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Direct Air Capture: Definition and Company Analysis

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Author

Grant Faber

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Disclaimer Statement

List of Acronyms, Initialisms, and Abbreviations

BiCRS	biomass carbon removal and storage
CCS	carbon capture and storage
CDR	carbon dioxide removal
CFR	Code of Federal Regulations
CO_2	carbon dioxide
COF	covalent organic framework
DAC	direct air capture
DAC+S	direct air capture and storage
DACC	direct air carbon capture // direct air capture and conversion
DACCS	direct air capture and carbon storage // direct air carbon capture and storage
DACS	direct air capture and storage
DACU	direct air capture and utilization
DOE	Department of Energy
EMF 37	Energy Modeling Forum 37
ERW	enhanced rock weathering
FECM	Office of Fossil Energy and Carbon Management
FFRDC	federally funded research and development center
GGR	greenhouse gas removal
HVAC	heating, ventilation, and air conditioning
IPCC	Intergovernmental Panel on Climate Change
M&A	mergers and acquisitions
MMRV	measurement, monitoring, reporting, and verification
MOF	metal organic framework
NET	negative emissions technology
NETL	National Energy Technology Laboratory
NREL	National Renewable Energy Laboratory
OCED	Office of Clean Energy Demonstrations
ppm	part(s) per million
PSC	point-source capture
RD&D	research, development, and demonstration
TRL	technology readiness level

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Executive Summary

Direct air capture (DAC) of carbon dioxide (CO_2) is expected to play an important role in the mitigation of climate change. Depending on the implementation levels of greenhouse gas emissions reduction technologies and other forms of carbon dioxide removal (CDR), DAC may ultimately be used to remove tens to hundreds of billions of tons of CO_2 from the atmosphere cumulatively during the 21st century. However, the technology is at a relatively early developmental stage compared to many other climate change mitigation and carbon management technologies. This results in uncertainties surrounding its ultimate scale, definition, and market landscape. The purpose of this report is to begin to address these uncertainties.

Based on a review of numerous existing definitions, DAC is defined herein as a technology that regenerates a capture medium in a closed loop and/or uses a mechanical air contactor to chemically or physically separate carbon dioxide directly from the outdoor or indoor ambient atmosphere without reliance on above-average carbon dioxide concentrations caused by nearby point sources of emissions. This definition results in three categories of DAC technologies that include CO_2-concentrating DAC, reactive DAC, and direct storage DAC. CO_2-concentrating DAC involves processes that produce more concentrated streams of CO_2, reactive DAC involves processes regenerating a capture medium that simultaneously captures and converts atmospheric CO_2, and direct storage DAC involves processes that use mechanical air contactors to extract atmospheric CO_2 and react it with various feedstocks for durable storage.

At the time of writing, an analysis of all global direct air capture companies reveals that there are approximately 142 incorporated companies working on DAC, with 121 working on CO_2-concentrating DAC, 13 working on reactive DAC, and 8 working on direct storage DAC. As with many industries, consolidation can be expected over the coming decades. Of the 142 companies working on DAC, 81 are headquartered in North America with another cluster present in Western Europe. Around two-thirds of the companies use a solid sorbent as their capture medium, and around one quarter of the companies use a liquid solvent medium. The remaining capture media are distributed among novel approaches including membranes and cryogenic separation. The vast majority of companies use some combination of changes in temperature, vacuum, and electrochemical conditions to regenerate their capture media. Remaining regeneration strategies include novel approaches using moisture, chemical conditions, and plasma. There are several subsets of companies advancing other notable material choices, co-products, and process designs.

Cultivating a diverse global portfolio of DAC technologies may help hedge against the risk of any one approach failing to materialize and provide multiple options that may be better suited to different climatic, environmental, and energetic conditions. Innovations in DAC may also have spillover effects in other fields, just as advances in fields such as materials science or machine learning may instigate advances in DAC. Further research, development, and demonstration support can help provide optionality and realize more benefits from the technology. Regardless of the technical progression of DAC, scaling it will require robust efforts in workforce development, enabling energy and CO_2 transport and storage infrastructure, supply chain management, community engagement, and market development.

Introduction

Objectives

Direct air capture, hereafter referred to as DAC, is an emerging technology that will be an important part of the portfolio of technologies enabling atmospheric carbon dioxide removal (CDR). This report provides a background on the technology, explains potentially required levels of deployment, discusses the U.S. Department of Energy's role in supporting DAC, offers a precise definition of the technology, and provides a list of companies working on DAC with corresponding analysis of trends. The intended audience includes those working in the CDR field as well as anyone generally interested in learning more about the development and status of direct air capture.

History and Context

Anthropogenic, non-photosynthetic removal of carbon dioxide (CO_2) from ambient air was first developed by Dutch inventor Cornelis Jacobszoon Drebbel in the early 1600s to remove exhaled carbon dioxide from the first operational submarines (McKendrick, 2023). In 1999, Klaus Lackner, Hans-Joachim Ziock, and Patrick Grimes at Los Alamos National Laboratory proposed that the approach could be used to address climate change if implemented at scale (Lackner et al., 1999). Since this proposal, research groups and companies around the world have developed a suite of related technologies now known as DAC. Other common phrases used to describe DAC and associated downstream activities include but are not limited to direct air carbon capture (DACC), direct air carbon capture and storage (DACCS), direct air capture and storage (DACS or DAC+S), and, in cases where captured CO_2 is converted to different compound, direct air capture and conversion (DACC) or direct air capture and utilization (DACU).

DAC provides a few key functions for addressing climate change. When life cycle emissions are minimized and captured CO_2 is isolated from the atmosphere for an extended period of time, such as in geologic reservoirs, DAC reduces the atmospheric concentration of CO_2. This could compensate for hard-to-abate sources of emissions to enable net-zero emissions at a lower economy-wide cost (Akimoto et al., 2021), and, upon achievement of global net-negative emissions, lead to a level of global cooling (Tokarska & Zickfeld, 2015).

Carbon dioxide captured from the air can also be processed into a variety of carbon-containing chemicals and fuels that are conventionally manufactured with hydrocarbon resources. Upon combustion or degradation, these chemicals and fuels release atmospheric carbon back into the atmosphere as opposed to fossil carbon, which can reduce overall emissions for these products.

When DAC is paired with long-term carbon storage, it falls under the broader category of CDR, also referred to as negative emissions technologies (NETs) or greenhouse gas removal (GGR). All models that limit global warming to the Paris Agreement-stipulated target of 1.5°C, while minimizing overshoot of climate goals, project the use of both CDR and conventional emissions reduction strategies (IPCC, 2018).

Direct Air Capture Requirements

The exact amount of DAC that will be required in the U.S. and globally by 2050 and throughout the 21st century is uncertain. However, it is possible to derive an order-of-magnitude estimate. Deployment of direct air capture for CO_2 removal will be dictated by the cost and deployment extent of conventional emissions reductions strategies, the competitiveness of DAC with other CDR approaches, and societal willingness to remove historical or "legacy" emissions. DAC deployment requirements for synthesizing carbon-neutral and carbon-negative chemicals and fuels will be dependent on the successful implementation and relative costs of alternative means of decarbonizing these products ranging from electrification to bio-based feedstocks and demand reduction measures.

Outputs from various modeling efforts provide an approximate estimate of DAC needs. The Energy Modeling Forum 37 (EMF 37) study combines the outputs of 16 different climate models using a common set of U.S. decarbonization scenarios. According to the EMF 37 models that include DAC, the U.S. will need to use DAC to capture between approximately one hundred million to two billion tons of CO_2 per year by 2050 to achieve net-zero emissions (Browning, 2023). For reference, current U.S. emissions are over six billion tons of CO_2-equivalent (EPA, 2024).

Many sources, including the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, indicate that tens to hundreds of billions of tons of direct air capture will be required cumulatively across all countries and throughout the 21st century to meet climate targets (IPCC, 2022; Chen & Tavoni, 2013; Realmonte et al., 2019; Smith et al., 2024; Fuhrman et al., 2021; Hanna et al., 2021; Ganti et al., 2024; Victor & Nichols, 2024; Schleussner et al., 2024). Even scenarios that involve aggressive emissions reductions may require billions of tons of annual DAC operation globally to achieve and maintain net-zero and net-negative emissions (Fuhrman et al., 2024).

This level of deployment will require rapid scaling as DAC facilities around the world currently only have a collective gross capture capacity of around 20,000 tons of CO_2 per year. This value is expected to sharply increase soon by around a factor of 25 with the launch of 1PointFive's 500,000-ton-per-year STRATOS facility, which is actively under construction and is expected to begin commercial operation at partial capacity in mid-2025 (McEwen, 2024). Deployment of billions of tons of annual DAC capacity by midcentury is technologically feasible (Caldecott & Johnstone, 2024; Zhang et al., 2024), particularly if DAC deployment increases comparably to other fast-growing technologies such as solar photovoltaics or ammonia synthesis (Edwards et al., 2024; Nemet et al., 2023; Roberts & Nemet, 2024). Large-scale deployment will require corresponding levels of supply chain build-out, workforce development, and resource consumption, all of which necessitate responsible, holistic, and early planning.

Regardless of the specific target, a significant amount of further DAC research and development is required to enable necessary deployment levels and minimize the eventual economic and environmental costs of the technology.

Role of the U.S. Department of Energy

The U.S. Department of Energy's (DOE's) Office of Fossil Energy and Carbon Management (FECM) and National Energy Technology Laboratory (NETL), in close coordination with numerous public and private stakeholders, leverage decades of experience in research and development of point-source carbon capture and storage (CCS) technologies to inform new initiatives centered on DAC. The Carbon Dioxide Removal (CDR) Program within the Office of Carbon Management, in coordination with the Office of Clean Energy Demonstrations (OCED), implements a significant fraction of its base appropriations and funds from the Bipartisan Infrastructure Law, including $3.5 billion for the Regional Direct Air Capture Hub program and $115 million for CDR prize competitions, to support a wide range of DAC research, development, and demonstration (RD&D) efforts. The NETL DAC Center is another key part of DOE's DAC strategy and offers testing and development of lab-scale prototypes, larger modules and components, and small pilot-scale systems to accelerate progress of DAC technology developers (NETL, 2024).

DOE's DAC work spans multiple technology readiness levels (TRLs) and includes materials discovery and testing; integrated bench-scale component development and testing; engineering studies; pilot plant operation; larger-scale demonstrations; life cycle and techno-economic assessment; system and process modeling; commercialization programming; measurement, monitoring, reporting, and verification (MMRV) development; and CDR credit procurement. The CDR Program is committed to taking a holistic and scientifically informed approach to responsibly enabling large-scale carbon dioxide removal in the U.S. by 2050 while simultaneously promoting community benefits and quality job creation.

Definitional Analysis

Existing Definitions

Despite the increasing amount of DAC RD&D (Casaban et al., 2022; Zolfaghari et al., 2022), there are still some inconsistencies in how DAC is precisely defined and how it is differentiated from both CCS and some other forms of CDR. Identifying a clear and science-driven definition of DAC that appropriately encompasses the full suite of technical approaches is important for both market development and policy implementation. For this report, various academic, government, and industry sources were reviewed to determine commonalities across definitions of DAC and arrive at a working definition suitable for technological classification. Definitions and descriptions from 16 review sources are included in Table 1.

Table 1: Definitions and descriptions of direct air capture from selected literature

Definition/Description	Source
"Chemical processes that capture CO_2 from ambient air and concentrate it"	NASEM, 2019
"Extract CO_2 directly from the atmosphere at any location, unlike carbon capture which is generally carried out at the point of emissions"	IEA, 2024
"Capturing CO_2 from ambient air through chemical processes"	de Coninck et al., 2018
"Removing CO_2 directly from the atmosphere, using scrubbers and chemical processes"	FECM, 2023
"Uses carbon capture equipment to capture carbon dioxide directly from the ambient air"	Credit for carbon oxide sequestration, 2022
"Process of capturing CO_2 from open atmospheres, i.e., separating the ultra-dilute CO_2 (today around 420 ppm) over other gases directly from atmospheric air"	Küng et al., 2023
"Capture CO_2 from the air and produce a more concentrated stream of CO_2"	McQueen et al., 2021a
"Capturing carbon dioxide directly from the atmospheric air"	Chowdhury et al., 2023
"Direct extraction of CO_2 from ambient air"	Sanz-Pérez et al., 2016
"Process that captures CO_2 directly from air"	Zeeshan et al., 2023
"Extract CO_2 directly from ambient air…can be used to capture CO_2 emissions unrelated to its source and time"	Jiang et al., 2023
"Direct removal of CO_2 from the atmosphere…independent of CO_2 emission origin"	Sodiq et al., 2023

Definition/Description	Source
"Capture CO_2 directly from the air"	Keith et al., 2006
"A system in which ambient air flows over a chemical sorbent that selectively removes the CO_2. The CO_2 is then released as a concentrated stream for disposal or reuse, while the sorbent is regenerated and the CO_2-depleted air is returned to the atmosphere"	Socolow et al., 2011
"Process of chemically scrubbing carbon dioxide directly from the air"	Lebling, 2020
"Extract CO_2 directly from the ambient atmosphere"	Direct Air Capture Coalition, n.d.

For further context, the language contained in Section 45Q of the Internal Revenue Code references "carbon capture equipment," which is further defined in 26 CFR § 1.45Q-2(c)(2) as generally inclusive of "components of property necessary to compress, treat, process, liquefy, pump or perform some other physical action to capture qualified carbon oxide" (Definitions for Purposes of §§ 1.45Q-1 through 1.45Q-5, 2021).

Full Definition of DAC and Distinctions

Based on these definitions and further analysis, this report defines DAC as follows:

Direct air capture is a technology that regenerates a capture medium in a closed loop and/or uses a mechanical air contactor to chemically or physically separate carbon dioxide directly from the outdoor or indoor ambient atmosphere without reliance on above-average carbon dioxide concentrations caused by nearby point sources of emissions.

The proposed definition intentionally excludes separation from flue gases and industrial process gases as well as a fundamental dependence on siting close to sources of these gases. Capture in these cases would be characterized as point-source capture (PSC). Also excluded is the direct use of photosynthesis or other biological processes for atmospheric CO_2 uptake, which could result in the process being characterized as biomass carbon removal and storage (BiCRS) or perhaps a biological form of aquatic CDR. The focus on atmospheric removal and the use of regenerable capture media in a closed loop is also necessary to separate DAC from aquatic CDR processes that involve CO_2 removal from the hydrosphere in a manner that depends on natural air–water gas exchange.

Enhanced mineralization (EM) processes, such as cropland or coastal enhanced rock weathering (ERW), may share some similarities with DAC in terms of chemical reactions. However, such processes do not regenerate their capture media in a closed loop nor do they utilize mechanical air contactors. There are some passive DAC technology designs that do not make use of traditional air contactors and may passively carbonate sorbents on the ground, but these processes can be characterized as DAC if they treat the sorbent as a regenerable capture medium and process it to produce a more concentrated stream of CO_2.

There are some hybrid approaches that couple DAC with other carbon management technologies. For instance, DAC can share infrastructure with point-source carbon capture (McQueen et al., 2021b) and can be powered by bioenergy with carbon capture and storage to enable additional negative emissions (Sagues et al., 2019). Additionally, some DAC processes may choose to produce concentrated CO_2 for use in separate carbon conversion systems to produce low-carbon fuels or chemicals.

General Categories of DAC

There are three general categories of DAC technologies that qualify under the DAC definition proposed here. These categories, described below, are used to differentiate companies in the company analysis section and may be relevant when comparing DAC to CO_2 conversion and enhanced mineralization processes.

1. CO_2-Concentrating DAC

CO_2-concentrating DAC technologies separate CO_2 from ambient air and produce a more concentrated stream of CO_2 for subsequent use, conversion, or storage. Such processes are the most common and unambiguous form of direct air capture. These processes most often aim to capture CO_2 from outdoor air, although some aim to capture CO_2 from indoor air where occupant exhalation can lead to CO_2 concentrations in the thousands of parts per million (Persily et al., 2022).

2. Reactive DAC

Reactive carbon capture or reactive CO_2 capture (Deutsch, 2021) processes involve separation of CO_2 from a stream and its conversion into a valuable product in one integrated step. Reactive DAC therefore involves the separation of CO_2 from ambient air with a regenerable capture medium that, upon regeneration, converts the captured CO_2 into a different chemical product like methane, methanol, and carbon monoxide (Zanatta, 2023). Processes using regenerable capture media to produce carbonate products—being deployed by companies like Alithic, Carbon To Stone, and EDAC Labs—are also included in this category in this report. Reactive capture processes often make use of dual-function materials (Omodolor et al., 2020) that capture and convert CO_2, and they may require hydrogen or other inputs to enable product synthesis.

3. Direct Storage DAC

Direct storage DAC technologies cover a range of processes that involve mechanical air contactors, chemical capture media selective to carbon dioxide, and other elements traditionally associated with DAC but that do not directly regenerate their capture media. These processes involve the production of carbonates or other durable compounds that can either be sold or directly disposed of for long-term storage of captured CO_2. While the production of valuable products could result in a definitional overlap with reactive DAC, direct storage DAC processes do not employ regenerable capture media and therefore generally require continuous addition of other capture-enabling feedstocks.

Often, these feedstocks are alkaline in nature and are necessary for continued carbonation or to manage acidic stream production inherent to the processes that could, if mismanaged, undo emissions benefits or otherwise cause environmental harm. As these feedstocks may have naturally participated in the carbon cycle on a longer time horizon if not used in these processes, it may be the case that these systems could also be considered as enhanced mineralization.

Company Lists

With billions of dollars of private capital invested in DAC to date (Underwood et al., 2024), many companies around the world are developing a wide range of DAC technologies. A benchmarking of global DAC companies was undertaken for this report to establish a baseline list and conduct trend analysis.

To qualify as a DAC company for the purposes of this report, the company **must be**:

- Developing a technology system to perform direct air capture as defined by this report; and
- A for-profit business incorporated as a Limited Liability Company, an S corporation, a C corporation, a public benefit corporation, or an equivalent business structure that requires registration or incorporation.

The company **must not be**:

- Developing only one component—such as a fan, air contactor, sorbent, etc.—of a DAC technology system;
- A sole proprietorship, a partnership, or an equivalent business structure that does not require registration or incorporation;
- A governmental entity, such as a federally funded research and development center (FFRDC);
- A university research group or student team;
- A testing center;
- A nonprofit;
- Exclusively an investor in DAC companies;
- Exclusively a DAC project developer;
- Exclusively a carbon credit marketplace or reseller; or
- Exclusively engaging in biological or photosynthetic capture/BiCRS, ERW, PSC, aquatic CDR, carbon transport or storage, or carbon conversion or utilization without an integrated/reactive DAC unit operation.

DAC does not have to be a company's primary line of business for it to be included. Companies intending to license or manufacture their DAC technology system in lieu of managing both technology and project development are also included.

Table 2 lists CO_2-concentrating DAC companies, **Table 3** lists reactive DAC companies, and **Table 4** lists direct storage DAC companies. As available and applicable, each company is listed with the location of its headquarters, its capture medium type, and further notes about its approach. CO_2-concentrating and reactive DAC companies are listed with their regeneration method. All data is sourced only from publicly accessible sources at the time of writing. When used throughout the tables, "N/A" indicates that the data for that cell is not publicly available or accessible.

Inclusion in this report or under the provided definitions does not (a) constitute endorsement; (b) imply eligibility for tax credits under Section 45Q, which is determined on a case-by-case basis by the Internal Revenue Service; or (c) establish eligibility for any DOE funding opportunity.

Table 2: CO_2-concentrating DAC company list and technology notes

Company Name	HQ Location	Capture Medium Type	Regeneration Method	Other Notes
280 Earth	U.S.	Solid	Temperature and vacuum	Can use data center waste heat; sorbent circulation design
8 Rivers	U.S.	Solid	Temperature	Calcium oxide sorbent
ADNOC	UAE	N/A	N/A	N/A
Advanced Cooling Technologies	U.S.	Solid	Temperature or electrochemical	Commercial adsorbent resin enabling acid/base ion-exchange process
Aeon Blue	Canada	Liquid	Electrochemical	Integrated e-fuel production
Aetherworks	U.S.	N/A	N/A	For use in greenhouse applications
Air to Earth	U.S.	Solid	Temperature and vacuum	Porous polymer network sorbents
Air View Engineering	UK	Solid	Temperature and vacuum	Sorbent circulation design
Airbus	The Netherlands	Solid	Temperature	Based on use in space and on submarines
Aircapture	U.S.	Solid	Temperature and vacuum	Polymeric amine sorbent
Aircela	U.S.	Liquid	Electrochemical	Potassium hydroxide solvent; integrated conversion to methanol or fuels
Airhive	UK	Solid	Temperature	Fluidized metal oxide sorbents; sorbent circulation design
AirMyne	U.S.	Liquid	Temperature	Low-temperature liquid process
Aramco	Saudi Arabia	N/A	N/A	N/A
Arbon	U.S.	Solid	Moisture	Short cycle times
AspiraDAC	Australia	Solid	Temperature and vacuum	Metal organic framework (MOF) sorbent

Company Name	HQ Location	Capture Medium Type	Regeneration Method	Other Notes
Atmosfuture	UK	(No capture medium)	Temperature (cryogenic)	Use liquid nitrogen to separate components of ambient air
Atoco	U.S.	Solid	Temperature	Reticular materials (MOFs and covalent organic frameworks)
Avnos	U.S.	Solid	Moisture and vacuum	Co-production of water
C-Fix	U.S.	Solid	Electrochemical	N/A
Captur Tower	Spain	N/A	Temperature	Can use cooling tower waste heat
Carbominer	Ukraine	Solid	Electrochemical	Passive system; transfers sorbent to solvent before regeneration
Carbon 1.5	France	Solid	N/A	Can deploy at high altitudes
Carbon Blade	U.S.	Liquid	Electrochemical	Passive system with integrated wind turbines
Carbon Capture & Commercialization	U.S.	Solid	Temperature	N/A
Carbon Collect	Ireland	Solid	Temperature and vacuum or moisture	Passive system
Carbon Engineering	U.S.	Liquid	Temperature	Potassium hydroxide solvent
Carbon Reform	U.S.	Solid	N/A	Applied to indoor HVAC systems; calcium oxide sorbent
Carbon Utility	U.S.	Liquid	Electrochemical	Co-production of hydrogen
CarbonAir Energy	Brazil	Solid	N/A	N/A
CarbonCapture Inc.	U.S.	Solid	Temperature and vacuum	Modular open systems architecture suitable for different sorbents
Carbyon	The Netherlands	Membrane	Temperature	Low cycle times with modified fiber membranes
CarpeCarbon	Italy	N/A	N/A	Can integrate with mineralization processes
China Energy Engineering Corporation	China	N/A	N/A	N/A

Company Name	HQ Location	Capture Medium Type	Regeneration Method	Other Notes
Clairity Technology	U.S.	Solid	Temperature	Alkali carbonate sorbent on monoliths
CleanCapture Tech	U.S.	Solid	Temperature	Solid sorbent with novel plate-and-frame heat exchanger design
Climeworks	Switzerland	Solid	Temperature and vacuum	Amine-based structured sorbents
CO_2CirculAir	The Netherlands	Membrane	Electrochemical	Passive system
CtrlZ Climate	U.S.	N/A	N/A	Decentralized system
DAC City	U.S.	Solid	Moisture and temperature	Porous carbon composite ceramic monoliths; targeting CO_2 utilizers
DACLab	U.S.	Solid	Temperature	Focus on mass manufacturable equipment
DACMA GmbH	Germany	Solid	Temperature and vacuum	N/A
Decarbon	U.S.	Solid	Temperature	MOF sorbent
DeCarbon Tech	China	Solid	N/A	N/A
Direct Carbon	Sweden	N/A	N/A	Distributed systems targeting CO_2 utilizers
E-quester	Canada	Liquid	Electrochemical	Electrochemically generate hydrochloric acid to regenerate calcium carbonate
Equinor	UK	Liquid	N/A	Amine-based liquid solvent
ExxonMobil	U.S.	Solid	N/A	N/A
Feather Fuels	U.S.	N/A	N/A	Integrated e-fuel production
Flow Aluminum	U.S.	Liquid	Electrochemical	Process integrated in aluminum–CO_2 battery
Freshean	U.S.	Solid	N/A	Aimed at indoor applications
Fugu	Australia	Solid	Temperature	Zeolite sorbent
Gaia Refinery	Canada	Liquid	Chemical	Integrated BiCRS and DAC system

Company Name	HQ Location	Capture Medium Type	Regeneration Method	Other Notes
GE Vernova	U.S.	Solid	Temperature and vacuum	MOF sorbent and unique thermal management design
GigaDAC/Victory Over Carbon	U.S.	Liquid	N/A	Unique spray-based, hollow air contactor design
Giner	U.S.	Liquid	Electrochemical	Potassium hydroxide solvent with carbonate electrolyzer
Global Thermostat	U.S.	Solid	Temperature and vacuum	Sorbent embedded on monolith
GreenCap Solutions	Norway	Solid	Temperature	Zeolite sorbent
Greenlyte Carbon Technologies	Germany	Liquid	Electrochemical	Electrochemical regeneration; co-production of hydrogen
Heimdal	U.S.	Solid	Temperature	Calcium oxide sorbent
Heirloom	U.S.	Solid	Temperature	Calcium oxide sorbent
High Hopes Labs	Israel	(No capture medium)	Temperature (cryogenic)	Super-high-altitude cryogenic approach with balloons
Holocene	U.S.	Liquid	Temperature	Low-temperature liquid process
Honda	Japan	N/A	N/A	N/A
Hydrocell	Finland	Solid	Temperature and vacuum	Adapted for indoor CO_2 purification
InnoSepra	U.S.	Solid	Temperature	May use air feed moisture removal
Ionada	Canada	Membrane	Temperature and vacuum	Hollow fiber membrane contactor reactor with solvent
Jeevan Climate Solutions	U.S.	Solid	Temperature	Amine sorbents with copper
Kanata	Canada	N/A	Temperature	Being developed with combined heat and power
Kawasaki	Japan	Solid	Temperature and vacuum	Amine-impregnated sorbent
Krajete/Audi	Austria	Solid	Temperature and vacuum	Inorganic sorbent with high loading

Company Name	HQ Location	Capture Medium Type	Regeneration Method	Other Notes
Linhe Climate Science & Technology	China	Solid	Moisture	Use ion exchange resin
LowCarbon	South Korea	N/A	N/A	N/A
Mission Zero	UK	Liquid	Electrochemical	Can integrate with intermittent renewables
Mosaic Materials	U.S.	Solid	Temperature and vacuum	MOF sorbent
MOVA Technologies	U.S.	N/A	N/A	Deployable for indoor farming
NEG8 Carbon	Ireland	Solid	Temperature and vacuum	Modular stackable system
NeoCarbon	Germany	Solid	Temperature and vacuum	Monolith reactor with hollow fibers; focus on using waste heat
Noya	U.S.	Solid	Temperature and vacuum	Sorbent on monolith design
NuAria	U.S.	Solid	N/A	Inorganic salt sorbent fabricated in wound membranes
Nūxsen	U.S.	Solid	N/A	N/A
OBRIST Group	Austria	Liquid	Electrochemical	Sodium hydroxide solvent; integrated methanol production
Octavia Carbon	Kenya	Solid	Temperature and vacuum	Amine sorbent
Orbital Materials	UK	Solid	Temperature	Can be integrated with data centers
Origen	UK	Solid	Temperature	Calcium oxide sorbent with oxy-fueled flash calciner
Parallel Carbon	U.S.	Solid	Electrochemical	Hydrogen co-production and can integrate with intermittent renewables
Phlair	Germany	Liquid	Electrochemical	Can integrate with intermittent renewables
Planet Savers	Japan	Solid	Temperature or vacuum	Zeolite sorbent
Porsche/Volkswagen	Germany	Solid	Temperature	Integrated with fuel production

Company Name	HQ Location	Capture Medium Type	Regeneration Method	Other Notes
Precision Combustion	U.S.	Solid	Temperature	Nanostructured engineered sorbent; targeting waste heat
Provocative	U.S.	N/A	N/A	Can use data center waste heat
RedoxNRG	Estonia	Membrane	Electrochemical	Integrated with conversion to formic acid
Removr	Norway	Solid	Temperature	Zeolite sorbent; dehydrate feed air with silica gel
RepAir	Israel	Membrane	Electrochemical	Identical electrodes separated with selective membrane
Rivan Industries	UK	Solid	Temperature	Calcium oxide sorbent; integrated with conversion to methane
SCW Systems	The Netherlands	N/A	N/A	Modular system requiring only electrical input
Shell	U.S.	Solid	Temperature	Sorbent on honeycomb monolith; mobile steam delivery
Sirona Technologies	Belgium	Solid	Temperature and vacuum	N/A
Skyrenu	Canada	Solid	Temperature	Amine sorbent on monolith; targeting integration with mine tailing carbonation
Skytree	The Netherlands	Solid	Temperature and vacuum	Suitable for small utilizers and larger industrial applications
SkyVac	U.S.	Solid	N/A	Molecular sieve for capture; integrated with conversion to methane
Soletair Power	Finland	Solid	Temperature and vacuum	Applied to indoor HVAC systems; amine sorbent
Sosna Metelyk	U.S.	(No capture medium)	Temperature (cryogenic)	Cryogenic approach freezing CO_2 from air
South Ocean Air	U.S.	Solid	Moisture	Uses altered cellulose sorbent; option to not regenerate and store

Company Name	HQ Location	Capture Medium Type	Regeneration Method	Other Notes
Southern Green Gas	Australia	Solid	Temperature and vacuum	MOF sorbents and potential integration with methane synthesis
Spiritus	U.S.	Solid	Temperature	Passive system; sorbent circulation design
Stathmos	France	Solid	Temperature	N/A
Sustaera	U.S.	Solid	Temperature	Utilizing structured materials assemblies and testing resistive heating
Synergetic	U.S.	N/A	N/A	Converting CO_2 into syngas for circular fuel production
TerraFixing	Canada	Solid	Temperature and vacuum	Use zeolites and intend to operate in cold, dry climates; dehydrate feed air with desiccant
Terraform Industries	U.S.	Solid	Temperature	Calcium oxide sorbent; integrated with conversion to methane
UAP	UK	N/A	N/A	Also removes greenhouse gases other than CO_2
Ucaneo	Germany	Liquid	Electrochemical	Leveraging bicarbonates in solvent
Unemit	U.S.	Solid	Temperature	N/A
UrjanovaC	India	N/A	N/A	Requires presence of water for capture
Valiidun	U.S.	N/A	N/A	N/A
Verdox	U.S.	Membrane	Electrochemical	Quinone chemistry allowing voltage-based method
WindCapture Technologies	Ireland	Solid	Temperature and vacuum	Self-powered system with sorbent on wind turbine
x/44	U.S.	Liquid	Electrochemical	Co-production of hydrogen
Yama	France	Liquid	Temperature and electrochemical	Hybrid electrochemical and thermal process
ZeoDAC	U.S.	Solid	Temperature	Pure zeolite sorbents and co-production of water

Table 3: Reactive DAC company list and technology notes

Company Name	HQ Location	Capture Medium Type	Regeneration Method	Other Notes
Advanced Energy Materials	U.S.	Solid	Plasma	Reactive capture to methanol
Aerleum	France	Solid	Temperature	Reactive capture to methanol
Alithic	U.S.	Liquid	Chemical	Reactive capture to supplementary cementitious material; cycling sodium hydroxide
Carbon Corp	U.S.	Liquid	Electrochemical	Reactive capture to solid carbon
Carbon To Stone	U.S.	Liquid	Chemical	Reactive capture to carbonates with potential for critical mineral recovery; cycling solvent
Carbon Xtract	Japan	Membrane	Temperature or electrochemical	Reactive capture to carbon monoxide, methane, etc.
Climatech Environment	India	Liquid	N/A	Reactive capture to solid carbon
EDAC Labs	U.S.	Liquid	Chemical	Reactive capture to carbonates; cycling sodium hydroxide
Homeostasis	U.S.	Liquid	Electrochemical	Reactive capture to solid carbon
Prometheus Fuels	U.S.	Liquid	Electrochemical	Reactive capture to hydrocarbons
Sora Fuel	U.S.	Liquid	Electrochemical	Reactive capture to syngas in liquid bicarbonate electrolyzer
SpiralWave	U.S.	N/A	Plasma	Reactive capture to methanol
Susteon	U.S.	Solid	Temperature	Reactive capture to methane

Table 4: Direct storage DAC company list and technology notes

Company Name	HQ Location	Capture Medium Type	Other Notes
BluSky Carbon	Canada	N/A	Powered by surplus energy from integrated biomass pyrolysis
Capture6	U.S.	Liquid	Can integrate with brine and wastewater processes
Carbon Energy	South Korea	N/A	Leverages electrochemistry to produce solid carbonates
Equatic	U.S.	Liquid	Generated (bi)carbonates deposited in ocean
Holy Grail	U.S.	Liquid	Targeting aboveground carbonate storage
Karbonetiq	U.S.	Solid	Passive alkaline feedstock aeration contactor enabling carbonation
Thalo Labs	U.S.	Solid	Capture from indoor air; storing directly in solid medium
Travertine	U.S.	Liquid	Co-production of critical minerals, hydrogen, and sulfuric acid

Analysis

Company Totals and Co-Products

Across the three DAC technology categories outlined in this report, there are 142 distinct companies. These companies include 121 CO_2-concentrating DAC companies, 13 reactive DAC companies, and 8 direct storage DAC companies engaging in processes that chemically separate CO_2 from ambient air using mechanical air contactors but without regeneration of a capture medium.

Emerging industries are often fragmented and experience increasing consolidation over time (Deans et al., 2002) due to factors like increasing capital requirements and enhanced dependence on economies of scale for cost competition. Therefore, while DAC and the broader CDR industry are growing rapidly (CDR.fyi, 2024), it can be expected that the overall number of companies will decrease over the long run as firms exit the market due to bankruptcies, managed dissolutions, and mergers and acquisitions (M&A). The DAC industry has already had several instances of M&A, including Climeworks' acquisition of Antecy, Baker Hughes' acquisition of Mosaic Materials, Occidental Petroleum's acquisition of Carbon Engineering, Zero Carbon Systems' acquisition of Global Thermostat, and Skytree's acquisition of ReCarbn. Continued consolidation could eventually result in a dramatically smaller number of larger DAC incumbents compared to the number of DAC companies in existence today.

Several companies classified as having CO_2-concentrating processes—including Aeon Blue, Aircela, Feather Fuels, OBRIST Group, Porsche/Volkswagen, RedoxNRG, Rivan Industries, Skyvac, Southern Green Gas, Synergetic, and Terraform Industries—have expressed intent to integrate their DAC processes exclusively with CO_2 conversion into low-carbon fuels and chemicals. Based on some definitions, these companies may be better characterized in the reactive carbon capture category despite seemingly still producing intermediate, concentrated streams of CO_2.

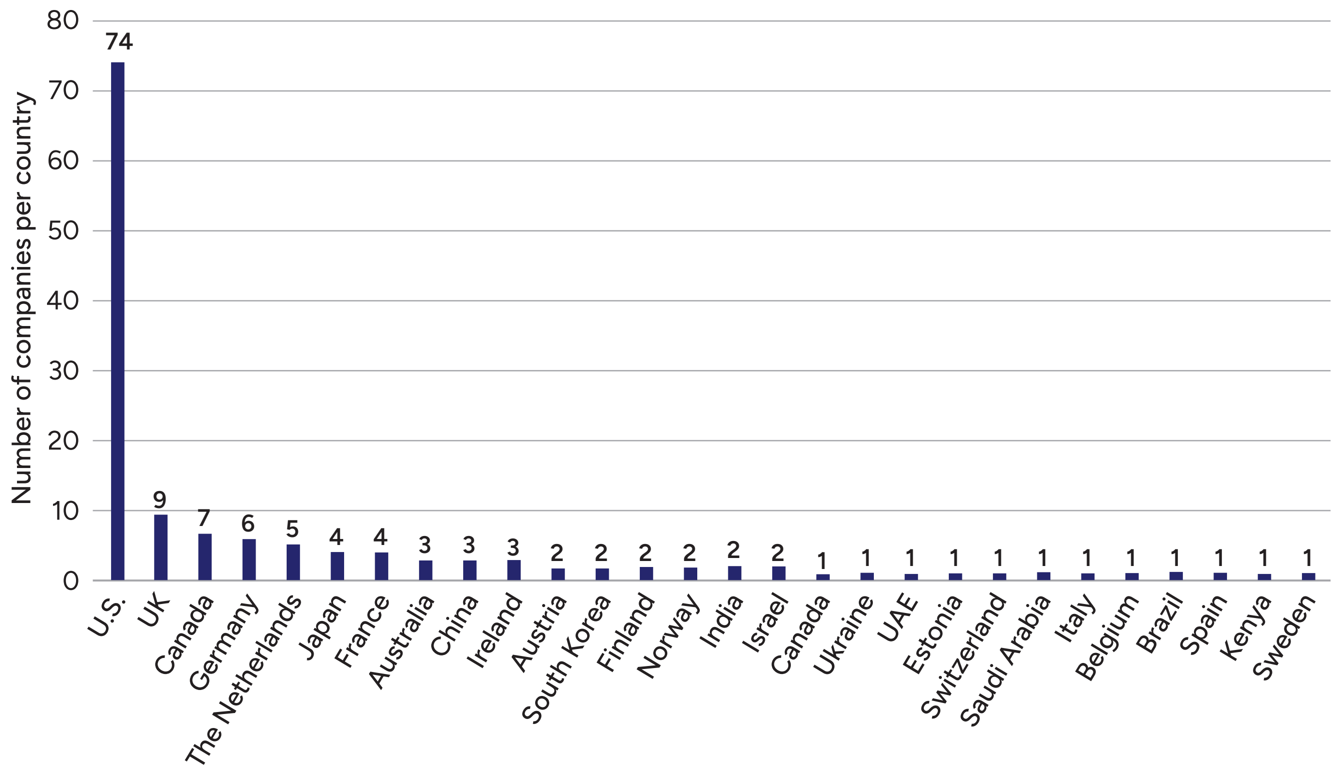
While most DAC companies primarily focus on capturing and storing CO_2 to generate compensatory emissions credits, a handful of companies have co-products like water, hydrogen, and even critical minerals that could provide additional revenue and potentially other co-benefits. While generation of valuable co-products could bolster project returns or subsidize DAC costs, it could also increase deployment complexity or result in siting and thus performance constraints.

While water is often co-adsorbed by and then desorbed from solid sorbents along with CO_2, only Avnos and ZeoDAC explicitly note a desire to directly collect potable water for sale. Four DAC companies with electrochemical regeneration methods including Carbon Utility, Greenlyte Carbon Technologies, Parallel Carbon, and x/44 appear to intend on co-producing electrolytic hydrogen with CO_2, which could be sold directly for use or perhaps used in tandem with captured CO_2 to manufacture low-carbon fuels and chemicals. Each reactive DAC company by definition generates products other than concentrated CO_2, but these are primary products rather than co-products.

Geographies

In terms of geographic distribution, over half of all DAC companies have their headquarters located in North America as shown in **Figure 1**. This may be a function of the favorable policy environment for DAC in the U.S. and Canada (De Luna, 2024) along with the countries' ample resources that could support deployment (Pett-Ridge et al., 2023). Many DAC companies outside of North America are clustered in Western Europe, which may also be partially a function of a relatively favorable policy climate for carbon removal in the EU (European Parliament and Council, 2024). Several exceptions exist, however, resulting in DAC companies being headquartered on every continent except Antarctica.

Figure 1: Global distribution of DAC companies



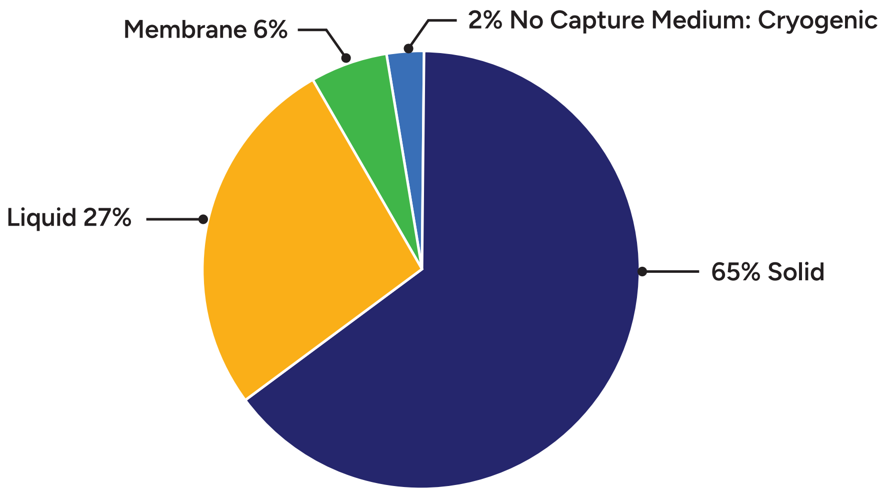
Different DAC technologies fare better under variable climatic conditions, and different approaches are more compatible with different forms of low-carbon energy or ultimate storage or conversion options. The inherent diversity of DAC systems naturally lends itself to a degree of global deployment, and experimentation in different climates and geographies is likely required to develop an economically, environmentally, and socially optimal DAC deployment strategy. Depending on the development of international carbon credit trading markets, commercializing DAC technologies suitable for deployment in a range of climates may also be necessary to allow more countries to use DAC to meet climate targets.

Capture Media

As shown in **Figure 2**, around two-thirds of DAC companies employ a solid sorbent as their capture medium. This data covers all DAC companies identified for this report except for 22 companies for whom this data was not publicly available. While Carbon Engineering's liquid approach is the most developed and analyzed solvent system to date, there are many other liquid solvent companies piloting different, and largely electrochemical, approaches.

Separately, a handful of companies are using membranes, which are technically in a solid phase but can be categorized differently from solid sorbents (Wilcox, 2012). These companies include Carbyon, CO_2CirculAir, Ionada, RedoxNRG, RepAir, Verdox, and Carbon Xtract. Only three companies—Atmosfuture, High Hopes Labs and Sosna Metelyk—intend to use cryogenic approaches that do not appear to involve a specific capture medium but would still produce more concentrated streams of CO_2.

Figure 2: Distinct types of capture media used by DAC companies



A significant amount of solid sorbent DAC work has focused on solid amine chemisorbents on a variety of supports (Erans et al., 2022). A separate-but-notable category of solid sorbents involves porous crystalline materials—which may or may not be aminated when used for DAC—including metal organic frameworks (MOFs), covalent organic frameworks (COFs), and zeolites. Of every DAC company identified for this report, Atoco was the only one that appeared to have an interest in using both MOFs and COFs for DAC (Atoco, 2023). Companies intending to primarily use MOFs include AspiraDAC, Decarbon, GE Vernova, Mosaic Materials, and Southern Green Gas. Six companies noted an intended use of zeolites as the capture medium including Fugu, GreenCap Solutions, Planet Savers, Removr, TerraFixing, and ZeoDAC.

Significant efforts are underway to use machine learning to discover new MOFs and other materials that may have superior performance for DAC, but various challenges remain (Sriram et al., 2024). Specific solid sorbent form factors—such as pellets, laminate sheets, monoliths, fiber mats, etc.—are not discussed here but are also highly relevant to DAC innovation as they influence key parameters such as pressure drop, water co-adsorption, and desorption heating strategies.

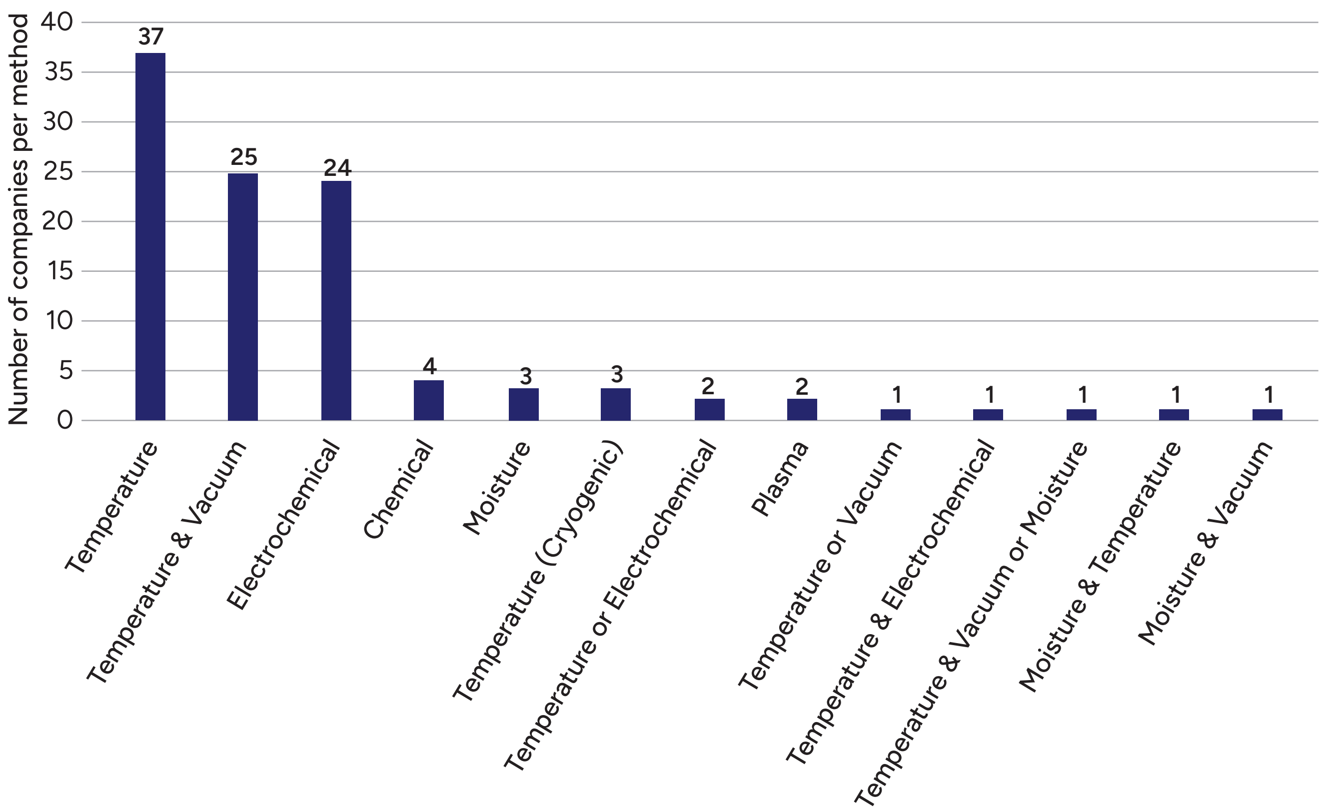
Regeneration Methods

Of the 134 DAC companies identified for this report making use of regenerable capture media, which excludes direct storage DAC processes, 105 had discernible, public data regarding regeneration methods. **Figure 3** shows a breakdown of companies using each regeneration method. Full information about vacuum swings is not always apparent when evaluating publicly available DAC company data, so it is likely that some of the apparently temperature-only companies are actually using both temperature and vacuum swings.

Notably, around one quarter of the companies sharing regeneration data intend to use electrochemical regeneration. Mission Zero, Parallel Carbon, and Phlair all explicitly note potential cost and environmental benefits from integrating their electrochemical DAC systems with intermittent renewable electricity. These benefits theoretically derive from the ability to oversize certain, energy-intensive parts of the system and then ramp these unit operations up and down quickly to leverage availability of and thus low prices for variable renewable resources.

Only six companies intend on using some form of direct moisture or humidity swing, sometimes combined with other methods: Arbon, Avnos, Carbon Collect, DAC City, Linhe Climate Science & Technology, and South Ocean Air. Companies using steam as a heat delivery mechanism are included under temperature-swing and not moisture-swing processes.

Figure 3: Different regeneration methods used by DAC companies



As with capture media, testing and developing a wide variety of regeneration methods can aid the discovery and implementation of advantageous DAC process designs under varying climatic and technological conditions (An et al., 2023). Controlling these conditions carefully is vital for optimizing adsorption, desorption, degradation, and other process parameters that contribute to the overall cost of removal. Additionally, these regeneration methods can be delivered and implemented in diverse ways depending on the form factor and system design. Processes using the same regeneration method could still manifest in materially different ways.

Process Designs

The vast majority of DAC systems are active or motive, meaning they make use of fans to move ample amounts of ambient air through the system and overcome the pressure drop generated by the system, both of which could decrease cycle times and therefore increase the capital utilization of the systems. However, a small handful of companies are piloting passive approaches to use natural wind patterns to reduce energy and equipment costs related to fan use. Identified companies that intend to use passive systems include Carbominer, Carbon Blade, Carbon Collect, CO_2CirculAir, Karbonetiq, and Spiritus. Cryogenic DAC processes could also be considered as passive depending on their implementation.

While DAC solvents are generally pumped between absorption and desorption phases, many solid sorbents remain in a fixed location that is sealed from ambient air before desorption occurs. However, at least four identified companies including 280 Earth, Air View Engineering, Airhive, and Spiritus intend to circulate solid sorbent materials between adsorption and desorption steps, possibly to reduce thermal losses from repeated heating and cooling of contactor structures and thus reduce energy-related costs and emissions. For such processes, optimization is needed to balance sorbent circulation costs with energy savings.

Finally, DAC can be integrated in the built environment in a way that could take advantage of existing heating, ventilation, and air conditioning equipment to reduce costs and potentially improve indoor air quality (Baus & Nehr, 2022). Six DAC companies including Carbon Reform, Freshean, Hydrocell, MOVA Technologies, Soletair Power, and Thalo Labs are working on such systems. Desorption with low-carbon energy and subsequent conditioning, compression, and transportation of captured CO_2 could be difficult in a decentralized environment, although it may be possible to decouple these processes from the capture step by collecting saturated sorbent materials for desorption elsewhere or perhaps for direct use as aggregates.

Conclusion

The precise and comprehensive definition of direct air capture laid out in this report enables clearer analysis of companies working on the technology and corresponding trends. This analysis in turn enables deeper insight into the progress of DAC and potential interventions that could enhance or hasten its deployment.

One key takeaway from evaluating the landscape of existing DAC companies is their geographic and technological diversity. This variety is notable given that the processes all have the same ultimate function of removing CO_2 from the ambient air. At a portfolio level, this diversity may help hedge against the risk of any one company or approach not materializing. It may also provide optionality across geographies, which could ultimately allow a larger number of regions and countries to receive associated economic and environmental benefits from implementing DAC.

Scaling DAC requires advances in science, engineering, workforce development, supply chains, community engagement efforts, and market development. Having access to low-carbon energy and CO_2 transport, storage, and conversion infrastructure is also fundamental for enabling rollout of the technology. Further RD&D support attuned to the research and company landscape can continue to enable the robust and responsible development of DAC.

References

Akimoto, K., Sano, F., Oda, J., Kanaboshi, H., & Nakano, Y. (2021). Climate change mitigation measures for global net-zero emissions and the roles of CO_2 capture and utilization and direct air capture. *Energy and Climate Change*, 2, 100057.

An, K., Li, K., Yang, C. M., Brechtl, J., & Nawaz, K. (2023). A comprehensive review on regeneration strategies for direct air capture. *Journal of CO_2 Utilization, 76,* 102587.

Atoco. (2023). Closing in on carbon capture.

Baus, L., & Nehr, S. (2022). Potentials and limitations of direct air capturing in the built environment. *Building and Environment*, 208, 108629.

Browning, M., McFarland, J., Bistline, J., Boyd, G., Muratori, M., Binsted, M., ... & Weyant, J. (2023). Net-zero CO_2 by 2050 scenarios for the United States in the energy modeling forum 37 study. *Energy and Climate Change,* 4, 100104.

Caldecott, B., & Johnstone, I. (2024). The Carbon Removal Budget: theory and practice. *Carbon Management*, 15(1), 2374515.

Casaban, D., Ritchie, S., & Tsalaporta, E. (2022). The impact of Direct Air Capture during the last two decades: A bibliometric analysis of the scientific research, part I. *Sustainable Chemistry for Climate Action, 1*, 100009.

CDR.fyi. (2024). 2024 Q2 Durable CDR Market Update - Microsoft: Market-Maker.

Chen, C., & Tavoni, M. (2013). Direct air capture of CO_2 and climate stabilization: a model based assessment. *Climatic Change*, 118, 59–72.

Chowdhury, S., Kumar, Y., Shrivastava, S., Patel, S. K., & Sangwai, J. S. (2023). A review on the recent scientific and commercial progress on the direct air capture technology to manage atmospheric CO_2 concentrations and future perspectives. *Energy & Fuels*, 37(15), 10733–10757.

Credit for carbon oxide sequestration, 26 U.S.C. § 45Q (2022).

de Coninck, H., Revi, A., Babiker, M., Bertoldi, P., Buckeridge, M., Cartwright, A., ... & Wollenberg, L. (2018). Strengthening and Implementing the Global Response. *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty,* 313–444. Cambridge University Press.

De Luna, P. (2024, September 4). How U.S. And Canadian Government Direct Air Capture Incentives Compare. *Forbes*.

Deans, G. K., Kroeger, F., & Zeisel, S. (2022). The Consolidation Curve. Harvard Business Review.

Definitions for Purposes of §§ 1.45Q-1 through 1.45Q-5, 26 C. F. R. § 1.45Q-2 (2021).

Deutsch, T. G., Baker, S., Agbo, P., Kauffman, D. R., Vickers, J., & Schaidle, J. A. (2021). Summary Report of the Reactive CO_2 Capture: Process Integration for the New Carbon Economy Workshop, February 18-19, 2020 (No. NREL/TP-5100-78466). National Renewable Energy Laboratory.

Direct Air Capture Coalition. (n.d.). Frequently Asked Questions.

Edwards, M. R., Thomas, Z. H., Nemet, G. F., Rathod, S., Greene, J., Surana, K., ... & McJeon, H. C. (2024). Modeling direct air carbon capture and storage in a 1.5° C climate future using historical analogs. *Proceedings of the National Academy of Sciences*, 121(20), e2215679121.

EPA. (2024). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2022 (No. EPA 430-R-24-004). U.S. Environmental Protection Agency.

Erans, M., Sanz-Pérez, E. S., Hanak, D. P., Clulow, Z., Reiner, D. M., & Mutch, G. A. (2022). Direct air capture: process technology, techno-economic and socio-political challenges. *Energy & Environmental Science*, 15(4), 1360–1405.

European Parliament and Council. (2024). Proposal for a Regulation of the European Parliament and of the Council establishing a Union certification framework for permanent carbon removals, carbon farming and carbon storage in products.

FECM. (2023). Carbon Dioxide Removal Factsheet.

Fuhrman, J., Clarens, A., Calvin, K., Doney, S. C., Edmonds, J. A., O'Rourke, P., ... & McJeon, H. (2021). The role of direct air capture and negative emissions technologies in the shared socioeconomic pathways towards +1.5 °C and +2 °C futures. *Environmental Research Letters*, 16(11), 114012.

Fuhrman, J., Speizer, S., O'Rourke, P., Peters, G. P., McJeon, H., Monteith, S., ... & Wang, F. M. (2024). Ambitious efforts on residual emissions can reduce CO_2 removal and lower peak temperatures in a net-zero future. *Environmental Research Letters*, 19(6), 064012.

Ganti, G., Gasser, T., Bui, M., Geden, O., Lamb, W. F., Minx, J. C., ... & Gidden, M. J. (2024). Evaluating the near- and long-term role of carbon dioxide removal in meeting global climate objectives. *Communications Earth & Environment*, 5(1), 377.

Hanna, R., Abdulla, A., Xu, Y., & Victor, D. G. (2021). Emergency deployment of direct air capture as a response to the climate crisis. *Nature Communications*, 12(1), 368.

IEA. (2024). Direct Air Capture.

IPCC. (2018). Summary for Policymakers. Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P. R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J. B. R., Chen, Y., Zhou, X., Gomis, M. I., Lonnoy, E., Maycock, T., Tignor, M., & Waterfield, T. (Eds.). *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*, 3–24. Cambridge University Press.

IPCC. (2022). Summary for Policymakers. Shukla, P. R., Skea, J., Slade, R., Al Khourdajie, A., van Diemen, R., McCollum, D., Pathak, M., Some, S., Vyas, P., Fradera, R., Belkacemi, M., Hasija, A., Lisboa, G., Luz, S., & Malley, J. (Eds.). *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press.

Jiang, L., Liu, W., Wang, R. Q., Gonzalez-Diaz, A., Rojas-Michaga, M. F., Michailos, S., ... & Font-Palma, C. (2023). Sorption direct air capture with CO_2 utilization. *Progress in Energy and Combustion Science*, 95, 101069.

Keith, D. W., Ha-Duong, M., & Stolaroff, J. K. (2006). Climate strategy with CO_2 capture from the air. *Climatic Change*, 74(1), 17–45.

Küng, L., Aeschlimann, S., Charalambous, C., McIlwaine, F., Young, J., Shannon, N., ... & Garcia, S. (2023). A roadmap for achieving scalable, safe, and low-cost direct air carbon capture and storage. *Energy & Environmental Science*, 16(10), 4280–4304.

Lackner, K., Ziock, H. J., & Grimes, P. (1999). Carbon dioxide extraction from air: is it an option? (No. LA-UR-99-583). Los Alamos National Laboratory.

Lebling, K. (2020). To Unlock the Potential of Direct Air Capture, We Must Invest Now. World Resources Institute.

McEwen, M. (2024, October 19). Occidental invests $1B in Texas carbon capture plant for low-carbon oil. *Midland Reporter-Telegram*.

McKendrick, P. (2023). *Scrubbing the Sky: Inside the Race to Cool the Planet*. Figure.1.

McQueen, N., Gomes, K. V., McCormick, C., Blumanthal, K., Pisciotta, M., & Wilcox, J. (2021a). A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future. *Progress in Energy*, 3(3), 032001.

McQueen, N., Desmond, M. J., Socolow, R. H., Psarras, P., & Wilcox, J. (2021b). Natural gas vs. electricity for solvent-based direct air capture. *Frontiers in Climate*, 2, 618644.

NASEM. (2019). *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*. The National Academies Press.

Nemet, G. F., Gidden, M. J., Greene, J., Roberts, C., Lamb, W. F., Minx, J. C., ... & Riahi, K. (2023). Near-term deployment of novel carbon removal to facilitate longer-term deployment. *Joule*, 7(12), 2653–2659.

NETL. (2024). NETL Direct Air Capture Center Begins Testing, Seeks Partnerships.

Omodolor, I. S., Otor, H. O., Andonegui, J. A., Allen, B. J., & Alba-Rubio, A. C. (2020). Dual-function materials for CO_2 capture and conversion: a review. *Industrial & Engineering Chemistry Research*, 59(40), 17612–17631.

Persily, A., Bahnfleth, W. P., Kipen, H., Lau, J., Mandin, C., Sekhar, C., Wargocki, P., & Nguyen Weekes, L. C. (2022). ASHRAE's Position Document on Indoor Carbon Dioxide. *American Society of Heating, Refrigerating and Air-Conditioning Engineers*.

Pett-Ridge, J., Kuebbing, S., Mayer, A. C., Hovorka, S., Pilorgé, H., Baker, S. E., ... & Zhang, Y. (2023). Roads to removal: options for carbon dioxide removal in the United States (No. LLNL-TR-852901). Lawrence Livermore National Laboratory.

Realmonte, G., Drouet, L., Gambhir, A., Glynn, J., Hawkes, A., Köberle, A. C., & Tavoni, M. (2019). An inter-model assessment of the role of direct air capture in deep mitigation pathways. *Nature Communications,* 10(1), 3277.

Roberts, C., & Nemet, G. (2024). Lessons for scaling direct air capture from the history of ammonia synthesis. *Energy Research & Social Science*, 117, 103696.

Sagues, W. J., Park, S., Jameel, H., & Sanchez, D. L. (2019). Enhanced carbon dioxide removal from coupled direct air capture–bioenergy systems. *Sustainable Energy & Fuels*, 3(11), 3135–3146.

Sanz-Pérez, E. S., Murdock, C. R., Didas, S. A., & Jones, C. W. (2016). Direct capture of CO_2 from ambient air. *Chemical Reviews, 116*(19), 11840–11876.

Schleussner, C. F., Ganti, G., Lejeune, Q., Zhu, B., Pfleiderer, P., Prütz, R., ... & Rogelj, J. (2024). Overconfidence in climate overshoot. *Nature, 634*(8033), 366–373.

Smith, S. M., Geden, O., Gidden, M. J., Lamb, W. F., Nemet, G. F., Minx, J. C., Buck, H., Burke, J., Cox, E., Edwards, M. R., Fuss, S., Johnstone, I., Müller-Hansen, F., Pongratz, J., Probst, B. S., Roe, S., Schenuit, F., Schulte, I., Vaughan, N. E. (Eds.). (2024). The State of Carbon Dioxide Removal 2024 - 2nd Edition.

Socolow, R., Desmond, M., Aines, R., Blackstock, J., Bolland, O., Kaarsberg, T., ... & Wilcox, J. (2011). Direct Air Capture of CO_2 with Chemicals: A Technology Assessment for the APS Panel on Public Affairs. American Physical Society.

Sodiq, A., Abdullatif, Y., Aissa, B., Ostovar, A., Nassar, N., El-Naas, M., & Amhamed, A. (2023). A review on progress made in direct air capture of CO_2. *Environmental Technology & Innovation*, 29, 102991.

Sriram, A., Choi, S., Yu, X., Brabson, L. M., Das, A., Ulissi, Z., Uyttendaele, M., Medford, A. J., & Sholl, D. S. (2024). The Open DAC 2023 dataset and challenges for sorbent discovery in direct air capture. ACS *Central Science*. 10(5), 923–941.

Tokarska, K. B., & Zickfeld, K. (2015). The effectiveness of net negative carbon dioxide emissions in reversing anthropogenic climate change. *Environmental Research Letters*, 10(9), 094013.

Underwood, O., Franzini, L., Schonberger, A., Magin, L., Batchelor, N., & Eisenberger, N. (2024). Circular Carbon Market Analysis: 2023 Analysis. *Circular Carbon Network*.

Victor, N., & Nichols, C. (2024). Impact of carbon dioxide removal technologies on deep decarbonization: EMF37 MARKAL–NETL modeling results. *Energy and Climate Change, 5*, 100143.

Wilcox, J. (2012). *Carbon capture*. Springer Science & Business Media.

Zanatta, M. (2023). Materials for direct air capture and integrated CO_2 conversion: advancement, challenges, and prospects. *ACS Materials Au*, 3(6), 576–583.

Zeeshan, M., Kidder, M. K., Pentzer, E., Getman, R. B., & Gurkan, B. (2023). Direct air capture of CO_2: from insights into the current and emerging approaches to future opportunities. *Frontiers in Sustainability*, 4, 1167713.

Zhang, Y., Jackson, C., & Krevor, S. (2024). The feasibility of reaching gigatonne scale CO_2 storage by mid-century. *Nature Communications*, 15(1), 6913.

Zolfaghari, Z., Aslani, A., Moshari, A., & Malekli, M. (2022). Direct air capture from demonstration to commercialization stage: A bibliometric analysis. *International Journal of Energy Research, 46*(1), 383–396.

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