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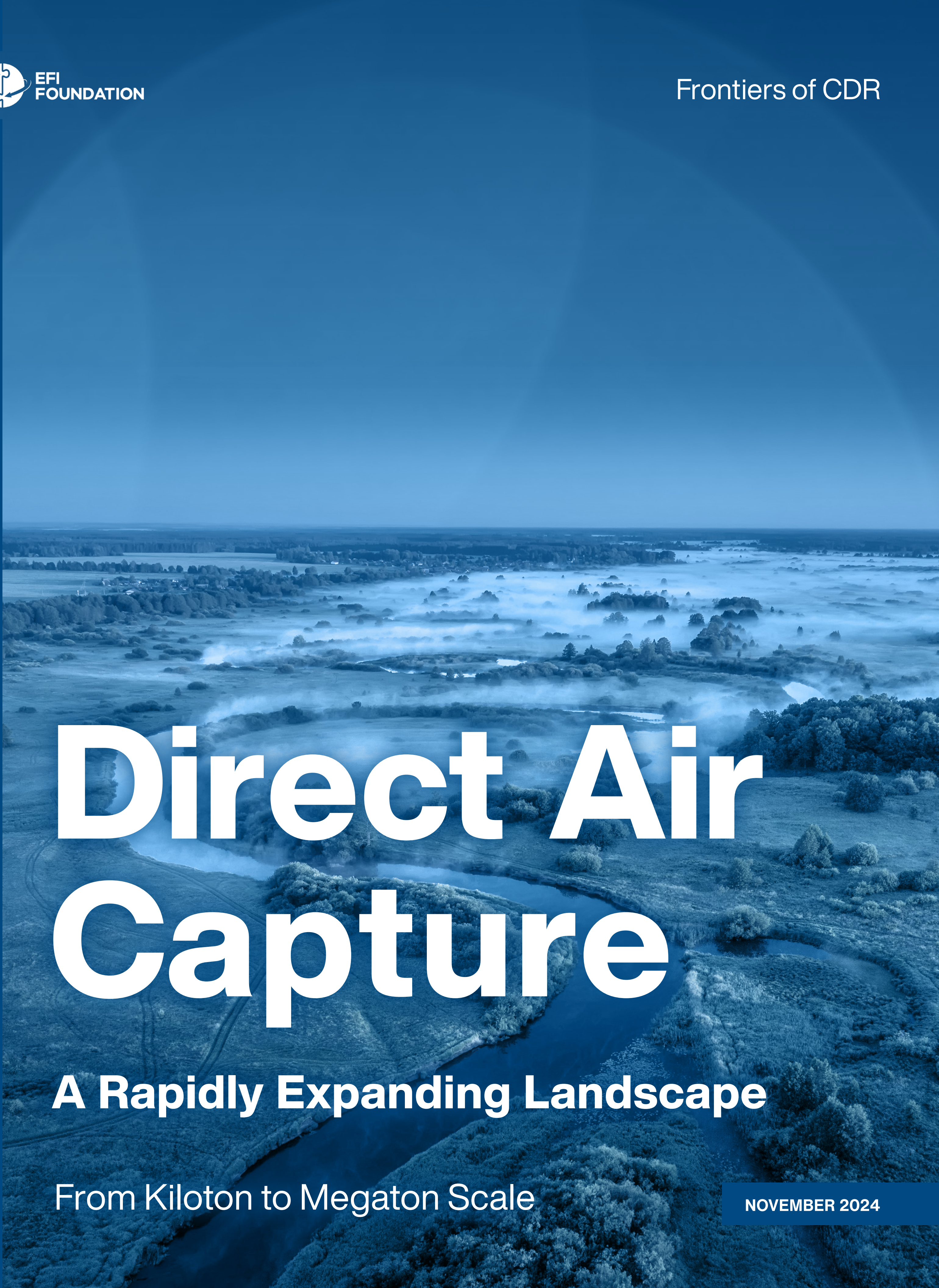

Direct Air Capture

A Rapidly Expanding Landscape

From Kiloton to Megaton Scale

NOVEMBER 2024

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Executive Summary

Within a decade, the direct air capture (DAC) industry has grown to more than 180 companies, with 90% of this growth occurring within the last five years.

This working paper takes stock of the rapid expansion of the DAC industry and the interplay of government incentives and private sector investment in spurring this growth. It analyzes the development of large-scale DAC projects, their funding and revenue sources, as well as the support mechanisms that have facilitated their growth. The analysis assesses projects that have moved beyond the pilot stage, demonstrating scalability and commercial viability.

Removal of legacy carbon dioxide (CO_2) emissions from the atmosphere and oceans is a key companion to the transition to lower-carbon sources and uses of energy in averting adverse climate change. DAC is expected to be one of the key technologies enabling large-scale carbon dioxide removal (CDR) because of its advantages in scalability, permanence, and verifiability.

The evolution of federal policies that combine incentives to accelerate DAC "technology push" supply with incentives to stimulate "market pull" demand for DAC carbon removals has had a powerful synergistic effect on DAC commercialization.

- The push to accelerate the supply of DAC technology solutions is being led by targeted U.S. Department of Energy (DOE) research, development, and demonstration funding, combined with new programs in the Bipartisan Infrastructure Law (BIL) for precommercial DAC prizes and regional DAC hubs. The private sector XPRIZE initiative also has been a complementary driving force.
- The pull to create a market for DAC carbon removal services has been driven primarily by the expansion of the Section 45Q tax credit in the Inflation Reduction Act (IRA). The DOE Commercial CDR Purchase Pilot Program has provided additional market stimulus. These efforts have facilitated the establishment of advance market commitments by individual companies as well as third-party demand aggregators to purchase the carbon emissions offsets from DAC.

The combination of the supply and demand incentives has enabled DAC start-up enterprises to attract venture capital and other forms of private sector equity investment in DAC startup enterprises.

The pipeline of DAC projects in development has been expanding rapidly. As of the date of this report, the current landscape of DAC developments include:

- On a global level, five commercial-scale DAC plants (capturing more than 1,000 tons of CO_2) are in operation. An additional 27 commercial-scale DAC projects have been identified as being in development globally.
- The DAC capacity worldwide in operation or development is estimated to provide about 15 million tons of CO_2 removal per year ($MtCO_2$/year); two-thirds of the capacity (10 $MtCO_2$/year) is located in the United States.
- 17 commercial-scale DAC projects have been identified as being in development in the United States. Of this total,12 projects were funded by DOE via the Regional DAC Hubs program or the funding for front-end engineering design (FEED) studies of advanced DAC systems.
- Of the 17 commercial-scale DAC projects in development in the United States, six are known to have secured advance market commitments for carbon removal.

The table has now been set for liftoff of the DAC industry. Maintaining the current BIL and IRA incentives, combined with continuing investment in technology innovation, and addressing permitting complexity for CO_2 storage, is needed to maintain the current pace of scale-up to megaton-scale DAC deployment.

While significant progress has been made for DAC to reach a megaton-scale market, two significant challenges remain.

- Significant reductions in the cost of DAC are needed. This will require continued investment in technology innovation, combined with the learning to be gained from early commercial-scale projects.
- Stronger demand-side programs are needed to build market development. Advance market commitments to support voluntary goals will likely be a niche market. Current government pilot purchase programs will help to demonstrate the mechanics of this concept, but they will require significant expansion in order to scale the DAC industry.

Further expansion toward gigaton-scale deployment will depend upon further cost reductions and additional measures for market development, including a large-scale government purchasing program.

1. Introduction

Direct air capture (DAC) of carbon dioxide (CO_2) from the atmosphere has been gaining momentum since the world's first commercial DAC plant was launched less than a decade ago.[1] More than 180 companies are now developing and offering DAC technologies worldwide, and about 90% of these companies started their businesses in the last five years.[2]

The successful liftoff of the DAC industry is the result of comprehensive and complementary government policies and private sector initiatives spanning the full life cycle of DAC from early-stage innovation through demonstration and initial deployment and ultimately market formation.

This working paper summarizes the current landscape of DAC technology development and deployment. It examines how the federal government and the private sector have partnered to establish a DAC industry in the United States. through a combination of supply-side "technology push" and demand-side "market pull" measures.

DAC is a leading form of carbon dioxide removal (CDR), an essential complement to mitigation measures for achieving net zero emissions to stabilize global temperature increases. Once net zero is achieved, continued deployment of CDR can achieve net-negative emissions, with the potential for reversing adverse climate change impacts by removing long-lived legacy CO_2 emissions from the environment.

DAC is a promising carbon removal technology. DAC systems are flexible in siting, require little land, and produce a verifiable stream of CO_2 that can be permanently sequestered. Because of these advantages, DAC is expected to be one of the key technologies enabling large-scale carbon removal.[3] As private companies have been looking into offsetting their carbon emissions, the number of DAC technology providers has been growing rapidly in recent years.[2]

2. Accelerating DAC Commercialization Through a Fast-Paced Framework of Federal Policies and Public-Private Partnerships

The pace of DAC commercialization has been swift. The idea of directly removing CO_2 from the air as a climate strategy was first proposed in 1999.[4] A 2015 report from the National Academies of Sciences, Engineering and Medicine (NASEM) acknowledged the relative paucity of research in this field and recommended development of a research agenda.[5]

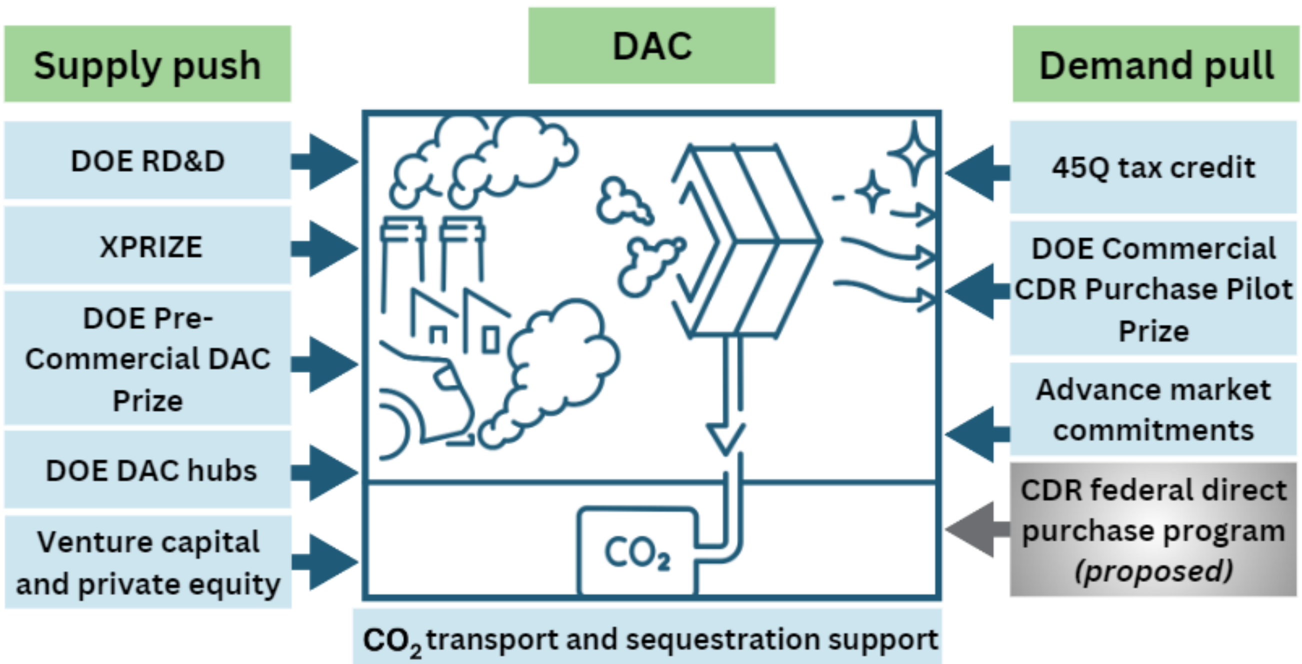
A second NASEM report in 2018[6] and a follow-on 2019 study by the Energy Futures Initiative[4] both recommended comprehensive federally sponsored research, development, and demonstration (RD&D) programs for a portfolio of CDR methods, including DAC. The NASEM and EFI reports emphasized the need for R&D efforts to reduce the cost of capture, lower energy requirements and improve capture performance levels.

Federal policies and programs have since evolved to support DAC commercialization focusing on both supply-side technology push programs as well as demand-side market pull initiatives. The concepts are illustrated in Figure 1 and summarized below.

- ***Supply-side technology push programs***: The initial U.S. Department of Energy (DOE) R&D funding for DAC was initiated by Congress in fiscal year (FY) 2020 with a line-item budget of $20 million. The Bipartisan Infrastructure Law (BIL) of 2021 broadened the RD&D direct funding by adding a DAC Pre-Commercial Technology Prize program aimed at cost reduction and technology scaleup. A companion private sector effort was the XPRIZE, a $100 million competition designed to accelerate the development of scalable carbon removal technologies, including DAC. The BIL also established a DAC Hubs program, providing $ 3.5 billion to establish up to four regional DAC hubs, each with the potential to scale to a capacity of 1 million metric tons (megaton) of CO_2 removal annually by the end of the decade. Private sector venture capital and other forms of equity investment provided the capital to scale several commercial DAC ventures as well.
- ***Demand-side market pull initiatives***: The principal federal incentive to create market demand was the Section 45Q tax credit for carbon capture and storage. The credit was initially enacted in 2008 and expanded significantly in the Inflation Reduction Act (IRA) of 2022. The 45Q credit of up to $180 per ton of CO_2 captured facilitates potential DAC demand by bridging the gap between consumers' willingness to pay for capture of CO_2 emissions and providers' costs of DAC services. In addition, a number of companies have stepped forward with advance market commitments (AMCs) to purchase CO_2 credits from DAC projects. Companies, including Microsoft

and Amazon, as well as demand aggregators such as Frontier, have entered into carbon removal purchase agreements with DAC providers to augment their greenhouse gas (GHG) emissions reduction commitments with carbon removal offsets. Also, DOE is in the process of implementing a pilot program for federal purchases of CO_2 credits from DAC through a Carbon Dioxide Removal Purchase Pilot Prize program established in the BIL. While this program is small, it will establish the basis for follow-on efforts needed to scale DAC to gigaton-scale deployment.

Figure 1. Federal supply-side and demand-side mechanisms for large-scale DAC deployment



XPRIZE Carbon Removal is a $100 million competition for solutions at a scale of at least 1,000 tons of CO_2 removed per year, funded by Elon Musk and the Musk Foundation. DOE = U.S. Department of Energy. Source: EFI Foundation

Federal support for building CO_2 transportation and sequestration infrastructure also has helped increase DAC deployments. Since 2021, DOE has announced more than $842 million of investments in CO_2 transport and sequestration, including a recent announcement of $500 million in grants for designing, developing, and building CO_2 transportation infrastructure.[7] DOE also has facilitated the development of commercial-scale CO_2 sequestration facilities via the Carbon Storage Assurance Facility Enterprise (CarbonSAFE) Initiative.

At the state level, clean fuel standards, such as California's Low Carbon Fuel Standard (LCFS) and Washington's Clean Fuel Standard, act as demand-side mechanisms by allowing DAC projects to generate credits for removing carbon from the atmosphere if they opt in to the programs. Clean fuel standards are market-based policies that aim to reduce the carbon intensity of transportation fuels by setting annual benchmarks. Fuels that meet or surpass these targets earn credits, while those that fall short generate deficits. No DAC projects have applied to California's LCFS program, but some have shown interest in doing so to sell credits under the program.[8] [9] California's LCFS credits can be stacked with the 45Q tax credit.[10]

Building upon these policies, DOE is exploring opportunities to expand demand-side federal support for DAC, complementing existing DOE programs focused on supporting the capital expenditure (capex) of facility construction. In October 2024, DOE issued a request for information (RFI) to obtain public input on demand-side support mechanisms (e.g., direct purchase of DAC credits, subsidies to credit purchases) and other non-capex mechanisms (e.g., subsidies to offset the costs of operations and maintenance, subsidies to complement 45Q tax credits).[11]

3. The Landscape of DAC Projects Currently Underway

As of April 2024, 27 DAC plants were in operation worldwide.[12] Most of these plants are small-scale, capturing less than 1,000 tons of CO_2 per year (tCO_2/year), with only five capturing more than that—two plants in Iceland and three in the United States. Mammoth in Iceland, the most recent addition, is the largest commercial DAC plant, capturing up to 36,000 tCO_2 annually.

More than 20 additional commercial-scale DAC projects are known to be in development worldwide. Many aim to capture more than 1 million metric tons of CO_2 ($MtCO_2$) annually (Table 1). Globally, the DAC capacity in development is estimated to remove about 15 $MtCO_2$/year. DAC projects under development in the United States comprise more than half of the total projects, with a combined total capacity of about 10 $MtCO_2$/year. Projects outside the United States comprise total capacity of about 5 $MtCO_2$/year in total.

Table 1. Large-scale DAC projects in operation and development						
United States – in operation						
Status	**Project**	**Location**	**Technology provider/project developer**	**Year announced**	**Operation year**	**Capacity (tCO_2/y)**
In operation	Heirloom California[13]	California	Heirloom Carbon Technologies	2021	2023	1,000
	Global Thermostat Colorado[14]	Colorado	Global Thermostat	2020	2023	1,000
	Bantam[15]	Oklahoma	Heimdal	2020	2024	5,000
Total capacity in operation – United States						***7,000 tCO_2/y***
United States – in development						
Status	**Project**	**Location**	**Technology provider/project developer**	**Year announced**	**Operation year**	**Capacity (tCO_2/y)**
In development with DOE support	Project Cypress[16]	Louisiana	Battelle, Climeworks, Heirloom Carbon Technologies	2023	2029	1,000,000
	South Texas DAC Hub[17]	Texas	1PointFive	2023	Unknown	1,000,000
	Southwest Regional DAC Hub[18]	Arizona	Arizona Board of Regents, CarbonCapture	2023	Unknown	Unknown
	California DAC Hub[18]	California	Electric Power Research Institute, Climeworks	2023	Unknown	Unknown
	Southeast DAC Hub[19]	Alabama	Southern States Energy Board, Aircapture	2023	Unknown	100,000
	Prairie Compass DAC Hub	North Dakota	University of North Dakota Climeworks	2023	Unknown	Unknown
	Project Bison[20,a]	Wyoming	CarbonCapture, Frontier Carbon Solutions	2022	On hold[21]	5,000,000
	Nuclear DAC with Carbon Storage[22]	Alabama	Battelle, Aircapture, Southern Company	2022	Unknown	5,000
	Climeworks DAC California[23]	California	University of Illinois, Climeworks	2022	Unknown	5,000
	Nuclear DAC in Illinois[24]	Illinois	Constellation, Carbon Engineering	2022	Unknown	250,000
	Indiana Waste Heat[25]	Indiana	University of Illinois, CarbonCapture, CarbonCure	2022	Unknown	5,000
	Washington Chemical Plant Waste Heat[26]	Washington	Aircapture, Nutrien	2022	Unknown	5,000
Total capacity in development supported by DOE						***> 7,370,000 tCO_2/y***

[a] On Sept. 2, 2024, CarbonCapture announced it would pause Project Bison and relocate the project outside of Wyoming because of the difficulty in securing renewable energy as the demand rapidly increased from data centers.

Status	Project	Location	Technology provider/project developer	Year announced	Operation year	Capacity (tCO_2/y)
In development without DOE support	Stratos DAC Project[27]	Texas	1PointFive	2019	2025	500,000
	Project Monarch[28]	California	Capture6, Palmdale Water District	2023	2026	Unknown
	HIF eFuels[29]	Texas	HIF	2022	2027	2,000,000
	The Dalles[30]	Oregon	280 Earth	2024	2025	5,000
	Heirloom in Louisiana[31]	Louisiana	Heirloom	2024	2026	17,000
Total capacity in development without DOE support						***2,522,000 tCO_2/y***
Total capacity in development – United States						***> 9,892,000 tCO_2/y***
Outside of the United States – in operation						
Status	**Project**	**Location**	**Technology provider/project developer**	**Year announced**	**Operation year**	**Capacity (tCO_2/y)**
In operation	Mammoth[32]	Iceland	Climeworks, Carbfix	2021	2024	36,000
	Orca[33]	Iceland	Climeworks, Carbfix	2019	2021	4,000
Total capacity in operation – outside of the United States						***40,000 tCO_2/y***
Outside of the United States – in development						
Status	**Project**	**Location**	**Technology provider/project developer**	**Year announced**	**Operation year**	**Capacity (tCO_2/y)**
In development	Removr Commericial Plant2[34]	Iceland	Removr, Carbfix	2023	2027	100,000
	Sizewell C DAC[35]	UK	Sizewell C	2023	Unknown	1,500,000
	DAC - Abu Dhabi[36]	UAE	iPointFive, ADNOC	2023	Unknown	1,000,000
	Project Octopus[37]	Korea	Capture6, K-water	2024	Unknown	500,000
	Project Skyscraper[38]	UK	Airhive	Unknown	2025	1,000
	Deep Sky Labs[38]	Canada	Airhive	Unknown	2024	1,000
	Project Carpenter[38]	UK	Airhive	Unknown	2025	5,000
	Kollsnes DAC project[39]	Norway	Carbon Removal, Carbon Engineering, Oxy	2021	Unknown	500,000-1,000,000
	Project Hummingbird[40]	Kenya	Octavia Carbon	2023	2024	1,000
	Kenya Great Rift Valley[41]	Kenya	Great Carbon Valley, Climeworks	2023	After 2028	~1,000,000
Total capacity in development – outside of the United States						***5,108,000 tCO_2/y***
Global total capacity in operation and in development						***15,047,000 tCO_2/y***

Note: The projects listed in this table are limited to those capturing more than 1,000 tCO_2/year and with a publicly known development status. Sources: Cited within the table.

4. Funding Partnerships for DAC Projects Currently in Development

The initial deployments of DAC projects have been financed through a mix of public and private sector funding facilitated by the interplay of the federal technology push combined with market pull incentives, private sector investment and AMCs. The range of variation among funding sources is illustrated by project in Table 2.

Table 2. Investments and purchase agreements in DAC projects in development			
United States			
Project	**Public funds**	**Private funds**	**Carbon removal purchase agreement**
Stratos DAC Project	Unknown	$550 million from Black Rock (joint venture)[42]	• Microsoft, 500,000 tCO_2, 6 years (July 2024)[43] • AT&T (March 2024)[44] • Trafigura, >50,000 tCO_2 (Jan. 2024)[45] • BCG, 20,000 tCO_2, 3 years (Jan. 2024)[46] • TD, 27,500 tCO_2, 4 years (Nov. 2023)[47] • Amazon, 250,000 tCO2, 10 years (Sept. 2023)[48] • All Nippon Airways 10,000 tCO_2/y, 3 years (Aug 2023) [49] • Houston Astros (March 2023)[50] • Houston Texans (Jan. 2023)[51] • Airbus, 100,000 tCO2/y, 4 years (March 2022)[52]
Project Monarch	>$8 million from California Energy Commission	Unknown	Frontier, 1,000 tCO_2, prepurchase (2024)[53]
HIF eFuels	Unknown	Unknown	Unknown
Project Cypress	• $50 million from DOE Regional DAC Hubs program (March 2024)[54] • Selected for up to $600 million by DOE Regional DAC Hubs program (Aug. 2023)[55]	Unknown (needs $51 million to begin)[56]	Microsoft, 315,000 tCO_2, multi-year period (Sept. 2023)[57]
South Texas DAC Hub	Selected for up to $600 million by DOE Regional DAC Hubs program (Aug 2023)[58]	Unknown	Unknown
Southwest Regional DAC Hub	Selected for $12 million by DOE Regional DAC Hubs program Topic Area 2 (Aug 2023)[59]	Non-DOE fund $12 million	Unknown
California Direct Air Capture Hub	Selected for $12 million by DOE Topic Area 2 (Aug 2023)[59]	Non-DOE fund $12 million	Unknown

Southeast DAC Hub	Selected for $10 million by DOE Topic Area 2 (Aug 2023)[59]	Non-DOE fund $10 million	Unknown
Prairie Compass DAC Hub	Selected for $13 million by DOE Topic Area 2 (Aug 2023)[59]	Non-DOE fund $15 million	Unknown
Project Bison	Selected for $13 million by DOE Topic Area 2 (Aug 2023)[59]	Non-DOE fund $15 million	Frontier, 45,000 tCO_2, multiyear period (Nov. 2023)[60] • BCG, 40,000 tCO_2, 5 years (June 2023)[61] • Microsoft (March 2023)[62]
Nuclear DAC with Carbon Storage	Selected for $2.5 million in DOE funding for FEED studies of advanced DAC systems (Apr 2022)[24]	Non-DOE fund $0.9 million	Unknown
Climeworks DAC California	Selected for $2.5 million in DOE funding for FEED studies of advanced DAC systems (Apr 2022)[24]	Non-DOE fund $0.6 million	Unknown
Nuclear Powered DAC in Illinois	Selected for $2.5 million in DOE funding for FEED studies of advanced DAC systems (Apr 2022)[24]	Non-DOE fund $0.6 million	Unknown
Indiana Waste Heat	Selected for $3.5 million in DOE funding for FEED studies of advanced DAC systems (Apr 2022)[24]	Non-DOE fund $0.9 million	Unknown
Washington Chemical Plant Waste Heat	Selected for $3 million in DOE funding for FEED studies of advanced DAC systems (April 2022)[24]	Non-DOE fund $0.7 million	Unknown
The Dalles	Unknown	Unknown	Frontier, 61,571 tCO_2, offtake delivered by 2030[63]
Heirloom in Louisiana	$3 million grants from the state of Louisiana ($7 million additional depending on performance) [64,b]	Unknown	Frontier, 26,889 tCO_2 offtake delivered by 2030[65]
Global			
Project	**Public funds**	**Private funds**	**Carbon removal purchase agreement**
Removr Commercial Plant2	Unknown	Unknown	Unknown
Sizewell C DAC	£3 million ($3.8 million) from UK government (March 2023)[66]	Unknown	Unknown
DAC - Abu Dhabi	Unknown	Unknown	Unknown
Project Octopus	Unknown	Unknown	Unknown
Project Skyscraper	Unknown	Unknown	Frontier, 943 tCO_2, prepurchase[60]
Deep Sky Labs	Unknown	XPRIZE finalist[67]	Unknown

[b] The fund from the state of Louisiana is for two facilities, including a facility developed as part of Project Cypress.

Project Carpenter	Unknown	Unknown	Unknown
Kollsnes DAC project	Unknown	Unknown	Unknown
Project Hummingbird	Unknown	XPRIZE finalist[67] Raised $5 million fund[68]	On track to generate >$1 million in revenue from the presale of carbon offsets[69]
Kenya Great Rift Valley	Unknown	Unknown	Unknown

FEED stands for front-end engineering design. Topic Area 2 of the DOE Regional DAC Hubs program indicates design-phase projects. This table excludes 14 projects selected under Topic Area 1 (feasibility phase) as they are in the very early stages of project development, such as a technical review of existing technologies, building relations among stakeholders, or a pre-feasibility study. Sources: Cited within the table.

DOE demonstration project grants and DAC hub funding serve as a core funding source for many projects. In addition, many DAC technology providers are startups supported by venture capital and other forms of private sector investors, including XPRIZE, BlackRock, and Occidental Petroleum. Advance market commitments by large corporations have provided a bankable revenue stream to support additional equity and debt financing. Especially important has been the availability of the Section 45Q tax credit to bridge the gap between consumers' willingness to pay to capture CO_2 emissions and providers' costs of DAC services.

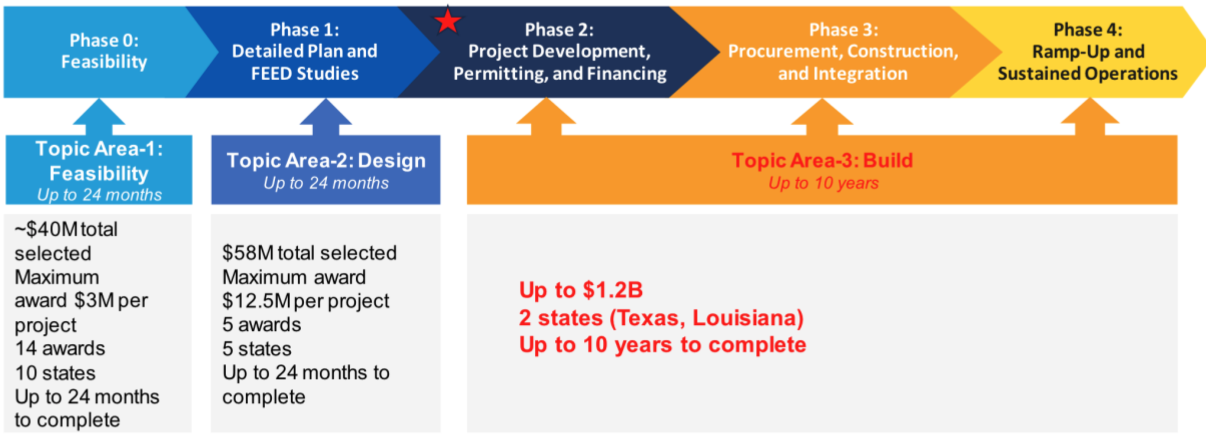
DOE direct funding: The role of the federal government has been critical in launching the current portfolio of DAC projects in development. For example, as shown in Table 2, DOE funded five DAC front-end engineering design (FEED) studies of $2.5 million to $3.5 million each in April 2022.24

Figure 2 illustrates DOE project implementation of the DAC hubs program. In August 2023 DOE selected two potential DAC hubs, Project Cypress and the South Texas DAC Hub. The two hubs could receive up to $600 million from the DOE Regional DAC Hubs program.[70]

In addition to selecting these two regional hubs, DOE awarded a total of $99 million to 19 additional projects to support earlier stages of project development—$40 million to 14 projects under Topic Area 1 (feasibility) and $58 million to five under Topic Area 2 (detailed plan and FEED studies). These are also shown in Figure 2.[71]

Finally, in September 2024, DOE released a notice of intent to offer an additional $1.8 billion to the DAC Hubs program.[72]

Figure 2. DOE Regional DAC Hubs program by phase and committed funds



Source: DOE Office of Clean Energy Demonstration, "South Texas DAC Hub Direct Air Capture Hub Community Briefing," September 20, 2023, https://www.energy.gov/sites/default/files/2023-10/2023.09%20Texas%20-%20OCED%20DAC%20Hubs%20Briefing%20Presentation.pdf

The U.S. government has offered broad support for DAC technologies beyond the project level. In 2021, DOE launched the Carbon Negative Shot, aiming to enable the scale-up of CDR pathways to gigaton scale with a cost of less than \$100/tCO_2 by 2032. The CDR pathways include DAC, soil carbon sequestration, biomass carbon removal and storage, enhanced mineralization, ocean-based carbon dioxide removal, and afforestation/reforestation. Since 2020, DOE has consistently increased the budget for CDR to enhance funding for programs like the Carbon Negative Shot (Table 3).[73,74]

Table 3. DOE budget for DAC, FY 2020-2024, $ million

	FY2020	FY2021	FY 2022	FY 2023	FY 2024
Carbon dioxide removal (including DAC and other CDR technologies)	20	40	49	70	70
Regional Direct Air Capture Hubs	-	-	700	700	700
Commercial Direct Air Capture Technology Prize Competitions	-	-	100	-	-
Pre-Commercial Direct Air Capture Technology Prize competitions	-	-	15	-	-

Sources: Department of Energy FY 2022 Budget Justification, https://www.energy.gov/cfo/articles/fy-2022-budget-justification; Department of Energy FY 2025 Budget Justification, https://www.energy.gov/cfo/articles/fy-2025-budget-justification

The costs of DAC are currently far above the \$100/tCO_2 Carbon Negative Shot target. Recent published information reported estimated DAC costs ranging from \$200/tCO_2 to \$1,000/tCO_2.[75, 76] Current DAC costs are high because the current DAC technologies have significant capital expenditure required to process large volumes of air containing dilute concentrations of CO_2, the energy-intensive processes for sorbent regeneration, and the cost of compression of CO_2 volumes to enable transport and storage of captured CO_2.[77] Projections of future DAC costs projections vary significantly, ranging from below $100/t$CO_2$ to around $500/t$CO_2$.[78]

DOE prizes and government purchases: Beginning in March 2023, DOE launched a suite of government prize and government purchase initiatives as authorized and funded in the BIL.

- The DAC Pre-Commercial Energy Program for Innovation Clusters (EPIC) Prize and the DAC Pre-Commercial Technology Prize support entrepreneurs and innovators by providing cash prizes and technical assistance for commercializing DAC technologies.
- The Commercial CDR Purchase Pilot Prize offers purchase agreements in addition to cash prizes.[79]

The CDR Purchase Pilot Prize Program will establish the basis for further expansion of DAC deployment, ultimately to gigaton-scale CO_2 removal. As an extension of this effort, DOE plans to launch the Voluntary Carbon Dioxide Removal Purchasing Challenge, calling on external organizations to join DOE in purchasing CDR credits in late 2024.[80] Meta and Google have joined the challenge, committing $35 million each for CDR credits.[81,82]

Private sector investment: Private investors have also directly invested in DAC projects. In November 2023, BlackRock announced its investment of $550 million in the Stratos project in Texas via a joint venture with 1PointFive.[83] BlackRock described Stratos as “an incredible investment opportunity for BlackRock’s clients to invest in this unique energy infrastructure project.”[83] The CO_2 captured by Stratos will be stored underground and used for enhanced oil recovery (EOR).[84] The XPRIZE Carbon Removal, a $100 million competition, selected 20 finalist teams, including five DAC teams—Airhive, Heirloom, Octavia Carbon, Project Hajar (a collaboration between 44.01 and Aircapture), and Skyrenu.[85] These finalists will compete for the grand prize of $50 million in April 2025, while $30 million will be distributed among the runners-up.

***Advance market commitments*:** In addition to attracting direct investments from the government and private investors, DAC projects have secured revenue sources via carbon removal purchase agreements. DAC has attracted much attention from private buyers of voluntary offsets because of concerns about the quality of traditional voluntary offsets, mostly from forestry projects.[86] Compared to other CDR technologies, DAC has advantages such as scalability, permanence, and verifiability advantages.[87] The land efficiency of DAC enhances its scalability. Since measuring the number of tons removed is straightforward for DAC, its carbon offsets are more easily verifiable than those of nature-based solutions.

According to 1PointFive parent Occidental, Stratos saw a strong demand for credits as they are “higher quality” than other types of carbon offsets relying on complicated emissions accounting methods. Occidental expects revenue of $580/t$CO_2$ to $810/t$CO_2$ from Stratos, including $130/t$CO_2$ to $180/t$CO_2$ of 45Q tax credits, exceeding its expected cost of

$400/t$CO_2$ to $500/t$CO_2$.[88] As shown in Table 2, several large corporations have signed agreements to purchase carbon offsets from Stratos.

Table 2 also identifies the carbon removal purchase agreements between DAC project developers and private buyers, including individual companies and demand aggregators such as Frontier. Frontier aggregates its members' demand for carbon removal offsets and makes purchase agreements with suppliers on their behalf. Frontier members include Stripe, Alphabet, Shopify, Meta, McKinsey Sustainability, Autodesk, H&M Group, JPMorgan Chase & Co., and Workday. As of October 2024, Frontier has purchased offsets from 43 carbon removal projects: 13 DAC, seven field weathering, eight mineralization, nine biomass carbon removal and storage, three direct ocean removal, and three ocean alkalinity enhancement projects.[60] DAC projects account for 22% of contracted tons and 26% of contracted dollars in Frontier's portfolio, indicating that buyers are willing to pay higher offset prices for DAC than for other CDR projects. Individual companies, including Microsoft, Amazon, Airbus, BCG, and AT&T, have signed direct offtake agreements with DAC project developers without using an aggregator like Frontier.

***Section 45Q tax credit*:** The 45Q tax credits, expanded by the Inflation Reduction Act of 2022 (IRA), offer up to $180/t$CO_2$ for DAC projects with geologic sequestration and $130/t$CO_2$ for DAC with EOR or other qualified CO_2 uses, provided projects meet conditions such as paying prevailing wages during construction and the first 12 years of operation and fulfilling registered apprenticeship requirements. Without meeting these labor standards, the incentive drops to a base rate of $36/t$CO_2$ for geologic sequestration and $26/t$CO_2$ for EOR, just 20% of the maximum credit, which is unlikely to effectively stimulate investment within the relevant timeframe.

5. Increasing Private Investments Beyond the Project-Level

In addition to funding agreements for individual projects, private investors are providing capital at the company level for DAC startup companies to help build corporate capability to pursue additional projects in the future.

DAC startups have raised substantial private investment from a range of investors, including venture capitalists, climate funds, and private equity firms. Examples include:

- In 2022, Climeworks secured $650 million in equity funding from a group of investors, including Partners Group, GIC, Carbon Removal Partners, and Swiss Re.[89]
- In March 2024, CarbonCapture closed $80 million Series A financing, led by Prime Movers Lab with participation from several venture investors, including Idealab X, TIME Ventures, Neotribe Ventures, and Alumni Ventures. It also added Amazon's Climate Pledge Fund, Aramco Ventures, and Siemens Financial Services as strategic investors.[90,c]
- In March 2022, Heirloom raised $53 million in a Series A financing round led by Carbon Direct Capital Management, Ahren Innovation Capital, and Breakthrough Energy Ventures, with the participation of the Microsoft Climate Innovation Fund.[91] This financing also includes investments from climate funds and entrepreneurs, including Breyer Capital, Grantham Environmental Trust, Lowercarbon Capital, TIME Ventures, Carbon Removal Partners, and Seven Seven Six.
- Global Thermostat launched the Global Thermostat Japan joint venture with ICMG, a Japan-based investment firm, and raised investment from Sumitomo Corp. in May 2023.

Private investors' growing interest in carbon removal also provides opportunities for DAC companies. In September 2024, Morgan Stanley closed its 1GT climate private equity fund at $750 million of equity capital commitments, investing in the companies to avoid or remove CO_2.[92] It also signed an agreement to purchase 40,000 tons of DAC credits from Climeworks in October 2024.[93] In May 2023, JPMorgan signed an agreement to purchase $200 million worth of DAC credits from Climeworks.[94]

[c] Series A funding is a company's first significant round of venture capital financing following "seed funding." In Series A funding, investors look for companies with solid strategies for turning their ideas into a money-making business.

6. Next Steps: A Federal Direct CO_2 Purchase Program for Gigaton-Scale Carbon Removal

Current DAC activities are rapidly transitioning DAC from a kiloton scale CO_2 removal industry to an early commercial megaton-scale CO_2 removal industry. For DAC and other CDR methods to make a material contribution to curbing global greenhouse gas emissions and associated adverse climate impacts, reaching gigaton-scale CO_2 removal is necessary. To reach that scale, the EFI Foundation in December 2022 proposed a major new initiative for federal purchases of CO_2 removal services.[95]

The proposed CO2-Secure initiative envisions government purchases of CO2 removals as a public good that warrants government investment. *CO2 Secure* encompasses a range of government mechanisms, from establishing a government-owned and -operated CDR program to purchasing CDR services provided by the private sector.[95] The principal elements of this initiative include:

- ***Organization and management***: The scale and pace of the program require the establishment of a sole-purpose federal organization, such as the proposed National Carbon Removal Authority.
- **Funding:** The initial phase would be authorized for 10 years, providing sufficient time for the initiative to gain experience with large-scale implementation of business models and innovation opportunities. The initial 10-year funding would be a lump-sum direct spending authority of $33.2 billion.
- ***Program implementation authorities***: Multiple forms of public-private partnerships will be pursued, including contracts for CDR capture and storage services, acquisition of captured carbon for government-owned, contractor-operated transport and storage facilities, and completion of end-to-end government-owned, contractor-operated implementation.
- ***Implementation schedule***: The CO2-Secure initiative would be organized and initiated by the end of this decade—to allow for further growth of the CDR industry under current incentives and to take advantage of the learning experience. The initiative's first CDR project investments are expected to become operational around 2035, growing to a scale of 1 gigaton/year of carbon removals annually by 2060.

Since the launch of the CO2-Secure concept paper, the EFI Foundation has met with stakeholders to engage in further discourse on the concept.

7. Conclusion and Recommendations

Direct air capture (DAC) projects are gaining momentum globally and in the United States, driven by growing recognition of the need for large-scale CO_2 removal, the power of current incentives—including both technology push and market pull mechanisms—and the straightforward accounting for CO_2 removed from the atmosphere using DAC compared with other carbon removal technologies. Market pull mechanisms, such as voluntary carbon offset purchases and tax credits like the 45Q credit, are having a material effect on market development. making a strong case for developing and expanding DAC technologies. **Expanded support for government purchases of carbon removal will be essential to scaling DAC to reach the longer-term goal of gigaton scale carbon removals.**

Increased adoption of DAC will lead to economies of scale as more facilities are built, which will help drive down the cost per ton of CO_2 captured. Still, innovation will need to play a key role in cost reduction. Several DAC projects have reported lower costs by using new techniques or materials, illustrating the impact of technological innovation in making DAC more commercially viable.[96] [97] **Increased federal funding for research, development and demonstration activities is needed to significantly reduce the cost of DAC through innovations in DAC materials and processes.**

Current DAC systems do not fully account for the life cycle emissions from energy used to capture CO_2. Separating CO_2 from ambient air is highly energy-intensive, with process heat accounting for over 80% of total DAC energy needs. Co-locating DAC systems near low-cost carbon free energy sources can help reduce emissions associated with the energy used in the process.[4] **Additional research and development are essential to implementing measures to reduce energy consumption and enhance the life cycle carbon footprint of DAC.**

Lastly, the complexity of permitting, particularly for Class VI wells used for CO_2 storage, has proven to be a major obstacle to several CDR projects.[98] **Legislative action on permitting reform could ease regulatory burdens and support the expansion of DAC procurement and deployment efforts.**

References

[1] Climeworks, “Climeworks makes history with world's first commercial direct air capture plant,” May 31, 2017, https://climeworks.com/press-release/today-climeworks-is-unveiling-its-proudest-achievement#:~:text=Today%20Climeworks%20has%20launched%20the,greenhouse%20to%20help%20grow%20vegetables.
[2] Grant Faber, “2024 Direct Air Capture Company List,” accessed July 16, 2024, https://docs.google.com/spreadsheets/d/1UobgHejUQe8PhMZoV4RLGC0q406M-lIrlRSJAghh8ys/edit?gid=0#gid=0
[3] Benjamin Sovacool et al., "Climate policy for a net-zero future: ten recommendations for Direct Air Capture." *Environmental Research Letters* 17, no. 7 (2022): 074014. https://iopscience.iop.org/article/10.1088/1748-9326/ac77a4/meta
[4] Lackner, K. S., P. Grimes, and H. J. Ziock. “Carbon Dioxide Extraction from Air: Is It an Option?” Coal and Slurry Technology Association, Washington, DC (US), July 1, 1999. https://www.osti.gov/biblio/20013487.
[5] National Research Council, 2015, Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration. Washington, DC: The National Academies Press. https://doi.org/10.17226/18805.
[6] Stephen Pacala et al., "Negative emissions technologies and reliable sequestration: a research agenda." National Academies of Sciences, Engineering, and Medicine: Washington, DC, USA (2018), https://nap.nationalacademies.org/catalog/25259/negative-emissions-technologies-and-reliable-sequestration-a-research-agenda.
[7] DOE Office of Fossil Energy and Carbon Management, “DOE Announces $500 Million to Build a Safe and Reliable Carbon Dioxide Transportation System,” May 2, 2024, https://www.energy.gov/fecm/articles/doe-announces-500-million-build-safe-and-reliable-carbon-dioxide-transportation#:~:text=—%20As%20part%20of%20President%20Biden's,reduce%20CO2%20emissions%20across
[8] CARB, “LCFS Credit Generation Opportunities | California Air Resources Board.” Accessed October 23, 2024. https://ww2.arb.ca.gov/our-work/programs/low-carbon-fuel-standard/lcfs-credit-generation-opportunities.
[9] 1PointFive P1, LLC. “313 Application from 1PointFive P1, LLC to Ector County ISD Series Submission – Build 6 of 6,” April 19, 2022. https://assets.comptroller.texas.gov/ch313/1794/1794-ector-1pointfive-app.pdf.
[10] Global CCS Institute, “The LCFS and CCS Protocol: An Overview for Policymakers and Project Developers.” accessed October 23, 2024. https://www.globalccsinstitute.com/resources/publications-reports-research/the-lcfs-and-ccs-protocol-an-overview-for-policymakers-and-project-developers/.
[11] DOE Office of Clean Energy Demonstration, “DE-FOA-0003478: Opportunities for Additional Support for Commercial Direct Air Capture (DAC) Demonstration Facilities,” October 29, 2024, https://oced-exchange.energy.gov/?utm_medium=email&utm_source=govdelivery#FoaId3ba2c154-ada1-4647-9966-9432ab5480d7
[12] IEA, “Direct Air Capture, accessed May 21, 2024, https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/direct-air-capture
[13] Heirloom, “Heirloom unveils America’s first commercial Direct Air Capture facility,” November 9, 2023, https://www.heirloomcarbon.com/news/heirloom-unveils-americas-first-commercial-direct-air-capture-facility
[14] Global Thermostat, “Global Thermostat unveils one of the world’s largest units for removing carbon dioxide directly from the air,” April 4, 2023, https://www.globalthermostat.com/news-and-updates/global-thermostat-colorado-headquarters
[15] Carlos Anchondo, “Largest US Direct Air Capture Plant Opens in Oklahoma.” E&E News by Politico, August 13, 2024, https://www.eenews.net/articles/largest-us-direct-air-capture-plant-opens-in-oklahoma-2/.
[16] Project Cypress, “Project Cypress: For a Better Net-Zero Tomorrow,” accessed May 21, 2024, https://www.projectcypress.com
[17] 1PointFive, “South Texas DAC Hub,” accessed May 21, 2024, https://www.1pointfive.com/projects/south-texas-dac

[18] DOE Office of Fossil Energy and Carbon Management, "Project Selections for FOA 2735: Regional Direct Air Capture Hubs – Topic Area 1 (Feasibility) and Topic Area 2 (Design)," accessed July 16, 2024, https://www.energy.gov/fecm/project-selections-foa-2735-regional-direct-air-capture-hubs-topic-area-1-feasibility-and

[19] Southern States Energy Board, "SEDAC Hub," accessed July 16, 2024, https://www.sseb.org/programs/sedac_hub/

[20] CarbonCapture, "Project Bison," accessed May 21, 2024, https://www.carboncapture.com/project-bison

[21] Vasil Velev, "CarbonCapture Inc. Pauses Development Of Project Bison In Wyoming," *Carbon Herald*, September 2, 2024, https://carbonherald.com/carboncapture-inc-pauses-development-of-project-bison-in-wyoming/.

[22] Brandon Webster, "NuDACCS – Nuclear Direct Air Capture with Carbon Storage," August 15-19, 2022, https://netl.doe.gov/sites/default/files/netl-file/22CM_CDR17_Webster.pdf

[23] Jason Dietsch, "FEED Study for Climeworks Direct Air Capture at a California Geothermal Facility with Long-Term Storage," November 14, 2022, https://www.ideals.illinois.edu/items/126230

[24] DOE Office of Fossil Energy and Carbon Management, "Selections for Funding Opportunity Announcement 2560: Direct Air Capture Combined with Dedicated Long-Term Carbon Storage, Coupled to Existing Low-Carbon Energy ," April 14, 2022, https://www.energy.gov/fecm/articles/selections-funding-opportunity-announcement-2560-direct-air-capture-combined

[25] Les Gloja et al., "FEED Study of Carbon Capture Inc DAC and CarbonCure Utilization Technologies Using United States Steel's Gary Works Plant Waste Heat," August 15-19, 2022, https://netl.doe.gov/sites/default/files/netl-file/22CM_CDR17_OBrien_2.pdf

[26] DOE Office of Fossil Energy and Carbon Management, "DOE Invests $14 Million to Scale Up Direct Air Capture and Storage Technology, Coupled to Low-Carbon Energy Resources," April 14, 2022, https://www.energy.gov/fecm/articles/doe-invests-14-million-scale-direct-air-capture-and-storage-technology-coupled-low

[27] 1PointFive, "Ramping up DAC," accessed May 21, 2024, https://www.1pointfive.com/dac-technology

[28] Capture6, "Project Monarch," accessed October 28, 2024, https://capture6.org/project-monarch/

[29] Bechtel, "HIF Global engages Bechtel, Siemens Energy, and Topsoe for eFuels project in the USA ," December 6, 2022, https://www.bechtel.com/newsroom/press-releases/hif-global-engages-bechtel-siemens-energy-and-topsoe-for-efuels-project-in-the-usa/

[30] Pontecorvo, "The U.S. Has Gotten 3 Direct Air Capture Plants in 13 Months," Heatmap News, accessed October 10, 2024, https://heatmap.news/technology/direct-air-capture-280-earth.

[31] Heirloom, "Heirloom to build two Direct Air Capture (DAC) facilities in Northwest Louisiana ," June 24, 2024, https://www.heirloomcarbon.com/news/two-direct-air-capture-facilities-in-northwest-louisiana

[32] Climeworks, "Mammoth: our newest facility," accessed May 21, 2024, https://climeworks.com/plant-mammoth

[33] Climeworks, "Orca: the first large-scale plant," accessed May 21, 2024, https://climeworks.com/plant-orca

[34] Removr, "Carbfix and Removr team up for Direct Air Capture and Storage in Iceland," May 25, 2023, https://www.removr.no/news/removr-partners-with-carbfix-100000t-plant-iceland

[35] Sizewell C, "Agreement for Direct Air Capture plans at Port of Lowestoft," March 24, 2023, https://www.sizewellc.com/news-views/agreement-for-direct-air-capture-plans-at-port-of-lowestoft/

[36] ADNOC, "ADNOC and Occidental to Advance Direct Air Capture Project in the UAE ," October 2, 2023, https://www.adnoc.ae/en/news-and-media/press-releases/2023/adnoc-and-occidental-to-advance-direct-air-capture-project-in-the-uae

[37] Capture6, "Project Octopus," accessed July 14, 2024, https://capture6.org/project-octopus/

[38] Airhive, "Catch carbon faster," accessed May 21, 2024, https://www.airhive.earth

[39] Carbon Engineering, "New partnership to deploy large-scale Direct Air Capture in Norway," November 23, 2021, https://carbonengineering.com/news-updates/partnership-dac-norway/

[40] Antony Sguazzin, "First Southern Hemisphere Direct Air Capture Plant Planned," *Bloomberg News,* July 19, 2023, https://www.bloomberg.com/news/articles/2023-07-19/first-southern-hemisphere-direct-air-capture-plant-planned?embedded-checkout=true.

[41] Climeworks, "Climeworks and Great Carbon Valley chart path to large-scale direct air capture and storage deployment in Kenya," September 21, 2023, https://climeworks.com/press-release/climeworks-and-great-carbon-valley-chart-path-to-large-scale-dac
[42] 1PointFive, "Occidental and BlackRock Form Joint Venture to Develop STRATOS, the World's Largest Direct Air Capture Plant," November 7, 2023, https://www.1pointfive.com/news/occidental-and-blackrock-form-joint-venture-to-develop-stratos#:~:text=HOUSTON%20and%20NEW%20YORK%20%E2%80%94%20November,%2C%20in%20Ector%20County%2C%20Texas.
[43] 1PointFive, "Microsoft agrees to purchase 500,000 Tonnes of DAC Carbon Removal Credits, July 9, 2024, https://www.1pointfive.com/news/1pointfive-and-microsoft-announce-agreement-for-direct-air-capture-cdr-credits
[44] 1PointFive, "1PointFive and AT&T Announce Direct Air Capture Carbon Removal Agreement," March 13, 2024, https://www.1pointfive.com/news/1pointfive-and-att-announce-direct-air-capture-carbon-removal-agreement
[45] 1PointFive, "1PointFive and Trafigura Announce Direct Air Capture Carbon Removal Credit Agreement," January 16, 2024, https://www.1pointfive.com/news/1pointfive-and-trafigura-announce-agreement-for-direct-air-capture-cdr-credits
[46] 1PointFive, "1PointFive and Boston Consulting Group Announce Strategic Agreement for Direct Air Capture Carbon Removal Credits," January 11, 2024, https://www.1pointfive.com/news/1pointfive-and-boston-consulting-group-announce-agreement-for-direct-air-capture-cdr-credits
[47] 1PointFive, "1PointFive and TD Announce One of the Finance Industry's Largest Purchases of Direct Air Capture Carbon Removal Credits," November 1, 2023, https://www.1pointfive.com/news/1pointfive-cdr-purchase-agreement-td-bank-group
[48] Proactive, "Amazon.com makes initial investment in carbon capture tech," September 12, 2023, https://www.proactiveinvestors.com/companies/news/1026272/amazon-com-makes-initial-investment-in-carbon-capture-tech-1026272.html
[49] 1PointFive, "ANA Announces Carbon Dioxide Removal Purchase from 1PointFive," August 1, 2023, https://www.1pointfive.com/news/ana-carbon-dioxide-removal-purchase-from-1pointfive
[50] 1PointFive, "1PointFive and the Houston Astros announce Direct Air Capture Carbon Removal Credit Agreement," March 7, 2023, https://www.1pointfive.com/news/1pointfive-and-the-houston-astros-announce-direct-air-capture-carbon-removal-credit-agreement
[51] 1PointFive, "1PointFive announces agreement with Houston Texans to purchase carbon removal credits and become the team's Preferred Carbon Removal Partner," January 6, 2023, https://www.1pointfive.com/news/1pointfive-announces-agreement-with-houston-texans
[52] 1PointFive, "1PointFive announces agreement with Airbus," March 17, 2022, https://www.1pointfive.com/news/1pointfive-announces-agreement-with-airbus
[53] Capture6, "Capture6 selected for pre-purchase facilitation by Frontier," September 18, 2024, https://capture6.org/2024/09/18/capture6-selected-for-pre-purchase-facilitation-by-frontier/
[54] DOE Office of Clean Energy Demonstration, "Regional Direct Air Capture Hubs Program – Project Cypress, accessed May 21, 2024, https://www.energy.gov/sites/default/files/2024-03/Project%20Cypress%20Fact%20Sheet_final.pdf
[55] DOE, "Biden-Harris Administration Announces Up To $1.2 Billion For Nation's First Direct Air Capture Demonstrations in Texas and Louisiana," August 11, 2023, https://www.energy.gov/articles/biden-harris-administration-announces-12-billion-nations-first-direct-air-capture
[56] Climeworks, "Project Cypress DAC Hub team awarded funding from U.S. Department of Energy ," March 27, 2024, https://climeworks.com/news/project-cypress-team-awarded-funding-from-us-doe
[57] Heirloom, "Heirloom and Microsoft sign one of the largest permanent CO2 removal deals to-date," September 7, 2023, https://www.heirloomcarbon.com/news/heirloom-and-microsoft-sign-permanent-co2-removal-deal
[58] DOE, "Biden-Harris Administration Announces Up To $1.2 Billion For Nation's First Direct Air Capture Demonstrations in Texas and Louisiana," August 11, 2023, https://www.energy.gov/articles/biden-harris-

administration-announces-12-billion-nations-first-direct-air-capture
[59] DOE Office of Fossil Energy and Carbon Management, "Project Selections for FOA 2735: Regional Direct Air Capture Hubs – Topic Area 1 (Feasibility) and Topic Area 2 (Design)," accessed July 16, 2024, https://www.energy.gov/fecm/project-selections-foa-2735-regional-direct-air-capture-hubs-topic-area-1-feasibility-and
[60] Frontier, "Our portfolio," accessed May 21, 2024, https://frontierclimate.com/portfolio
[61] BCG, "Boston Consulting Group Enters 40,000-ton Carbon Removal Credit Agreement with CarbonCapture Inc.," June 21, 2023, https://www.bcg.com/press/21june2023-bcg-enters-carbon-removal-credit-agreement-with-carboncapture
[62] Businesswire, "CarbonCapture Inc. to Supply Microsoft Carbon Removal Credits Based on Direct Air Capture Technology," March 22, 2023, https://www.businesswire.com/news/home/20230322005154/en/CarbonCapture-Inc.-to-Supply-Microsoft-Carbon-Removal-Credits-Based-on-Direct-Air-Capture-Technology
[63] Corbin Hiar, "Tech Giants Back Data Center-Powered Carbon Removal Startup," *E&E News by Politico*, July 11, 2024, https://www.eenews.net/articles/tech-giants-back-data-center-powered-carbon-removal-startup/.
[64] Heirloom, "Heirloom to build two Direct Air Capture (DAC) facilities in Northwest Louisiana ," June 24, 2024, https://www.heirloomcarbon.com/news/two-direct-air-capture-facilities-in-northwest-louisiana
[65] Frontier, "Heirloom, accessed October 24, 2024, https://frontierclimate.com/portfolio/heirloom
[66] Sizewell C, "Direct Air Capture and SZC," accessed July 16, 2024, https://www.sizewellc.com/environment/szc-energy-hub/dac/
[67] XPRIZE, "20 Teams Bring Cutting-Edge Solutions to XPRIZE Carbon Removal Final," May 8, 2024, https://www.xprize.org/prizes/carbonremoval/articles/20-teams-bring-cutting-edge-solutions-to-xprize-carbon-removal-finals
[68] Sasha Renevska, " Octavia Carbon Unveils Project Hummingbird, Global South's First DAC Plant," October 25, 2024, Carbon Herald, https://carbonherald.com/octavia-carbon-unveils-project-hummingbird-global-souths-first-dac-plant/
[69] Geoffrey Kamadi, "Can Kenya become a direct-air-capture hub?" January 5, 2024, https://cen.acs.org/environment/climate-change/Kenya-become-direct-air-capture/102/i1
[70] DOE, "Biden-Harris Administration Announces Up To $1.2 Billion For Nation's First Direct Air Capture Demonstrations in Texas and Louisiana," August 11, 2023, https://www.energy.gov/articles/biden-harris-administration-announces-12-billion-nations-first-direct-air-capture
[71] DOE Office of Clean Energy Demonstration, "South Texas DAC Hub Direct Air Capture Hub Community Briefing," September 20, 2023, https://www.energy.gov/sites/default/files/2023-10/2023.09%20Texas%20-%20OCED%20DAC%20Hubs%20Briefing%20Presentation.pdf
[72] DOE Office of Clean Energy Demonstration, "Notice of Intent No.: DE-FOA-0003429: Regional Direct Air Capture Hubs –Recurring Program," September 27, 2024, https://oced-exchange.energy.gov/Default.aspx#FoaId52499773-a2a0-4c43-984d-3fbb7bf57343
[73] DOE, "Department of Energy: FY 2025 Congressional Justification," March 2024, https://www.energy.gov/sites/default/files/2024-03/doe-fy-2025-budget-vol-4-v5.pdf
[74] DOE, "Department of Energy: FY 2022 Congressional Budget Request," June 2021, https://www.energy.gov/sites/default/files/2021-06/doe-fy2022-budget-in-brief-v4.pdf
[75] Desport, Lucas, Angelo Gurgel, Jennifer Morris, Howard Herzog, Yen-Heng Henry Chen, Sandrine Selosse, and Sergey Paltsev. "Deploying direct air capture at scale: How close to reality?." *Energy Economics* 129 (2024): 107244. https://doi.org/10.1016/j.eneco.2023.107244
[76] Sievert, Katrin, Tobias S. Schmidt, and Bjarne Steffen. "Considering technology characteristics to project future costs of direct air capture." *Joule* 8, no. 4 (2024): 979-999.
[77] Herzog, Howard, Jennifer Morris, Angelo Gurgel, and Sergey Paltsev. "Getting real about capturing carbon from the air." *One Earth* 7, no. 9 (2024): 1477-1480.
[78] Sievert, Katrin, Tobias S. Schmidt, and Bjarne Steffen. "Considering technology characteristics to project future costs of direct air capture." *Joule* 8, no. 4 (2024): 979-999.
[79] DOE American Made Challenges, "Direct Air Capture Prizes," accessed May 21, 2024,

https://americanmadechallenges.org/challenges/direct-air-capture
[80] DOE Office of Fossil Energy and Carbon Management, "U.S. Department of Energy Announces Intent to Launch Voluntary Carbon Dioxide Removal Purchasing Challenge," March 14, 2024, https://www.energy.gov/fecm/articles/us-department-energy-announces-intent-launch-voluntary-carbon-dioxide-removal
[81] Meta, "Growing Our Commitment to Carbon Removal with the U.S. Department of Energy." *Meta Sustainability* (blog), October 11, 2024. https://sustainability.atmeta.com/blog/2024/10/11/growing-our-commitment-to-carbon-removal-with-the-u-s-department-of-energy/.
[82] Randy Spock, "Our Pledge to Support Carbon Removal Solutions," *Google* (blog), March 14, 2024, https://blog.google/outreach-initiatives/sustainability/pledge-to-support-carbon-removal-solutions/.
[83] 1PointFive, "Occidental and BlackRock Form Joint Venture to Develop STRATOS, the World's Largest Direct Air Capture Plant," November 7, 2023, https://www.1pointfive.com/news/occidental-and-blackrock-form-joint-venture-to-develop-stratos#:~:text=HOUSTON%20and%20NEW%20YORK%20%E2%80%94%20November,%2C%20in%20Ector%20County%2C%20Texas.
[84] David Gelles, "Can We Engineer Our Way Out of the Climate Crisis?" *The New York Times*, March 31, 2024, sec. Climate, https://www.nytimes.com/2024/03/31/climate/climate-change-carbon-capture-ccs.html.
[85] XPRIZE, "20 Teams Bring Cutting-Edge Solutions to XPRIZE Carbon Removal Final," May 8, 2024, https://www.xprize.org/prizes/carbonremoval/articles/20-teams-bring-cutting-edge-solutions-to-xprize-carbon-removal-finals
[86] Grayson Badgley et al., "Systematic over-crediting in California's forest carbon offsets program," *Global Change Biology* 28, no. 4 (2022): 1433-1445, https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.15943.
[87] World Economic Forum, "Achieving net zero: Why costs of direct air capture need to drop for large-scale adoption," August 9, 2023, https://www.weforum.org/agenda/2023/08/how-to-get-direct-air-capture-under-150-per-ton-to-meet-net-zero-goals/
[88] Kevin Crowley and Silla Brush, "BlackRock Invests $550 Million in Occidental Carbon Capture," *Bloomberg News,* November 7, 2023, https://www.bloomberg.com/news/articles/2023-11-07/blackrock-bets-550-million-on-occidental-carbon-capture-plant.
[89] Climeworks, "Accelerating the direct air capture industry: Climeworks raises CHF 600 million in equity funding, " April 5, 2022, https://climeworks.com/uploads/documents/climeworks-press-release-finalized_05.04.22_.pdf
[90] PR Newswire, "Direct air capture company CarbonCapture Inc. closes $80 million Series A financing," March 12, 2024, https://www.prnewswire.com/news-releases/direct-air-capture-company-carboncapture-inc-closes-80-million-series-a-financing-302086698.html?tc=eml_cleartime
[91] PR Newswire, "Direct Air Capture Startup Heirloom Raises $53MM Series A, Among the Largest Investments in New Carbon Removal Technologies," March 17, 2022, https://www.prnewswire.com/news-releases/direct-air-capture-startup-heirloom-raises-53mm-series-a-among-the-largest-investments-in-new-carbon-removal-technologies-301505399.html
[92] Morgan Stanley, "Morgan Stanley Investment Management Closes 1GT Climate Private Equity Fund at $750 Million," September 30, 2024, https://www.morganstanley.com/press-releases/msim-closes-1gt-climate-private-equity-fund
[93] Climeworks, "Morgan Stanley partners with Climeworks to remove 40,000 tons of CO_2 from the air ," October 24, 2024, https://climeworks.com/press-release/morgan-stanley-partners-with-climeworks-to-remove-co2
[94] JPMorganChase, "JPMorgan Chase seeks to scale investment in emerging carbon removal technologies, announces agreements intended to durably remove and store 800,000 tons of carbon," May 23, 2023, https://www.jpmorganchase.com/newsroom/press-releases/2023/jpmorgan-chase-seeks-to-scale-investment-in-emerging-carbon-removal-technologies
[95] Energy Futures Initiative, "CO2-Secure: A National Program to Deploy Carbon Removal at Gigaton Scale," December 7, 2022. https://energyfuturesinitiative.org/reports/co2-secure-a-national-program-to-deploy-carbon-removal-at-gigaton-scale/.

[96] Randy Spock, "Our First-of-Its-Kind Direct Air Capture Deal Forges a Path to Lower Costs," *Google* (blog), September 10, 2024, https://blog.google/outreach-initiatives/sustainability/google-holocene-direct-air-capture/.
[97] Carlos Anchondo, "Largest US Direct Air Capture Plant Opens in Oklahoma," *E&E News by Politico*, August 13, 2024, https://www.eenews.net/articles/largest-us-direct-air-capture-plant-opens-in-oklahoma-2/.
[98] Energy Futures Initiative (EFI), "Turning CCS Projects in Heavy Industry & Power into Blue Chip Financial Investments," February 2023. https://efifoundation.org/wp-content/uploads/sites/3/2023/02/20230212-CCS-Final_Full-copy.pdf.