require stable and predictable funding. A starting point for consideration of the organization, management, and funding arrangements for CO2-Secure is to consider the experience with other past and current governmental endeavors with similar programmatic characteristics. This report's supplementary materials summarize a review of other governmental endeavors that are mission-focused, with long lifetimes and special funding requirements. This information provided a baseline of information, as well as important insights into the experience and lessons learned from these analogs, to inform the design of the CO2-Secure initiative.

Organizational and Management Structure

Government programs are organized, managed, and funded in diverse ways. Organizational and management structure is dependent upon a number of factors, with the nature of the authority, the form of funding, and the degree of public-private interaction being principal considerations. The importance of program timescale and resilience to short-term political volatility also are important factors in the design of organization and management. The principle of "form follows function" remains applicable.

New programs that build upon existing ones are typically assigned to their existing program offices. The expansion of DOE's Office of Fossil Energy to encompass new programs in CCS, with a modification of the office name to the Office of Fossil Energy and Carbon Management, is a good case in point. In other cases where entirely new programs are created, the nature of the program may merit an entirely new organization within an existing federal department or agency. The establishment of the DOE Office of Energy Infrastructure, with responsibility for implementation of many of the new authorities in the Infrastructure Investment and Jobs Act (IIJA), is such an example. In some cases, the nature of new program initiatives, particularly those requiring large-scale public-private partnerships, may be best implemented in a new stand-up organization and operated in a manner very similar to private companies, especially if the activity is self-financed. The establishment of the Tennessee Valley Authority, and the transformation of the historical DOE Uranium Enrichment Enterprise to a government corporation and subsequent privatization are representative examples.

The organizational and management framework for CO2-Secure is drawn from consideration of its mission, scale, authorities, and financing parameters. As a first step, various analogs from existing organizations were examined to identify the strengths, weaknesses, and lessons learned, including policy and political dynamics, of various existing federal organizations. A summary analysis of the various analogs is described in this report's supplementary materials. Drawing from these analogs, it is possible to generalize three broad options for organizing the CO2-Secure initiative, ranging from a new federal program office in DOE, a new government corporation, or a government-sponsored enterprise (GSE). The three options are summarized in Table 2.

Table 2 | Key Characteristics of Government Entities

	Government-Sponsored Enterprise	Government Corporations	Federal Program Office
Examples	**FNMA, Farm Credit System**	**TVA, Amtrak, CCC**	**SPR, LWCF, DPA, Title III, Superfund, BPA**
Management	Board of directors selected by equity holders; government equity interests represented by presidential appointees	Board of directors consists of a mix of federal officials and public members appointed by the president	Federal official appointed by the president or agency head
Funding	Typical corporate financial structure, budget transactions are usually not part of the federal budget (off-budget) **Funding sources:** Raise capital in equity and debt markets, also can be supplemented with congressionally authorized borrowing from Treasury and/or congressional appropriations (typically only in special circumstances)	Typical corporate financial structure; included in federal budget totals **Funding sources:** Revenues from the public; direct spending authority; borrowing from Treasury; and/or annual appropriations **Spending controls:** Annual spending not subject to annual appropriations process	Funded through annual federal budget process; all budgetary transactions on-budget **Funding sources:** Dedicated revenue stream or from General Fund of the Treasury **Spending controls:** Congressionally set direct (or mandatory) spending or annual discretionary appropriations

Federal Programs

Federal program offices typically are housed in a Cabinet department (e.g., DOE) or independent agency (e.g., EPA). The program is managed by a federal official appointed by the agency head or other senior official under authority delegated by the agency head; the program manager also could be appointed by the president (with Senate confirmation) if so specified in the authorizing legislation (e.g., assistant secretaries at DOE). Personnel management, procurement, legal services, and operational support services would be provided by the department or agency, typically pursuant to agencywide policies and procedures, although some exemptions may be permissible. Examples of different arrangements within DOE currently include the following:

- The National Nuclear Security Administration (NNSA) is authorized by statute as a separate office within DOE headed by a statutory under secretary. NNSA has authority to establish its own general counsel, CFO, and public and congressional affairs offices separate from and independent of their counterpart departmental offices.
- The Bonneville Power Administration (BPA) is authorized by statute as a separate office within DOE. It also has authority to establish its own internal organizational structure.
- The DOE Loan Programs Office (LPO) is established by secretarial order. Its placement within the department also is administratively determined. Though LPO is integrated within the department, it has been given authority to establish its own self-contained administrative services such as legal counsel.

All funding transactions for federal programs are included within the federal budget. Spending authority could be provided in three ways: (1) through annual or lump sum appropriations; (2) through direct spending authority (established by the congressional authorizing committees and outside the jurisdiction of the appropriations committees): or (3) by authorization of borrowing authority from the Treasury in cases where there is a revenue stream that can support repayment. The spending authority can be financed from revenues in the Treasury General Fund or from specifically earmarked revenue sources. There are a wide range of current examples:

- The DOE **Western Area Power Administration (WAPA)** is funded through a combination of annual appropriations (mostly for capital investment) and revenues from the sale of federally generated hydroelectricity that cover operations and maintenance expenses. Power sales revenues in excess of operation and maintenance costs are held in the Treasury.
- The DOE **Bonneville Power Administration (BPA)**, by comparison, receives no annual appropriations. Operations and maintenance are self-financed from power sales revenues. New capital investment is financed through an authorization to borrow from the Treasury, with repayment from future power sales revenues. All BPA financial transactions are recorded in the federal budget, but they are not subject to annual spending controls.
- The DOE **Strategic Petroleum Reserve (SPR) program** is funded from annual appropriations that cover both facilities management and petroleum acquisition; the program is authorized to retain revenues from the sale of petroleum if the reserve

Figure 7 | Summary of Key Analogs

Category	NY CDRLA New York Carbon Dioxide Removal Leadership Act	FNMA Federal National Mortgage Association	CCC Commodity Credit Corporation	DPA Title III Defense Production Act	LWCF Land & Water Conservation Fund	SPR Strategic Petroleum Reserve
Purpose	Finance CDR removal services up to 35 Mt/yr by 2050 (15% of 1990 statewide emissions)	Establish government-backed secondary market for home mortgages	Mechanism to fund USDA programs for conservation, aid & financial security	Obtain supplies for national defense & disaster response	Acquire lands for recreation, conservation & cultural preservation	Government oil stockpile to mitigate severe disruption to oil markets
Organization & Management	State program; NY Dept of Environmental Conservation; contractors own & operate	GSE; shareholder-owned with federal government holding warrants to 79.9% of equity shares	Gov't corporation within USDA, president appoints USDA officials to the board	Federal program managed by interagency committee; DPA Fund administered by DOD	Treasury Fund with DOI/NPS oversight; funds allocated to FWS, BLM, FS, and grants to states	DOE program office
Implementation Mechansism	Annual reverse auctions beginning 2024, with increasing capacity & decreasing price targets (max. $350/ton in 2025)	Purchase of mortgages from lending institutions that are packaged into mortgage-backed securities	Primarily price support crop loan contracts; authority to make grants and loan guarantees	Contracts, grants, loans, loan guarantees	Land acquisition & conservation improvements; state grants used similarly	Oil acquired through competitive purchases; drawdowns of oil via auction sales or exchanges
Dedicated Revenue	Reinstated aviation fuel tax	Revenues from mortgage-backed securities	Loan repayments	Some revenues from resale of products	O&G leasing revenues	Receipts from drawdown/sale of oil
Funding Mechanism	Spending levels limited to specified tax receipts; 5-yr. initial authorization	Corporate financial structure with backstop authority to borrow from Treasury; payment of annual dividend to Treasury on $120B bailout	Permanent indefinite appropriations equal to net losses; $30B in permanent borrowing authority; funding in farm bills	Statuatory cap of $750M (temporarily raised in 2020-2021 for COVID); annual appropriations	Permanent authorization; direct spending not subject to annual appropriations	Annual appropriations for initial development and operation; receipts from sale of oil permanently authorized for re-purchases
Financial Scale	$35M (0.1 Mt, $350/t) initial year target in 2025, increasing to $B scale in 2050 (60 Mt target)	$100B in total revenue, $30B in net revenue, $22B net income in 2021	$6.1B in assets, $20.4B in liabilities, $12.4B net outlays in 2021	$234M fund balance in 2022	$1.0B in 2022 (O&G: $900M, GOMESA: $128M)	$226M appropriations in 2022

is drawn down in the event of an energy market disruption, but those revenues can only be used (without further appropriation) to replace inventories once the market disruption has been resolved.[e]

- The DOE **Nuclear Waste Fund** collects fees from nuclear utilities to cover the cost of final disposition of spent nuclear fuel, but even though the program is fully user-fee funded, spending levels are subject to annual appropriations. (Note: Due to court decisions finding the government in partial breach of default on its contractual obligations to take and dispose of commercially used fuel, the user-fee payments have been indefinitely suspended.)

- The U.S. Department of the Interior **Land and Water Conservation Fund** is financed through earmarks of federal royalties from leasing of energy resources, but the spending levels were subject to annual appropriations. For many years, congressional appropriation levels for the LWCF were significantly less than collections, creating a large fund surplus. The ensuing political pressure from stakeholder groups eventually led to restructuring of the fund in 2020 to authorize direct spending without annual appropriations limits.

- The EPA **Superfund** program and the DOE Uranium Enrichment Decontamination and Decommissioning Fund are supported by a combination of industry fees and allocations from the Treasury General Fund, but in both cases annual spending of any monies in the funds is subject to annual appropriations. (Note: In both cases, the authorization to collect industry fees has expired, except that the Superfund fees were recently reinstated in the Inflation Reduction Act.)

If CO2-Secure is established as a federal program office within DOE, it could be organized in several different ways, including:

- Expansion of the existing DOE Office of Fossil Energy and Carbon Management (FECM), which houses the existing CDR and CCUS programs, but which is focused on RD&D and has a current budget that would be dwarfed by CO2-Secure

- Creation of a new office reporting to the newly created under secretary for infrastructure, similar to offices created in the wake of the Bipartisan Infrastructure Law (e.g., the Grid Deployment Office)

- Creation of a new office that reports directly to the secretary of energy, a structure that has worked well for offices that benefit from a greater degree of independence, such as the Advanced Research Projects Agency—Energy (ARPA-E) and Energy Information Administration (EIA)

Any version of CO2-Secure will by necessity work closely not just with DOE but also with EPA (which regulates CO_2 as both an injectant and air pollutant) and possibly other agencies such as the Departments of Agriculture, Commerce, and the Interior.

Currently proposed federal legislation, the Federal Carbon Dioxide Removal Leadership Act and the Carbon Removal and Emissions Storage Technologies (CREST) Act, would assign the proposed new CO_2 acquisition program to DOE, without specification of its internal assignment within the department. The proposed new

e The 21st Century Cures Act of 2016 made an exception to this restriction. The act mandated a series of sales of petroleum from the SPR with the receipts to be deposited in the General Fund to offset the cost of an expanded research initiative at the National Institutes of Health.

authority would be assigned to the secretary of energy, to allow for administrative delegation within the department. Absent specific direction establishing a new sub-Cabinet organizational unit, the new authorities under the act likely would be assigned to the Office of Fossil Energy and Carbon Management. Alternatively, the secretary could administratively establish a new Office of Carbon Removal within the under secretary for infrastructure.

> **The focused mission, business model, and funding requirement for CO2-Secure can be more effectively and efficiently served through the establishment of a new, business-like organization and management structure.**

The CO_2 acquisition programs authorized by the proposed legislation would be somewhat experimental in nature, as it would test new acquisition and contractual models for CO_2 purchase, storage, and liability management. It also could serve to demonstrate a variety of scientific and technical approaches for carbon removal and storage. As such, the nature of this program would be in keeping with largely energy RD&D mission responsibilities of the department.

The fact that the programs would be dependent upon annual appropriations also reinforces the merit of inclusion of the programs within a Cabinet department with a current total annual appropriations level of about $16 billion (FY 2022 appropriations total for all energy and science activities). By comparison, the proposed CO2-Secure initiative would be financed (as discussed later) with direct spending authority not subject to annual appropriations.

While the proposed CO2-Secure initiative would build upon the experience with the proposed Federal Carbon Dioxide Removal Leadership Act, the scale, pace, project oversight, and financing requirements would quickly outgrow the existing capabilities and experience of other DOE programs. (These parameters are discussed in more detail later in this paper, but suffice it to say that the levels of activity would be an order of magnitude or more relative to current DOE experience). The focused mission, business model, and funding requirement for CO2-Secure can be more effectively and efficiently served through the establishment of a new, business-like organization and management structure.

Government-Sponsored Enterprises

A government-sponsored enterprise (GSE) is a nongovernmental organization or corporation created (or chartered) through an act of Congress for public policy purposes. These entities have the benefit of being almost entirely separate from the day-to-day functioning of the federal government and are ideal for certain market-facing purposes. Typically seeded through government funding upon its creation, continued funding is provided through nongovernmental sources. Because they are private entities, they are not included in the federal budget totals—but reported separately—and are not backed by the full faith and credit of the U.S. government.

A GSE is organized and managed in a manner similar to a private sector corporation. The GSE may sell equity, and equity owners select members to a board of directors that manages the entity. The GSE also may issue debt in capital markets. The GSE may have either a federal equity contribution or, in some cases, congressionally authorized borrowing authority from the Treasury. If government funding is provided, the president may have authority to appoint additional directors, typically with the advice and consent of the Senate. The board of directors is responsible for hiring senior executives. Financial transactions are typically not included in the federal budget or are not subject to annual government-wide spending controls.

The U.S. Office of Management and Budget reports on five GSEs, three of which provide primary or secondary credit support for housing and community development activities and two others that support agriculture and rural real estate and housing. The most noteworthy GSEs are Fannie Mae (the Federal National Mortgage Association) and Freddie Mac (Federal Home Loan Mortgage Corporation). These GSEs created a secondary market for home mortgages by purchasing mortgages from banks and other lending institutions and packaging them into larger investment vehicles that are then marketed to large institutional investors. The financing mechanism was designed to be free from the federal treasury, but the 2007 mortgage crisis and subsequent Great Recession put their financial structures in serious jeopardy, necessitating congressional action to inject federal investment to maintain liquidity and place Fannie Mae under government conservatorship. As part of this government intervention, Fannie Mae stock was delisted from the New York Stock Exchange and the federal government has an outstanding warrant to purchase up to 79.9 percent of its stock.

The scale and nature of the public-private partnerships required for implementation of the CO2-Secure initiative would merit the establishment of a GSE organization. As is described later in this report, CO2-Secure, for example, would need to enter thousands of project transactions (depending upon the magnitude of carbon removal in each individual transaction) to achieve a Gt/yr of carbon removals. The oversight of this many individual projects, distributed across the country, will require a large-scale, business-like organization. However, in view of the near disastrous experience with Fannie Mae and Freddie Mac during the Great Recession, with need for a massive intervention by the Obama administration and Congress, it is highly unlikely that Congress will authorize a major new venture such as CO2-Secure as a new GSE.

Box 10. A Foundation for CO2-Secure?

A variant on the concept of government-sponsored enterprises is what the Congressional Research Service (CRS) refers to as "agency-related nonprofit research foundations."[77] This structure also could be considered as a possible vehicle for implementing CO2-Secure.

The agency-related nonprofit research foundations have many of the characteristics of GSEs: They are chartered by Congress, receive federal funding (in addition to private-sector funding), have boards appointed by federal agencies, and are separate entities incorporated under the laws of a particular state.[78,79] These foundations' establishing statutes make their independent status clear, stating that they are not "agenc[ies] or instrumentalit[ies] of the United States Government."[80] They do not meet the full statutory definition of GSEs, however, because they are not financial institutions.[81]

The first research foundation established was the Henry M. Jackson Foundation for the Advancement of Military Medicine, created in 1983 as an affiliate of the Uniformed Services University of the Health Sciences (a part of the U.S. Department of Defense).[82] Since then, a number of other foundations related to medical research have been set up to serve agencies at the Departments of Health and Human Services and Veterans Affairs.

These research entities are not the only "foundations" with connections to federal agencies. Several other entities, such as the National Park Foundation and the Fish and Wildlife Foundation, have programmatic missions broader than research and development, along with different funding and management structures.

Most recently, Congress created two new foundations with missions relevant to climate change: the U.S. Department of Agriculture-affiliated Foundation for Food and Agriculture Research (FFAR),[f] and the U.S. Department of Energy-affiliated Foundation for Energy Security and Innovation (FESI).[83,84]

FESI—created by the CHIPS and Science Act—is intended to "support the mission" of its affiliated department, facilitate public-private collaboration, and bring in philanthropic funding.[85] Specific focus areas for FESI identified in its authorizing legislation include:

- Technology commercialization
- Regional economic development
- Job creation
- Prize competitions
- Participation from underrepresented groups in energy technology development
- Facilitating access to DOE facilities and expertise
- Support for individual National Laboratory-affiliated foundations

FESI, like other agency-related nonprofit research foundations, is primarily a vehicle for obtaining private sector funding that could augment federally funded programs and projects. FESI is authorized to receive up to $31.5 million in federal appropriations over its first two years, followed by $3 million annually in subsequent years.[86] FFAR also has authority to receive federal funding, but with a different funding model that involves federal matching of private donations.[87] In general, these foundations are expected to receive most of their budget from non-federal philanthropy.[88,89]

A government-sponsored foundation could be considered as an organizational model for CO2 -Secure. It would be, however, almost exclusively dependent on federal financial support due to its public good mission (and its budget would exceed those of the existing foundations).[90] This structure could facilitate solicitation of private sector and philanthropic contributions to supplement that federal support. Many of the organizational and management features of an agency-related nonprofit foundation are similar to those of a government corporation, discussed further in this report.

f For more on FFAR's relevance to CDR, see EFI's previous report: *From the Ground Up: Cutting-Edge Approaches for Land-Based Carbon Dioxide Removal*.

> **Simply stated, government corporations are created to serve a public purpose in a business-like manner.**

Government Corporations

Government corporations are similar but distinct from GSEs in that they are market-facing corporations that are wholly owned by the federal government. Simply stated, government corporations are created to serve a public purpose in a business-like manner. Government corporations are authorized by Congress. They are typically managed by a board of directors composed of a mix of existing federal officials (e.g., secretary of treasury, secretary of energy) and public members appointed by the president with advice and consent of the Senate. The corporate CEO also could be a presidential appointee (with Senate confirmation) or could be appointed by the board, as specified in the enabling authorization act. The operations of government corporations are generally governed by the Government Corporation Control Act, which sets general requirements regarding personnel matters, financial management, contracting and procurement, oversight by the Government Accountability Office, and other operational policies and procedures.

Government corporations have broad financial powers. Government corporations may receive equity contributions from the Treasury (if authorized by Congress) and also may be authorized to issue debt to the Treasury (within limits set by Congress and under terms and conditions established with Treasury). Government corporations typically are prohibited from borrowing in capital markets, and because they are wholly owned by the federal government, they cannot issue equity to the public. Any operating revenues from the sale of goods and services would be retained by the government corporation and used to offset costs, repay debt, and possibly pay a return on equity. The financial transactions of a government corporation are managed in a typical corporate financial structure. All financial transactions are included in federal budget totals, but spending is not subject to annual spending controls.

The Congressional Research Service (CRS) identified a total of 17 government corporations. They generally share the general characteristics described above, namely that they are mission-focused, business-like in operation, and have permanent financing mechanisms.

- Several government corporations—such as the St. Lawrence Seaway Development Corporation, the Tennessee Valley Authority, the Presidio Trust, and the Valles Caldera Trust—are mission-focused on regional or location-specific issues.
- Others, while national in scope, are mission-focused on specific services—such as the Pension Benefit Guaranty Corporation, Commodity Credit Corporation, the Federal Crop Insurance Corporation, the U.S. Postal Service, and Amtrak.

The organization and management structures of two of these corporations—TVA and the Commodity Credit Corporation—have features that could serve as possible models for CO2-Secure:

- The **Tennessee Valley Authority (TVA)** is the only government corporation with an energy- or environmentally focused mission. TVA is governed by a five-person board of directors appointed by the president on staggered five-year terms with advice and consent of the Senate. The board appoints the CEO and establishes all internal personnel, financial management, and other operational policies and procedures. Power sales revenues are collected and retained within the corporation and can be applied consistent with the purposes of the TVA Authorization Act. TVA also is authorized to borrow from the Treasury, on terms and conditions mutually agreed to, up to a statutory limit of $30 billion. All financial transactions are included in the federal budget but are not subject to annual spending controls. Historically, TVA received annual appropriations, in addition to its revenues and borrowing authority, for selected purposes deemed to provide national benefits beyond those garnered by TVA customers, but this practice has been eliminated for several decades.

- The **Commodity Credit Corporation (CCC)** is a distinct model of a government corporation, as it is housed within a Cabinet department and is not an independent organization. The board of directors of the CCC is appointed by the president but is limited to appointed officials of the U.S. Department of Agriculture (USDA). The CCC has permanent borrowing authority from Treasury up to a cap of $30 billion. Borrowings from Treasury are in turn used to finance loans and loan guarantees to support crop prices. Any losses on loans are automatically repaid to the Treasury from General Fund revenues through permanent congressional authorization. CCC also receives direct spending authority from Congress to implement targeted agricultural conservation and other programs.

The government corporation structure may provide the "Goldilocks" solution for CO2-Secure. A government corporation structure would empower CO2-Secure to operate effectively and efficiently at the scale and pace needed to reach gigaton-scale carbon removal, with a firm funding plan and a stable personnel management structure. This structure would facilitate ongoing congressional oversight by giving Congress authority to advise and consent on board appointments as well as hold oversight hearings.

Based on a spreadsheet model analysis, CO2-Secure is estimated to cost $33 billion over its first 10 years of operation (the typical time horizon for federal budget projections and legislative budget scoring), with a cumulative cost of $106 billion by 2050.

Program Cost and Financing

The cost parameters for the CO2-Secure initiative are discussed in this section. The cost estimate is based on assumptions regarding the pace of implementation and the unit cost of CO_2 capture and storage. Based on a spreadsheet model analysis, CO2-Secure is estimated to cost $33 billion over its first 10 years of operation (the typical time horizon for federal budget projections and legislative budget scoring), with a cumulative cost of $106 billion by 2050. On an annualized basis, the cost of the program will ramp up to $17 billion annually in 2050, with 200 Mt being sequestered annually in that year. Beyond 2050, the program is estimated to reach a peak annual funding level of $88 billion once implementation reaches gigaton scale in 2060. These estimates are based on an initial modeling analysis of the program implementation path.

Program Implementation Plan Schedule and Cost Assumptions

The program implementation plan assumes that CO2-Secure will be initiated by 2035—over a decade into the future. The plan assumes that the CO2-Secure initiative will be preceded by implementation of a DOE precursor CO_2 acquisition program as outlined in the proposed Federal CDR Leadership Act or Carbon Removal and Emissions Storage Technologies (CREST) Act.

The proposed Federal CDR Leadership Act, for example, authorizes a 10-year CDR acquisition program, beginning in 2024, administered by DOE. This precursor program, if adopted by Congress, would provide important initial experience with federal CDR acquisition on a range of implementation issues, including contractual models, cost, performance, and MRV processes. The experience with the program also will determine the feasibility of funding a large CO_2 removal program with discretionary incremental appropriations that are subject to the annual budget process. The scale of this program, however, is limited, starting at 50,000 tons of CO_2 in 2024, rising to 10 Mt/yr in 2035, an order of magnitude less than needed to achieve material levels of climate remediation. Based on the cost ceilings specified in the legislation, the Federal CDR Leadership Act, if fully implemented, is estimated to cost a cumulative total of $5.2 billion from 2024 to 2034.

The experience with the DOE program also will provide a body of information to further assess and affirm the need for establishing a new government corporation entity, together with a mandatory multi-year financing mechanism, to scale the program to gigaton levels of annual CO_2 removal. The CREST Act, by comparison, authorizes a total of $230 million over five years for a competitive pilot program to procure CO_2 from private sector services. The price paid for CDR services would be set by reverse auction, with different performance tiers based on the length of time proposed for carbon removal and storage. DOE would be required to set a cost cap for each auction based on the current market price per net carbon dioxide removals at the time of the auction. At a cost cap of $200 per ton, for example, the CREST Act could fund a cumulative total of 55 Mt CDR.

Building from this precursor program, the estimated cost for the CO2-Secure initiative is based on the following parameters:

- Initiation of the program in 2035
- Program composition of DAC (75 percent of CDR tons) and BECCS (25 percent of tons) (Note: This composition was adopted for simplicity of cost estimating; the program eligibility criteria are designed to be technology neutral and will allow for a broader suite of carbon removal approaches.)
- Initial unit cost assumptions (in 2035) for capture and storage of $200/ton for DAC and $90/ton for BECCS, declining over time to $100/ton and $50/ton respectively (Note: The DAC cost assumptions are conservative; for example, the cost target for the DOE Negative Carbon Shot program initiative is $100/ton by 2030.)
- Program ramp-up at approximately a 20 percent compound annual growth rate
- Increase of average project size over time to 1 Mt/year/project as experience is gained

The cost model structure and methodology were adapted from a previously published CDR cost modeling analysis by the Rhodium Group. Rhodium modeled the cost of large-scale CDR deployment using the Regional Investment and

Operations (RIO) Platform coupled with the open source EnergyPATHWAYS model.[g,91] The CDR deployment scenario modeled by Rhodium was the “83by50” scenario, a straight-line reduction pathway from 26 percent below 2005 CO_2 levels in 2025 to 83 percent below 2005 CO_2 levels in 2050.

Sensitivity Analysis of the Program Schedule and Cost Estimates

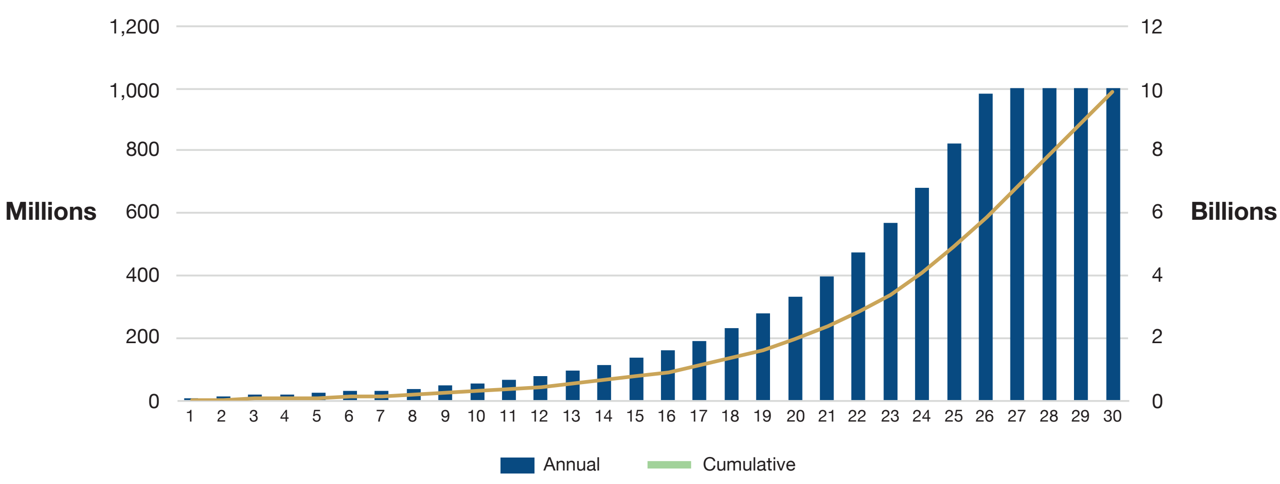
Three main factors shape the cost and schedule estimates:

1. The size of the CDR industry at the start of the program in 2035, which in turn depends upon the private sector response to the new financial incentive in the IIJA and Inflation Reduction Act (IRA) legislation, and the enactment of the proposed Federal Carbon Dioxide Removal Leadership Act or CREST Act
2. The pace of implementation toward the 1 Gt/yr goal once the initiative is underway
3. The unit cost assumptions for carbon removal and storage, which in turn is dependent upon the success of innovation in current CDR RD&D efforts and the learning experience from early deployments, including experience with the Federal Carbon Dioxide Removal Leadership Act or CREST Act (if enacted)

The importance of the pace of implementation is illustrated in Figure 8. The 20 percent compound annual growth rate is crucial to enabling the growth over the second and third decades of implementation to ramp up to the gigaton scale goal by midcentury. This rate of expansion underscores the need to transition program implementation from a multi-function U.S. Department of Energy organizational home to a government corporation business model.

g Both modeling tools are owned, maintained, and configured for the U.S. energy system by Evolved Energy Research.

Figure 8 | CDR Program CO_2 Captured



> **The U.S. Office of Management and Budget recently estimated that the enactment of the Inflation Reduction Act will yield climate benefits with a present value estimate in the range of $0.7 to $1.9 trillion (2022 $).[92]**

Achieving continued innovation in cost reduction also is an important element in the overall program cost estimate. The unit cost estimates at the starting point of CO2-Secure are well within the range of the goals established for the current CDR RD&D programs. Current cost estimates for carbon removal technologies however are uncertain; only a handful of pilot- and demonstration-scale projects exist, and even fewer at full commercial scale. By contrast, cost assumptions for CO_2 storage are better understood, as the technology and subsurface engineering to support geologic storage is well known and has been implemented for other applications by the oil and gas industry for decades. Similarly, the transportation of CO_2 via pipeline is an established service industry where implementation is readily achievable at a relatively low incremental cost.

Putting the Cost of CO2-Secure into Perspective

The investment in CO2-Secure is substantial—the cumulative cost over the initial 10 years is estimated at $33.2 billion, with an estimated cumulative cost of $106 billion through 2050. Annual costs rise to a peak of $87.5 billion in 2060. The cost estimates could prompt discussion of its relative contribution to the benefits and costs of the broader portfolio of federal investments in climate change mitigation and adaptation, as well as how the cost will be accommodated within the federal budget.

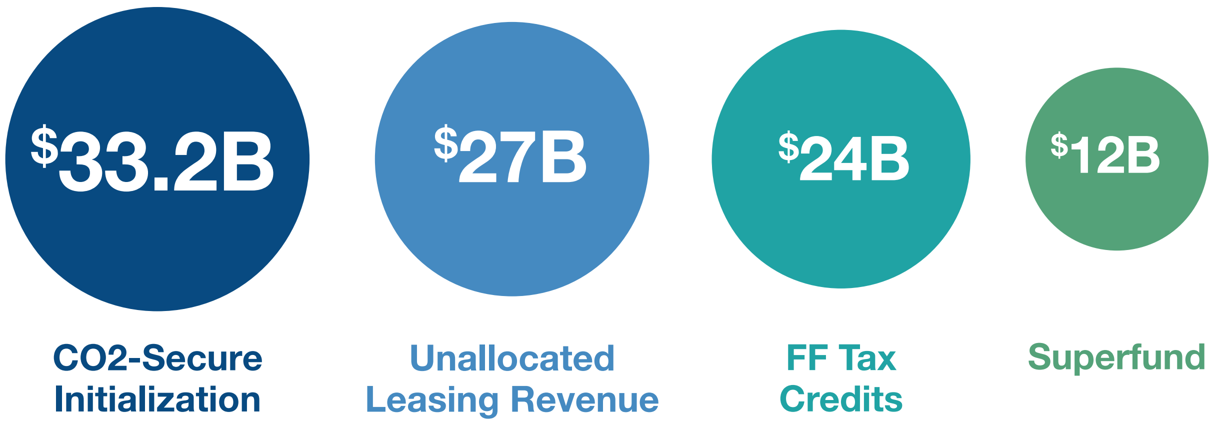
One yardstick is to compare the cost of CO2-Secure with the estimated benefit of climate remediation. The U.S. Office of Management and Budget recently estimated that the enactment of the Inflation Reduction Act will yield climate benefits with a present value estimate in the range of $0.7 to $1.9 trillion (2022 $).[92] The budgetary cost of the climate and clean energy programs funded in the IRA total $369 billion in as-spent dollars over the next 10 years.

Another yardstick for comparative purposes is the cost of CO2-Secure relative to other programs in the federal budget. Over the initial 10 years of implementation, the cumulative cost of CO2-Secure ($33.2B) would constitute about 0.03 percent of projected cumulative federal expenditures over the same period. The cost of CO2-Secure also could be compared to existing energy- and environmental-related revenues and tax expenditures within the federal budget total. For example, as shown in Figure 9, the proposed investment in CO2-Secure is of a similar magnitude to the Superfund Excise Tax, newly reinstated in the IRA. The cost of CO2-Secure also is comparable to the projected level of the unallocated portion of royalties from federal oil and gas leasing, and the projected cost of existing fossil fuel tax credits for the same 10-year period.

The estimates of the possible comparative tax and revenue benchmarks in Figure 9 are based on the following:

- The federal government currently collects royalties from leasing of federal oil and natural gas resources of nearly $10 billion annually. Most of these royalties are earmarked in current law to finance existing federal programs, but about $2.7 billion of

Figure 9 | Comparative 10-Year Budget Estimates of CO2-Secure with Selective Energy and Environmental Revenue and Tax Credit Programs



leasing revenue (including a small amount of nonfuel lease payments) is unallocated within the Treasury. Increasing royalty rates, as recently proposed for onshore oil and gas leasing, could raise additional unencumbered revenues to the Treasury.

- The Congressional Joint Committee on Taxation (JCT) estimates that existing tax credits for fossil fuel deployment results in a federal budget cost of about $24 billion over 10 years.[h]
- The newly reinstated Superfund Excise Tax will help fund environmental remediation efforts at hazardous waste sites where the responsible party no longer exists or is unable to assume liability. The JCT estimates that this tax will generate a total of $11.7 billion over the coming decade.[93]

h As proposed in S. 1298, the Clean Energy for America Act.

While an investment this size into climate remediation would be unprecedented, it is not impossible, and building at a reasonable pace toward this financial scale will be the key to success for CO2-Secure.

Beyond the initial 10 years, the cost of CO2-Secure continues to scale, eventually reaching $87 billion annually in 2060, when annual removals reach 1 Gt/yr. If the cost of CO2-Secure was simply added to the federal budget, this cost would add about 2 percent to the projected total federal budget. It's also roughly equivalent to the revenue that could be raised from a theoretical $18/ton carbon tax. While an investment this size into climate remediation would be unprecedented, it is not impossible, and building at a reasonable pace toward this financial scale will be the key to success for CO2-Secure.

CONCLUSIONS, RECOMMENDATION, AND NEXT STEPS

Overarching Conclusions

Current climate science indicates that avoiding the most serious adverse impacts of climate change will require actions to hold average global temperature increases to 1.5 degrees Celsius or less by midcentury.

These actions will require not only large reductions in the rate of new greenhouse gas emissions, but also removal of carbon from the atmosphere and oceans resulting from historical unabated emissions.

Comprehensive assessments by the Intergovernmental Panel on Climate Change, supported by extensive analytical modeling analyses, indicate that carbon removal needs to be implemented on a scale of up to 7 gigatons (Gt) of CO_2 per year by midcentury.

By comparison, new investment in CDR deployment, spurred by the Infrastructure Investment and Jobs Act (IIJA) and Inflation Reduction Act (IRA), may be able to achieve carbon removal on the order of 10 megatons (Mt)/yr of CO_2 by the end of this decade. The proposed Federal Carbon Dioxide Removal Leadership Act would authorize new federal appropriations funding for a CDR acquisition program beginning in 2024 and increasing to a target level of 10 Mt/yr in 2035. The Carbon Removal and Emissions Storage Technologies (CREST) Act would authorize a total of $230 million for a competitive pilot program of CO_2 removal projects, selected on the basis of a reverse auction.

Scaling carbon removal to the gigaton scale is a recognition that climate remediation is a form of public good that merits large-scale federal government investment, not unlike taxpayer support for other public goods, such as public land and recreational resources or other forms of environmental remediation.

Design Framework for CO2-Secure: The Proposed National Carbon Removal Authority

While current efforts, as well as proposed legislation, can be housed within the U.S. Department of Energy (DOE) for implementation, the substantial expansion of these programs needed to achieve gigaton scale carbon removal will require a new, more business-like organizational and management framework. Drawing from the framework analysis and the experience with possible analogs, the proposed design for CO2-Secure rests on the establishment of a new wholly owned government corporation, the National Carbon Removal Authority (NCRA). The major elements of the NCRA framework include the following:

- NCRA would be led by a seven-person board of directors consisting of the heads of the Treasury, DOE, and the U.S. Environmental Protection Agency, along with four public members appointed by the president and confirmed by the Senate. Board members would serve staggered terms. The president would designate a public member as chair of the board.
- The board would appoint a CEO with full executive powers.
- NCRA would be seeded with $33 billion for the first 10 years of its operation. The funding source—the Treasury General Fund

or dedicated existing or new revenues—would be determined in the legislative process. The NCRA would be charged to develop a subsequent funding plan based on the experience over its first decade of operation.

- Financial transactions would be on-budget, but not subject to annual spending controls, such as annual appropriations.
- Contracts and authority taken on by predecessor programs, such as the proposed Federal Carbon Dioxide Removal Leadership Act or purchasing pilot program proposed in the CREST Act, will be gradually handed over to NCRA upon its activation.
- NCRA could enter into multiple forms of public-private partnerships, including contracting for CDR capture and storage services; acquiring captured carbon for government-owned, contractor-operated (GOCO) transport and storage (T&S) facilities; or implementing end-to-end GOCO. Contracting for services would be the preferred model, with other models available as a backstop.
- Carbon purchased by NCRA would be offered to any buyer intending to use it in a permanent utilization purpose at a low cost, feeding its revenue into a revolving fund that could offset a portion of the cost of the program.
- NCRA would have broad authority to solicit projects and make awards, including using reverse auctions, tenders, and RFPs. Fixed price, competitively awarded contracts would be the preferred mechanism, supplemented with targeted RFPs to provide for needed diversity in the program portfolio.
- NCRA would be liable for leakage of carbon that is owned by the government and stored in government-owned facilities. Private entities would be liable for carbon stored in nongovernment-owned facilities, regardless of the title, for 20 to 25 years after completion of injection; liability would be automatically transferred to NCRA after that. NCRA would establish a dedicated fund to mitigate leakage in cases of government liability. This fund would be used to either correct the leakage or acquire offsets. Leakage mitigation insurance could be sold to private entities to cover their liability for the initial period of 20 to 25 years post injection.
- NCRA would operate under the general policies and procedures set forth in the Government Corporation Control Act.

Attracting bipartisan political support is essential, both for enactment of the needed legislation as well as for sustaining support for implementation over time.

Implementation

Establishment of CO2-Secure, built on the framework of the proposed National Carbon Removal Authority as recommended above, will require enactment of new authorizing legislation. Attracting bipartisan political support is essential, both for enactment of the needed legislation as well as for sustaining support for implementation over time.

The proposed framework embodies a number of characteristics that are not only necessary for effective implementation but also attractive to broad-based support. The proposed framework:

- Builds upon DOE precursor pilot programs in current legislative proposals
- Is additive to current law, policies, programs and incentives for voluntary actions, and is separate and independent from any new proposals for mandated greenhouse gas emissions reductions or carbon pricing
- Has a flexible program design—with multiple forms of public-private partnerships and multiple acquisition methods—and is technologically neutral and technology inclusive if performance criteria are met
- Has strong monitoring, reporting, and verification (MRV) and permanence requirements backed by a long-term, advance-funded program to manage liability
- Involves regional implementation with benefits of job creation, workforce development, and community benefits
- Addresses social, environmental, and community concerns
- Is resilient to short-term volatility in the political environment, providing the program stability to enable the long-term purchase commitments needed by CDR projects

Perhaps most important, CO2-Secure can be enacted separately and independently from any other proposed climate policy proposal for new mandates or carbon pricing.

Next Steps

This paper discusses multiple possible options for designing CO2-Secure and presents a proposed concept for further consideration. But more work is needed to refine the ideal design of the program, refine the implementation process including transition from current and proposed programs, and most important, to move this concept further into the public eye. EFI plans to continue this effort by engaging experts, policymakers, and other stakeholders on issues and questions emerging from this paper. This outreach—which could include topic-focused workshops, broad-scope webinars, and expert reviews of this paper to validate the concepts and resolve open design issues—will be conducted along the lines of EFI's ongoing coalition-building work in other technology areas (such as offshore wind, hydrogen, and CCUS). Along with this stakeholder outreach, the concepts discussed here will need to be distilled to a final, detailed program design, including a detailed implementation plan for the proposed program, delineation of new administrative and legislative authorities required, and draft legislation or executive orders.

This outreach—which could include topic-focused workshops, broad-scope webinars, and expert reviews of this paper to validate the concepts and resolve open design issues—will be conducted along the lines of EFI's ongoing coalition-building work in other technology areas (such as offshore wind, hydrogen, and CCUS).

REFERENCES

1 International Panel on Climate Change (IPCC), "Global Warming of 1.5°C - Headline Statements," 2018, https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Headline-statements.pdf.

2 Intergovernmental Panel on Climate Change (IPCC), "The evidence is clear: the time for action is now. We can halve emissions by 2030," April 4, 2022, https://www.ipcc.ch/2022/04/04/ipcc-ar6-wgiii-pressrelease/.

3 Ellie Johnston, "Achieving a Balance of Sources and Sinks," World Resources Institute, March 20, 2018, https://www.wri.org/climate/expert-perspective/achieving-balance-sources-and-sinks.

4 Mustafa Babiker, et al., "Cross-sectoral perspectives" in *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change,* Intergovernmental Panel on Climate Change, accessed October 26, 2022, https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_Chapter_12.pdf, p. 40.

5 Mustafa Babiker, et al., "Cross-sectoral perspectives" in *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change,* Intergovernmental Panel on Climate Change, accessed October 26, 2022, https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_Chapter_12.pdf, p. 40.

6 Stephen Pacala, et al., *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda,* The National Academies Press, 2019, https://nap.nationalacademies.org/catalog/25259/negative-emissions-technologies-and-reliable-sequestration-a-research-agenda, p. 9.

7 Based on International Panel on Climate Change (IPCC) estimates for greenhouse gases (GHGs) in 2019, https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_SPM.pdf, p. 11.

8 Mischa Repmann, et al., *The insurance rationale for carbon removal solutions,* The Swiss Re Institute, June 2021, https://www.swissre.com/dam/jcr:31e39033-0ca6-418e-a540-d61b8e7d7b31/swiss-re-institute-expertise-publication-insurance-%20rationale-for-carbon-removal-solutions.pdf.

9 Energy Futures Initiative (EFI), *Clearing the Air: A Federal RD&D Initiative and Management Plan for Carbon Dioxide Removal Technologies,* September 2019, https://energyfuturesinitiative.org/reports/clearing-the-air/, p. 12-13.

10 Stephen Pacala, et al., *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda,* The National Academies Press, 2019, https://nap.nationalacademies.org/catalog/25259/negative-emissions-technologies-and-reliable-sequestration-a-research-agenda, p. 354-358.

11 EFI analysis of data from Princeton University (annual 2050 data across all non-reference scenarios; categories: BECCS-electricity, BECCS-H2, Bio-FT w/ CC, BECCS-pyrolysis, Bio-SNG w/CC, DAC), "Net-Zero America: Potential Pathways, Infrastructure, and Impacts," accessed April 13, 2022, https://netzeroamerica.princeton.edu/#explore.

12 U.S. Department of State and U.S. Executive Office of the President, *The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050,* November 2021, https://www.whitehouse.gov/wp-content/uploads/2021/10/US-Long-Term-Strategy.pdf, p. 3.

13 John Larsen, et al., *Capturing Leadership: Policies for the US to Advance Direct Air Capture Technology,* Rhodium Group, May 2019, https://rhg.com/wp-content/uploads/2019/05/Rhodium_CapturingLeadership_May2019-1.pdf. p. 4.

14 Hannah Ritchie, "Who Has Contributed Most to Global CO_2 Emissions?," Our World in Data, October 1, 2019, https://ourworldindata.org/contributed-most-global-co2.

15 Leda Zimmerman, "Cracking the Carbon Removal Challenge," *MIT News,* September 15, 2022, https://news.mit.edu/2022/cracking-carbon-removal-challenge-verdox-0915.

16 "Carbon Business Council," n.d. Carbon Business Council, accessed November 2, 2022, https://www.carbonbusinesscouncil.org/.

17 John MacDonagh, *Carbon & Emissions Tech Launch Report,* PitchBook Data, Inc., https://pitchbook.com/news/reports/q2-2022-carbon-emissions-tech-launch-report, p. 10.

18 John MacDonagh, *PitchBook Analyst Note: Postcombustion Carbon Removal,* PitchBook Data, Inc., https://pitchbook.com/news/reports/q3-2022-pitchbook-analyst-note-postcombustion-carbon-removal, p. 8-10.

19 The Carbon Removal and Emissions Storage Technologies Act of 2022, S. 4420, 117th Congress, 2021-2022, https://www.congress.gov/bill/117th-congress/senate-bill/4420/text.

20 Mustafa Babiker, et al., "Cross-sectoral perspectives" in *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change,* Intergovernmental Panel on Climate Change, accessed October 26, 2022, https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_Chapter_12.pdf, p. 40.

21 Mustafa Babiker et al., "Cross-sectoral perspectives" in *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change,* Intergovernmental Panel on Climate Change, accessed October 26, 2022, https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_Chapter_12.pdf, p. 40.

22 Based on International Panel on Climate Change (IPCC) estimates for greenhouse gases (GHGs) in 2019: https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_SPM.pdf, p. 11.

23 Mustafa Babiker, et al., "Cross-sectoral perspectives" in *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change,* Intergovernmental Panel on Climate Change, accessed October 26, 2022, https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_Chapter_12.pdf, p. 40.

24 EFI analysis of data from Princeton University (annual 2050 data across all non-reference scenarios; categories: BECCS-electricity, BECCS-H2, Bio-FT w/ CC, BECCS-pyrolysis, Bio-SNG w/CC, DAC), "Net-Zero America: Potential Pathways, Infrastructure, and Impacts," accessed April 13, 2022, https://netzeroamerica.princeton.edu/#explore.

25 U.S. Department of State and U.S. Executive Office of the President, "The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050," November 2021, https://www.whitehouse.gov/wp-content/uploads/2021/10/US-Long-Term-Strategy.pdf, p. 3.

26 John Larsen, et al., "Capturing Leadership," Rhodium Group, May 2019, https://rhg.com/wp-content/uploads/2019/05/Rhodium_CapturingLeadership_May2019-1.pdf, p. 4.

27 National Academies of Sciences, Engineering, and Medicine (NASEM), "Negative Emissions Technologies and Reliable Sequestration: A Research Agenda," The National Academies Press, 2019, https://nap.nationalacademies.org/catalog/25259/negative-emissions-technologies-and-reliable-sequestration-a-research-agenda, p. 360.

28 National Academies of Sciences, Engineering, and Medicine (NASEM), "Negative Emissions Technologies and Reliable Sequestration: A Research Agenda," The National Academies Press, 2019, https://nap.nationalacademies.org/catalog/25259/negative-emissions-technologies-and-reliable-sequestration-a-research-agenda, p. 360.

29 National Academies of Sciences, Engineering, and Medicine (NASEM), "Negative Emissions Technologies and Reliable Sequestration: A Research Agenda," The National Academies Press, 2019, https://nap.nationalacademies.org/catalog/25259/negative-emissions-technologies-and-reliable-sequestration-a-research-agenda, p. 8, 13-21.

30 EFI analysis of U.S. Code via Office of the Law Revision Counsel, "United States Code," U.S. House of Representatives, accessed April 13, 2022, https://uscode.house.gov/.

31 National Defense Authorization Act for Fiscal Year 2020, Pub. L. No. 116-92, 133 Stat. 1198 et seq., December 2019, https://www.govinfo.gov/content/pkg/PLAW-116publ92/pdf/PLAW-116publ92.pdf.

32 Bipartisan Budget Act of 2018, Pub. L. No. 115-123, 132 Stat. 64 et seq., February 2018, https://www.govinfo.gov/content/pkg/PLAW-115publ123/pdf/PLAW-115publ123.pdf.

33 Office of Tax Analysis, Tax Expenditures, U.S. Department of the Treasury, December 2021, https://home.treasury.gov/system/files/131/Tax-Expenditures-FY2023.pdf, Table 2, Line 39.

34 Joint Committee on Taxation, Estimated Revenue Effects of the Revenue Provisions of Title I – Committee on Finance, of an Amendment in the Nature of a Substitute to H.R. 5376, The Inflation Reduction Act of 2022, July 28, 2022, https://www.jct.gov/publications/2022/jcx-18-22.

35 Consolidated Appropriations Act, 2021, Pub L. No. 116-260, 134 Stat. 1182 et seq., December 2020, https://www.govinfo.gov/content/pkg/PLAW-116publ260/pdf/PLAW-116publ260.pdf.

36 Congressional Record, Vol. 168, No. 42, Book III, 117th Congress, March 9, 2022, https://www.govinfo.gov/content/pkg/CREC-2022-03-09/pdf/CREC-2022-03-09-bk3.pdf, p. H2241.

37 Steve Capanna, et al., *Early Deployment of Direct Air Capture with Dedicated Geologic Storage: Federal Policy Options,* Environmental Defense Fund (EDF), August 2021, https://www.edf.org/sites/default/files/documents/DAC%20Policy_Final.pdf, p. 8.

38 Infrastructure Investment and Jobs Act, Pub L. No. 117-58, 135 Stat. 429 et seq., November 2021, https://www.govinfo.gov/content/pkg/PLAW-117publ58/pdf/PLAW-117publ58.pdf.

39 Infrastructure Investment and Jobs Act, Pub L. No. 117-58, 135 Stat. 429 et seq., November 2021, https://www.govinfo.gov/content/pkg/PLAW-117publ58/pdf/PLAW-117publ58.pdf.

40 Jackson Morris and Miles Farmer, "Unpacking New York's Big New Climate Bill: A Primer," Natural Resources Defense Council, June 20, 2019, https://www.nrdc.org/experts/miles-farmer/unpacking-new-yorks-big-new-climate-bill-primer-0.

41 National Conference of State Legislatures (NCSL), "State Forest Carbon Incentives and Policies," September 22, 2021, https://www.ncsl.org/research/environment-and-natural-resources/state-forest-carbon-incentives-and-policies.aspx.

42 Energy Futures Initiative (EFI), *Surveying the BECCS Landscape,* January 10, 2022, https://energyfuturesinitiative.org/reports/surveying-the-beccs-landscape/, p. 46.

43 Alex Townsend and Ian Havercroft, *The LCFS and CCS Protocol: An Overview for Policymakers and Project Developers,* Global CCS Institute, 2019, https://www.globalccsinstitute.com/wp-content/uploads/2019/05/LCFS-and-CCS-Protocol_digital_version-2.pdf, p. 9.

44 Energy Futures Initiative (EFI) analysis of Environmental Protection Agency (EPA) annual budgets for FY 2012-2021, https://www.epa.gov/planandbudget/archive.

45 Julian Reiss, "Public Goods," *The Stanford Encyclopedia of Philosophy (Fall 2021 Edition),* Edward N. Zalta (ed.), July 21, 2021, https://plato.stanford.edu/archives/fall2021/entries/public-goods/.

46 Steve Capanna, et al., *Early Deployment of Direct Air Capture with Dedicated Geologic Storage: Federal Policy Options,* Environmental Defense Fund (EDF), August 2021, https://www.edf.org/sites/default/files/documents/DAC%20Policy_Final.pdf, p. 20.

47 Noah Deich, "Net zero isn't enough. We need to get to net negative," *Fortune,* September 23, 2021, https://fortune.com/2021/09/23/net-zero-emissions-carbon-removal-net-negative-cop26/.

48 Energy Futures Initiative (EFI), *Clearing the Air: A Federal RD&D Initiative and Management Plan for Carbon Dioxide Removal Technologies,* September 2019, https://energyfuturesinitiative.org/reports/clearing-the-air/, p. 23.

49 House Ways and Means Committee, "COMMITTEE PRINT CONSISTING OF SUBTITLES F, G, H, AND J," September 10, 2021, https://waysandmeans.house.gov/sites/democrats.waysandmeans.house.gov/files/documents/SUBFGHJ_xml.pdf, p. 198-202.

50 Jim Skea, et al., "Mitigation pathways compatible with long-term goals," in *Climate Change 2022: Mitigation of Climate Change,* Intergovernmental Panel on Climate Change (IPCC), April 2022, https://www.ipcc.ch/report/ar6/wg3/, p. 67.

51 Jim Skea, et al., "Agriculture, Forestry, and Other Land Uses (AFOLU)," in *Climate Change 2022: Mitigation of Climate Change,* Intergovernmental Panel on Climate Change (IPCC), April 2022, https://www.ipcc.ch/report/ar6/wg3/, p. 47.

52 Jim Skea, et al., "Agriculture, Forestry, and Other Land Uses (AFOLU)," in *Climate Change 2022: Mitigation of Climate Change,* Intergovernmental Panel on Climate Change (IPCC), April 2022, https://www.ipcc.ch/report/ar6/wg3/, p. 44.

53 Jim Skea, et al., "Agriculture, Forestry, and Other Land Uses (AFOLU)," in *Climate Change 2022: Mitigation of Climate Change,* Intergovernmental Panel on Climate Change (IPCC), April 2022, https://www.ipcc.ch/report/ar6/wg3/, p. 78.

54 Federal Energy Management Program (FEMP), "Appendix A: Green Power Considerations for Federal Agencies," in *Guide to Purchasing Green Power: Renewable Electricity, Renewable Energy Certificates, and On-Site Renewable Generation,* September 2018, https://www.epa.gov/sites/default/files/2016-01/documents/purchasing_guide_for_web.pdf, p. A7-A10.

55 New York State Assembly, Bill No. A08597, https://assembly.state.ny.us/leg/?defaultfld=%E2%8B%9Avideo=&bn=A08597&term=&Summary=Y&Memo=Y&Text=Y, accessed February 2, 2022.

56 Rep. Paul Tonko, H.R. 7434 Federal Carbon Dioxide Removal Leadership Act of 2022, https://www.govinfo.gov/content/pkg/BILLS-117hr7434ih/pdf/BILLS-117hr7434ih.pdf.

57 Andrew Bergman, et al., "Give Communities Control of Carbon Removal," *The New Republic,* April 11, 2022, https://newrepublic.com/article/166067/public-carbon-capture-climate.

58 General Services Administration, "Federal Acquisition Regulation," subpart 16.1, 2019, https://www.acquisition.gov/sites/default/files/current/far/pdf/FAR.pdf.

59 General Services Administration, "Federal Acquisition Regulation," subpart 16.2, 2019, https://www.acquisition.gov/sites/default/files/current/far/pdf/FAR.pdf.

60 Timothy DiNapoli, et al., "Reverse Auctions: Additional Guidance Could Help Increase Benefits and Reduce Fees," U.S. Government Accountability Office (GAO), July 2018, https://www.gao.gov/assets/gao-18-446.pdf, p. 5.

61 Timothy DiNapoli, et al., "Reverse Auctions: Additional Guidance Could Help Increase Benefits and Reduce Fees," U.S. Government Accountability Office (GAO), July 2018, https://www.gao.gov/assets/gao-18-446.pdf, p. 18-19.

62 Timothy DiNapoli, et al., "Reverse Auctions: Additional Guidance Could Help Increase Benefits and Reduce Fees," U.S. Government Accountability Office (GAO), July 2018, https://www.gao.gov/assets/gao-18-446.pdf, p. 41.

63 U.S. Department of Energy (DOE), "L-Prize Competition," Office of Energy Efficiency and Renewable Energy, accessed February 7, 2022, https://www.energy.gov/eere/ssl/l-prize-competition.

64 Marcy E. Gallo, "Federal Prize Competitions," Congressional Research Service, April 6, 2020, https://crsreports.congress.gov/product/pdf/R/R45271, p. 2.

65 Marcy E. Gallo, "Federal Prize Competitions," Congressional Research Service, April 6, 2020, https://crsreports.congress.gov/product/pdf/R/R45271, p. 7.

66 General Services Administration, "Federal Acquisition Regulation," subpart 16.3, 2019, https://www.acquisition.gov/sites/default/files/current/far/pdf/FAR.pdf.

67 U.S. Geological Survey Geologic Carbon Dioxide Storage Resources Assessment Team, 2013, "National Assessment of Geologic Carbon Dioxide Storage Resources—Results," ver. 1.1, September 2013: U.S. Geological Survey Circular 1386, http://pubs.usgs.gov/circ/1386, p. 41 (Supersedes ver. 1.0 released June 26, 2013.).

68 Jessie Stolark, "Great Plains Institute Provides Update on EPA's Class vi Well Program & State Primacy Efforts," Carbon Capture Coalition, February 24, 2022, https://carboncapturecoalition.org/great-plains-institute-provides-timely-update-on-epas-class-vi-well-program-state-primacy-efforts/.

69 Mischa Repmann, et al., "The Insurance Rationale for Carbon Removal Solutions," Swiss Re Institute, July 2021, https://www.swissre.com/institute/research/topics-and-risk-dialogues/climate-and-natural-catastrophe-risk/expertise-publication-carbon-removal-technologies.html.

70 Mischa Repmann, et al., "The Insurance Rationale for Carbon Removal Solutions," Swiss Re Institute, July 2021, https://www.swissre.com/institute/research/topics-and-risk-dialogues/climate-and-natural-catastrophe-risk/expertise-publication-carbon-removal-technologies.html.

71 National Petroleum Council, "Meeting the Dual Challenge: A Roadmap to At-Scale Deployment of Carbon Capture, Use, and Storage," December 2019, https://dualchallenge.npc.org/files/CCUS-Chap_3-030521.pdf.

72 Angela C. Jones, *Carbon Storage Requirements in the 45Q Tax Credit,* Congressional Research Service, June 28, 2021, https://crsreports.congress.gov/product/pdf/IF/IF11639/5.

73 U.S. Environmental Protection Agency (EPA), "Geologic Sequestration of Carbon Dioxide Underground Injection Control (UIC) Program Class VI Well Plugging, Post Injection Site Care, and Site Closure Guidance," December 2016, https://www.epa.gov/sites/production/files/2016-12/documents/wp-pisc-sc_guidance_final_december_clean.pdf.

74 California Air Resources Board (CARB), "Carbon Capture and Sequestration Protocol under the Low Carbon Fuel Standard," August 13, 2018, https://ww2.arb.ca.gov/sites/default/files/2020-03/CCS_Protocol_Under_LCFS_8-13-18_ada.pdf.

75 West Virginia Legislature, House Bill 4491, March 2022, https://www.wvlegislature.gov/Bill_Status/Bills_history.cfm?input=4491&year=2022&sessiontype=RS&btype=bill.

76 National Energy Technology Laboratory (NETL), "REGIONAL CARBON SEQUESTRATION PARTNERSHIPS (RCSP) INITIATIVE," accessed April 26, 2022, https://netl.doe.gov/coal/carbon-storage/storage-infrastructure/regional-carbon-sequestration-partnerships-initiative.

77 Marcy E. Gallo, et al., *Agency-Related Nonprofit Research Foundations and Corporations,* Congressional Research Service, 2022, https://www.everycrsreport.com/files/2022-06-02_R46109_e83bb41e1fd807332d2ee74c027a5f6de90307fd.pdf, Summary page.

78 Peter Winokur, et al., *An Innovation Foundation for DOE: Roles and Opportunities,* National Academy of Public Administration, 2021, https://s3.us-west-2.amazonaws.com/napa-2021/NAPA__DOE-Report-__-FINAL.pdf, p. 18-28.

79 Congressional Research Service (CRS), *The Quasi Government: Hybrid Organizations with Both Government and Private Sector Legal Characteristics,* Congressional Research Service, 2011, https://www.everycrsreport.com/files/20110622_RL30533_b8952608c94fe4c60a9b4a9a4d434467c424ddd9.pdf, p. 12-18.

80 U.S. Code - Foundation for Food and Agriculture Research, (b)(2) § 5939, accessed November 2, 2022, https://www.law.cornell.edu/uscode/text/7/5939.

81 Congressional Research Service (CRS), *The Quasi Government: Hybrid Organizations with Both Government and Private Sector Legal Characteristics,* Congressional Research Service, 2011, https://www.everycrsreport.com/files/20110622_RL30533_b8952608c94fe4c60a9b4a9a4d434467c424ddd9.pdf, p. 7.

82 Marcy E. Gallo, et al., *Agency-Related Nonprofit Research Foundations and Corporations,* Congressional Research Service, 2022, https://www.everycrsreport.com/files/2022-06-02_R46109_e83bb41e1fd807332d2ee74c027a5f6de90307fd.pdf, p. 12-13.

83 Marcy E. Gallo, et al., *Agency-Related Nonprofit Research Foundations and Corporations.* Congressional Research Service, 2022, https://www.everycrsreport.com/files/2022-06-02_R46109_e83bb41e1fd807332d2ee74c027a5f6de90307fd.pdf, p. 10-12.

84 Kerry Duggan and David Hart, "The Foundation for Energy Security and Innovation: A Flexible New Tool to Build the Economy, Strengthen Science, and Fight Climate Change," Information Technology & Innovation Foundation, August 2, 2022, https://itif.org/publications/2022/08/02/foundation-for-energy-security-and-innovation/.

85 Supreme Court Security Funding Act of 2022 (also known as CHIPS and Science Act), H.R.4346 §, accessed November 2, 2022, https://www.congress.gov/bill/117th-congress/house-bill/4346/text.

86 Supreme Court Security Funding Act of 2022 (also known as CHIPS and Science Act), H.R.4346 §, accessed November 2, 2022, https://www.congress.gov/bill/117th-congress/house-bill/4346/text.

87 Peter Winokur, et al., *An Innovation Foundation for DOE: Roles and Opportunities,* National Academy of Public Administration, 2021, https://s3.us-west-2.amazonaws.com/napa-2021/NAPA__DOE-Report-__-FINAL.pdf, p. 20.

88 Marcy E. Gallo, et al., *Agency-Related Nonprofit Research Foundations and Corporations,* Congressional Research Service, 2022, https://www.everycrsreport.com/files/2022-06-02_R46109_e83bb41e1fd807332d2ee74c027a5f6de90307fd.pdf, p. 22-23.

89 Kerry Duggan and David Hart, "The Foundation for Energy Security and Innovation: A Flexible New Tool to Build the Economy, Strengthen Science, and Fight Climate Change," Information Technology & Innovation Foundation, August 2, 2022, https://itif.org/publications/2022/08/02/foundation-for-energy-security-and-innovation/.

90 Peter Winokur, et al., *An Innovation Foundation for DOE: Roles and Opportunities,* National Academy of Public Administration, 2021, https://s3.us-west-2.amazonaws.com/napa-2021/NAPA__DOE-Report-__-FINAL.pdf, p. 18.

91 Rhodium Group, *Capturing Leadership: Policies for the US to Advance Direct Air Capture Technology,* May 2019, https://rhg.com/wp-content/uploads/2019/05/Rhodium_CapturingLeadership_May2019-1.pdf, p. 11.

92 Office of Management and Budget (OMB), "OMB Analysis: The Social Benefits of the Inflation Reduction Act's Greenhouse Gas Emission Reductions," accessed October 26, 2022, https://www.whitehouse.gov/wp-content/uploads/2022/08/OMB-Analysis-Inflation-Reduction-Act.pdf, p. 3.

93 Joint Committee on Taxation, "Estimated Budget Effects Of The Revenue Provisions Of Title I – Committee On Finance, Of An Amendment In The Nature Of A Substitute To H.R. 5376, An Act To Provide For Reconciliation Pursuant To Title II Of S. Con. Res. 14,'" https://www.jct.gov/publications/2022/jcx-18-22, p. 3.

ENERGY FUTURES
INITIATIVE