U.S. Department of ENERGY

Strategy for the Carbon Negative Shot™

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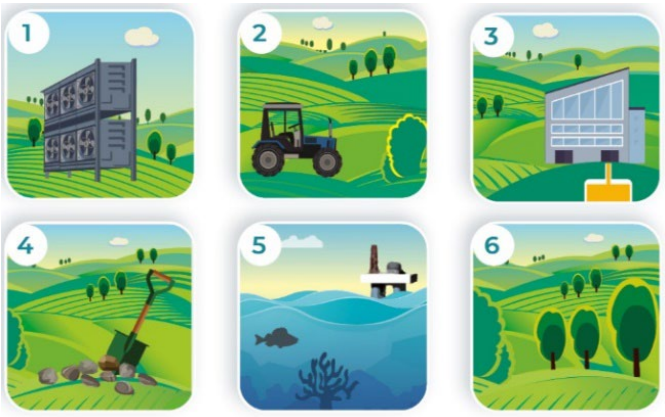
The Carbon Negative Shot™ is an all-hands-on-deck call for innovation in carbon dioxide removal pathways that will capture carbon dioxide from the atmosphere and store it at gigaton scales for less than $100/net metric ton of carbon dioxide-equivalent.

Overview

To accomplish the Unites States' climate goals, including net zero emissions by 2050[1], the U.S. needs to remove gigatons of carbon dioxide from the atmosphere cost-effectively. Distinct from other clean energy technologies, carbon dioxide removal (CDR) does not have a natural market yet but serves as a public good. The Department of Energy's (DOE) Carbon Negative Shot™[2] will meet these joint challenges using innovation, development, demonstration, and commercialization of high-quality CDR pathways. It will support market development by enhancing measurement, monitoring, reporting and verification approaches, building confidence for private markets that will supply the majority of early demand during the development phase to 2030.

CDR pathways, like any clean energy technology, will require both private markets and public policy to scale, and market development will require and reinforce public investment in innovation. The Carbon Negative Shot follows the successful approach of DOE research and development (R&D) programs like solar and wind energy: it aligns the expertise, capabilities, and cutting-edge science across DOE to deliver technology improvements that reduce the cost of CDR, facilitating rapid commercialization and scale-up. This Carbon Negative Shot strategy outlines DOE's implementation approach to drive down costs of CDR to enable policy, markets, and the private sector to scale the industry at the magnitude and pace required. The Carbon Negative Shot supports six major classes of removal pathways:

1. Direct Air Capture with Storage (DACS)
2. Soil Carbon Sequestration
3. Biomass Carbon Removal and Storage (BiCRS)
4. Enhanced Mineralization
5. Marine (Ocean-Based) CDR
6. Afforestation/Reforestation



[1] whitehouse.gov/wp-content/uploads/2021/10/us-long-term-strategy.pdf; https://www.fedcenter.gov/programs/eo14057/
[2] https://www.energy.gov/fecm/carbon-negative-shot

2030 Objectives

Over all six pathways, DOE's Carbon Negative Shot aims to accomplish the following 2030 objectives:

1. Channel at least $1 billion in new R&D investment across each CDR pathway, in collaboration with private equity firms, corporations, and philanthropic organizations[3].
2. Advance commercial deployments of at least 3 technologies and pilot demonstrations of at least 6 additional technologies per pathway across all relevant pathways.
3. Create a registry and definition of standards for all CDR approaches for voluntary carbon market (VCM) credits and for national greenhouse gas (GHG) inventories.
4. Support the creation of at least 25 million metric tons of CDR demand.
5. Develop analyses to predict the mixes of CDR pathways that can provide a portfolio of 1 billion tons of removals in 2050 at less than $100 net per metric ton cost within appropriate environmental and social constraints.

Science and Innovation in Six CDR Pathways

To ensure gigaton scale CDR deployment by 2050, DOE will focus on the science and innovation required to enable an interim target of 25 million metric tons of CDR demand by 2030. The composition of this interim target will reflect the diversified composition of the above six CDR pathways, and ensure that each of the pathways at least achieves million-ton scale. This is because over the six possible CDR pathways, there is no clear "winner" today, or an ideal CDR solution: each pathway has unique benefits, tradeoffs, and challenges related to costs, technology maturity, land and energy needs, confidence in measurement, monitoring, reporting, and verification (MMRV), and storage duration. For example, technologies like DAC currently require substantial infrastructure investments and energy inputs but are highly measurable and verifiable. In contrast, approaches such as improved forest management leverage the photosynthetic productivity of natural and working ecosystems but can be challenging to measure at high spatial and temporal resolution and provide less durable storage.

Therefore, given the criticality of the Carbon Negative Shot to achieve net-zero emissions by 2050, DOE must, in this decade, advance enough viable CDR pathways to ensure that DOE has adequate technology maturity, a 25 million ton portfolio capacity by 2030, and a gigaton-scale CDR portfolio by 2050. Innovation and research alone will not build the CDR projects at the scale required. However, DOE's support of transformative improvements in existing CDR pathways as well as discovery and development of novel approaches will reduce costs, paving the way for market development and public policy support globally.

Today, the six CDR pathways are at various stages of viability and maturity – and not all pathways are ready for million ton-scale capacity. Therefore, to have a robust portfolio of solutions, DOE will support innovative R&D efforts across each of the six pathways. For less mature pathways like some marine CDR (mCDR) and enhanced

[3] $1 billion is the level of funding authorized by the CHIPS and Science Act of 2022. Independent analyses by the National Academies (https://www.nationalacademies.org/our-work/developing-a-research-agenda-for-carbon-dioxide-removal-and-reliable-sequestration) recommend similar investments to ensure gigaton-scale CDR by 2050.

mineralization, these efforts will primarily be in research and development in the near term to enable larger-scale deployments by the end of the decade. The pathways with more established technical viability--like soil carbon sequestration and some BiCRS pathways--will benefit from earlier support in demonstration and deployment of at-scale systems, as well as continued foundational research for improvements in efficiency and costs.

These tradeoffs and distinct innovation and commercialization opportunities will involve an appropriate and corresponding sequence of R&D approaches in the six pathways. Some DAC technologies and biological systems (such as afforestation) are ready for demonstration and deployment-scale investment today, and DAC is receiving that from Infrastructure Investment and Jobs Act investments[4]. Soil carbon sequestration and BiCRS are ready to be evaluated in field-scale deployments – with improvements in MMRV they will be ready for deployment-scale investment in the next few years. Many marine CDR and enhanced weathering still require significant R&D, such as that being considered for mCDR by the multi-agency Fast Track Action Committee on Marine Carbon Dioxide Removal of the Subcommittee on Ocean Science and Technology National Science and Technology Council.

The recent "Technological Innovation Opportunities for CO_2 Removal" National Lab report[5] evaluates opportunities for technological innovation to enhance the economic viability of CDR, leveraging diverse technological, modeling, and analysis expertise from across the DOE national lab complex to identify and characterize these innovation opportunities across DACS, BiCRS, mineralization, and mCDR pathways. The findings of this report are intended to inform future DOE R&D to drive down the costs of CDR.

DOE's Role in CDR Innovation

DOE innovation efforts in advancing CDR technologies across the six pathways will involve the following goals:

1. Enable less than $100/net metric ton CO2e for both capture and storage.
2. Ensure robust accounting of full lifecycle emissions (i.e., ensures emissions created when running and building the removal technology are accounted for).
3. Secure geologic storage or equivalent storage with costs demonstrated for monitoring, reporting and verification.
4. Enable necessary gigaton-scale removal.

DOE has a leading role in DAC, BiCRS, and enhanced mineralization, and partners with the National Oceanic and Atmospheric Administration (NOAA) on mCDR and the Department of Agriculture on forests and soils CDR. A key DOE role in all technologies is demonstrating that there is adequate MMRV technology to support market purchases of millions of tons of removals. This strategy outlines DOE's role in coordinating those efforts.

The United States has the physical resources to meet our Carbon Negative Shot goals and gigaton-scale CDR capacity. A recent national lab-led report, Roads to Removal: Options for Carbon Dioxide Removal in the United States[6], demonstrated that the United States has sufficient available land, below ground geologic storage, and the opportunity to construct enough clean energy capacity to remove carbon dioxide at the scale needed to achieve net-zero emissions, while also providing economic opportunity, ecological benefits, and public health benefits.

DOE's role as a leader on science, innovation, and demonstration through the Carbon Negative Shot is clear. The markets and policies that ultimately finance gigaton-scale CDR are less defined and will be shaped by the cost-reductions and co-benefits observed across the portfolio. Today, a private and largely voluntary market for CDR has been shaped by early movers paying for CDR in the form of credits. More recently, Congress has given direction to DOE to establish a CDR purchasing pilot program, initiating a role for public sector procurement to

[4] https://www.energy.gov/oced/DACHubs
[5] https://www.energy.gov/sites/default/files/2024-11/Carbon%20Negative%20Shot_Technological%20Innovation%20Opportunities%20for%20CO2%20Removal_November2024.pdf
[6] Roads to Removal: Options for Carbon Dioxide Removal in the United States, Lawrence Livermore National Laboratory, December 2023, available at https://roads2removal.org/

accelerate demand for high-quality CDR.[7] The Carbon Negative Shot provides DOE a strategic framework to target research and development toward the most impactful innovations, while also setting standards and best practices for CDR markets. Alongside voluntary and compliance markets for CDR credits, ecosystem services and community benefits, such as mitigation of ocean acidification or improved resilience in agricultural systems can drive deployment of CDR for impacts beyond climate benefit.

Strategic Pillars for DOE's Carbon Negative Shot

DOE's CDR portfolio encompasses its basic science, applied research, and demonstration and infrastructure programs, as well as partnerships with other Federal agencies including the U.S. Department of Commerce's NOAA, U.S. Department of the Interior, U.S. Department of Agriculture, and the Environmental Protection Agency. Subject to available funds, working across its portfolio programs, interagency partners, and state and local communities, DOE's Carbon Negative Shot efforts over the next decade will involve the following four pillars.

Pillar 1: RD&D and Assessment of CDR Pathways

DOE will expand the pipeline of applied innovation from early stage to early deployment efforts across the six CDR pathways by at least a factor of 10 by 2030, or on par with with direct air capture efforts to date. The pathways are at varying stages of technological maturity and readiness, have received varying levels of support, and DOE has different roles in each of the six. For instance, DOE has a multibillion-dollar DAC portfolio with investments from the IIJA, while pathways like marine CDR and enhanced mineralization have been funded at lower levels – primarily for foundational research and development. Future DOE efforts will aim to scale up each pathway by funding RD&D (research, development, and demonstration) and deployment projects based on each pathway's technology maturity and viability, while also supporting innovation at any stage of technology development. Specifically, DOE will aim to demonstrate at least 6 novel technologies (sub pathways) per CDR pathway. These efforts will include investing in innovation test beds like the National Energy Technology Laboratory's (NETL) DAC Center[8], and expanding testing capabilities for biomass, enhanced weathering, soil carbon, and mCDR. DOE will work with our partner agencies to establish the appropriate roles for each partner, as has been recently done with NOAA on marine CDR[9]. Over the next ten years, DOE will develop plans to invest approximately $1B in each of the pathways to achieve these goals, subject to available funds. This will bring all six pathways to same state of development as DAC today.

As part of these RD&D efforts, DOE will conduct technology assessments over the next decade to model the projected growth and evolution of different CDR pathways beyond 2030, and invest in tools for robust measurement, verification, and reporting (MRV). This analysis will aim to identify the most promising CDR solutions meriting public and private investment. Specifically, DOE will establish the initial costs for various CDR approaches, estimate the cost reductions possible through scaling up production (learning curves), and develop 'waterfall chart' models showing the cumulative cost impacts. These models will then inform technology development priorities and policy options to achieve cost reductions or "curve jumps" for different pathways. The waterfall cost analyses will inform successive DOE investments for targeted RD&D activities to de-risk the most relevant CDR pathways for large-scale deployment towards the Carbon Negative Shot's 25 million ton demand target. Investments will focus on addressing the primary cost drivers identified for each pathway.

Pillar 2: Deployments and Community Collaboration

DOE will build on the RD&D investments and analyses over a wide range of CDR pathways and sub-pathways to inform the most viable paths for larger demonstration and deployment projects– similar to investments made by

[7] https://docs.house.gov/billsthisweek/20240304/FY24%20EW%20Conference%20JES%20scan.pdf
See page 76: "The agreement includes $20,000,000 to continue the competitive purchasing pilot program that was directed to be established in the fiscal year 2023 Act, consistent with Division D of Public Law 117-328. The Department is directed to provide to the Committees not later than 180 days after enactment of this Act a report on the progress of the competitive purchasing pilot program."
[8] https://netl.doe.gov/dac
[9] https://www.noaa.gov/sites/default/files/2024-06/EXEC-2024-003330-Final_NOAA-DOE_MOA_05222024_GR_RS_Signed.pdf

DOE in direct air capture projects. Specifically, DOE will aim to support commercial-scale deployments of at least 3 technological pathways. In this effort, DOE will work with the private sector to enable 25 million tons of annual CDR demand across all viable CDR pathways is available by 2030 as an interim milestone toward the gigaton-scale target for 2050.

These large-scale CDR projects with meaningful community engagement for all major CDR pathways are critical for demonstrating the full portfolio of CDR solutions and derisking the gigaton-scale CDR portfolio. They will make use of shared infrastructure and human capital to ensure responsible deployment of CDR with a focus on community benefits, enabling job creation and economic growth. DOE will work with communities and workers to ensure CDR delivers benefits and mitigates risks, with an emphasis on robust analysis of life cycle impacts of the various pathways, including rigorously evaluating CDR, defining conditions for success and leveraging leadership and expertise.

DOE will also collaborate with other governments through Mission Innovation's CDR initiative[10] to promote the development of CDR solutions worldwide, given the global nature of the climate challenge and the need for a worldwide CDR portfolio to achieve gigaton-scale carbon removal by 2050. DOE will participate in relevant U.S. Government interagency efforts, like the mCDR Fast Track Action Committee (FTAC)[11].

Pillar 3: Map Gigaton Scale Pathways

Complementary to the RD&D and deployment efforts, DOE will carry out robust analyses to develop 2050 gigaton-scale CDR roadmaps, detailing the projected CDR portfolio, costs, and resource needs. The analysis will incorporate trends in clean energy sources and costs, technological advancements, resource needs, community engagement, and carbon transportation and storage infrastructure. DOE will establish the energy, water, and material requirements for a gigaton-scale CDR portfolio encompassing all viable nature-based, technology-based and hybrid pathways. This will involve evaluating clean energy, land, and mineral resources, as well as materials like steel, aluminum, and amines. These resource assessments will be contextualized within other climate and decarbonization priorities.

Over the coming years and decades through 2050, DOE will continually assess CDR pathways, resources, and competing priorities for scaling up to gigatons of CDR based on several key factors. In addition to resource availability and technology advancements within CDR pathways, these include advancements in emerging renewable energy technologies like enhanced geothermal, offshore wind and marine energy that could significantly increase clean energy availability. DOE will also evaluate synergies with other clean energy technologies such as hydrogen production and carbon utilization, as well as the development of infrastructure for carbon transportation and storage.

Based on the analyses of the 2030s intermediate CDR portfolio, DOE will be able to model the cost evolution, resource needs, and constraints for CDR capacity growth to gigaton-scale by 2050, including the pursuit of R&D towards "curve-jumping" cost reduction measures.

Pillar 4: Enable and Encourage CDR Markets

Unlike other clean energy and climate technologies, a unique characteristic of CDR is the current lack of a natural market. Therefore, it requires both supply and demand side support to reach commercial maturity. Today's CDR purchases are largely driven by a growing voluntary carbon purchase market (VCM) and initial policy (compliance markets and tax credits). Voluntary purchases are currently running at much higher prices than the Carbon Negative Shot goal of $100, and tax incentives like 45Q (the production tax credit for carbon capture and storage that was reformed in the Inflation Reduction Act of 2022 to include a dedicated incentive for direct air capture) are insufficient for CDR technologies given its current costs. The DOE technology programs are directly contributing to driving down the costs in the voluntary market by improving technology, and building confidence in the market through robust MRV.

[10] Launched at COP26, the Carbon Dioxide Removal Mission is a group of nine governments working together to accelerate innovation of CDR technologies. Their goal is to enable 100 million tonnes of technological CDR per year by 2030. More details are at https://mission-innovation.net/missions/carbon-dioxide-removal/

[11] https://www.noaa.gov/sites/default/files/2023-10/mCDR_FTAC_charter_2023_09_19_approved.pdf

DOE will aim to ensure market transparency and credit integrity in these markets to enable the unlocking of private capital for CDR investments. Alongside scaling up CDR RD&D and deployments, DOE plans to continue to purchase carbon credits created by CDR projects in the US and setting standards for high-quality carbon dioxide procurement,including through the ongoing Carbon Dioxide Removal Purchase Prize[12]., and supporting the voluntary carbon market to create demand and incentives for CDR solutions. Specifically, DOE will create a registry and standards definition for all CDR approaches for VCM credits and support IPCC efforts to establish rules for CDR in national GHG inventories, expanding current efforts like the Voluntary Carbon Dioxide Removal Purchase Challenge[13] and the Purchase Prize. The overall goal of these programs is to build confidence in the value of durable carbon removal credits so that private investment can support capacity growth.

Role of the National Labs in the Carbon Negative Shot

The scientific and technical expertise and capabilities at DOE's National Labs are crucial to accomplishing the Carbon Negative Shot. The National Labs work with DOE's various programs and technology offices and can effectively integrate the spectrum of foundational science with development activities, as well as relevant technical analyses. Some examples of National Lab activities are as follows:

1. NETL's CDR program[14] fosters R&D focused on DAC, with emerging research in the areas of BiCRS, enhanced mineralization, and ocean-based and terrestrial CDR approaches to remove carbon dioxide. NETL projects range from conceptual engineering and materials design at laboratory and bench scale to large-scale testing and front-end engineering and design (FEED) studies to lower both capital and operating costs and improve the economics of CDR.
2. Two Energy Earthshot Research Centers[15] are focused on fundamental research to advance the Carbon Negative Shot – the Center for RESTORation of soil Carbon by precision biological strategies (RESTOR-C) led by Lawrence Berkeley National Laboratory (LBNL) and the Terraforming Soil Research Center led by Lawrence Livermore National Laboratory (LLNL).
3. A National Renewable Energy Laboratory (NREL)-led team, including Pacific Northwest National Laboratory (PNNL), LLNL, and LBNL, are developing a CDR Innovation Roadmap which includes assessments of the cost reduction potentials, technical barriers, and research needs of a range of CDR pathways.
4. Four National Lab projects[16], led by LLNL, PNNL, and NREL, with additional participation from LBNL, Oak Ridge National Laboratory, and industry partners are working on accelerating the commercialization of CDR technologies through advancing MRV best practices and capabilities.

[12] https://www.energy.gov/fecm/funding-notice-carbon-dioxide-removal-purchase-pilot-prize
[13] https://www.energy.gov/fecm/articles/doe-helping-you-buy-good-carbon-dioxide-removal-credits
[14] https://netl.doe.gov/carbon-management/carbon-dioxide-removal
[15] https://science.osti.gov/Initiatives/SCEarthshots/EERCs
[16] https://www.energy.gov/technologytransitions/articles/doe-selects-four-national-laboratory-led-teams-accelerate

DOE Offices Involved in Carbon Dioxide Removal

The table below highlights the extent of current and potential future DOE-wide efforts in the various aspects of the distinct CDR pathways.[17]

CDR Pathway	DOE Program					
	SC BER	SC BES	FECM	EERE BETO	EERE WPTO	OCED
Direct Air Capture with Storage (DACS)		FR	R&D, PD	R&D		MD, LD
Soil Carbon Sequestration	FR		R&D, PD	R&D		
Biomass Carbon Removal and Storage, BiCRS	FR		R&D, PD	R&D, PD		
Enhanced Mineralization	FR	FR	R&D, PD			
Marine CDR	FR		R&D, PD	R&D	R&D, PD	
Afforestation/ Reforestation			R&D			
Enabling Infrastructure (Storage, Transport, Permitting)			R&D, PD			MD, LD
System-wide Analysis & Integration			A	A	A	A

Table Key

SC – Office of Science
BES – Basic Energy Sciences
BER – Biological and Environmental Research
FECM – Office of Fossil Energy and Carbon Management
EERE – Office of Energy Efficiency and Renewable Energy
BETO – Bioenergy Technologies Office
WPTO – Water Power Technologies Office
OCED – Office of Clean Energy Demonstrations

FR – Foundational Research
R&D – Research and Development
PD – Pilots Demonstrations
MD– Mid-scale Demonstrations
LD – Large-scale Demonstrations

A – Analysis programs

[17] Some of the offices in the table are already active in these areas, but others will consider programs in these areas based on mission fit, opportunities, and funding