Boston University Institute for Global Sustainability

DIRECT AIR CARBON CAPTURE AND STORAGE
Market Scan

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All results and any errors in this report are the responsibility of the authors.

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Acronyms

BECCS	Bioenergy with Carbon Capture and Storage
BERDO	Building Emissions Reduction and Disclosure Ordinance
CAP	Climate Action Plan
CBM	Coalbed methane
CCU	Carbon Capture and Utilization
CDR	Carbon Dioxide Removal
DAC	Direct Air Capture
DACCS	Direct Air Carbon Capture and Storage
DOE	Department of Energy
EERE	(Office of) Energy Efficiency and Renewable Energy
EOR	Enhanced oil recovery
GHG	Greenhouse gas
GRC	Green Ribbon Commission
HVAC	Heating, ventilation, and air conditioning
IAM	Integrated assessment model
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRA	Inflation Reduction Act
LCA	Life-cycle analysis
NETL	National Energy Technology Laboratory
NGO	Nongovernmental Organization
PI	Process intensification
PPA	Power Purchase Agreement
PSC	Point-Source Capture
REC	Renewable Energy Credit
RGGI	Regional Greenhouse Gas Initiative
SJB	San Juan Basin

Executive Summary

The global consensus among climate scientists is that future temperature increases must be limited to 1.5° to 2°C above pre-industrial levels to avoid the most severe consequences of climate change. Most scenarios of future emissions assign a critical role to so-called "negative emissions." These refer to a range of technologies that actively remove carbon dioxide (CO_2) from the atmosphere and permanently store ("sequester") that carbon.

Direct Air Carbon Capture and Storage (DACCS) is a negative emissions technology that has garnered significant scientific, engineering, and commercial interest. A complete DACCS system includes the capture of CO_2, its compression and transport, and storage deep underground. Some components of a DACCS system are mature technologies. For example, companies have for decades captured CO_2 from oil and gas processing (and other industrial sources), transported it via pipeline, and injected it into oil and gas reservoirs to boost production. However, a complete DACCS system has yet to be demonstrated as a commercially viable technology that can be deployed at scale to yield large net reductions in atmospheric CO_2 concentrations.

Many states, cities, companies, and other regulated entities use approved "compliance pathways" to meet emissions reductions targets. Compliance typically comes through direct emissions reductions via fuel switching and energy efficiency, power purchase agreements, and renewable energy credits. In principle, the deployment of DACCS can be accelerated *if* it is a feasible and cost competitive means of reducing CO_2 from the atmosphere. DACCS must therefore compete with existing compliance mechanisms.

Cost estimates for DACCS ($\$/tCO_2$) are based on assumed design and performance attributes. Current estimates range from 100 to 1,000 $\$/tCO_2$ captured over a wide range of assumptions regarding technological readiness and scale of deployment. It is important to note that most estimates are for capture only; they exclude the cost of transport and storage. For context, consider the City of Boston's 2021 revision of its Building Emissions Reduction and Disclosure Ordinance (BERDO) that requires owners of buildings larger than 20,000 square feet to demonstrate emissions reductions.

The current options and approximate associated costs for Boston building owners are power purchase agreements (\$12/ tCO_2), Class I renewable energy credits (\$10.50/ tCO_2), and an "alternative compliance pathway" (\$234/ tCO_2). Thus, even if one assumes technical viability, in its current state DACCS is not economically viable as a compliance pathway. This could change because many new energy technologies exhibit rapidly falling unit costs as deployment scales. Economic viability goes hand in hand with the need to rapidly scale: thousands of complete DACCS systems are required to yield a sizable reduction in atmospheric CO_2.

Economic issues aside, DACCS must meet a suite of additional critical criteria to be considered a viable and desirable climate mitigation option. First, there must be transparent and rigorous third party standards for verifying that a given quantity of CO_2 is permanently stored; such a verification system currently does not exist. Second, a transparent and rigorous carbon accounting framework must be in place that measures the *net* reduction in atmospheric CO_2 from DACCS, taking into account emissions from energy use, manufacture, materials, and transportation. Third, DACCS cannot be presented as a substitute for emissions reductions. Fourth, DACCS must be incorporated into regulatory schemes for emissions reduction compliance; this is in the nascent stages. Finally, the deployment of DACCS infrastructure must demonstrate that it does not exacerbate existing energy and environmental inequities in vulnerable and marginalized communities.

Introduction

In 2017, then-Mayor Walsh pledged to make the City of Boston carbon-neutral by 2050 [1], and asked the Boston Green Ribbon Commission (GRC) to establish a Working Group to support the City in achieving this goal. *Imagine Boston 2030*, the City's long-term strategic plan, also set an interim carbon reduction goal of 50 percent by 2030 [1]. The Report and the City hold that carbon neutrality is not merely about tracking emissions to reach a numerical goal, but also "a public health, economic, and social equity imperative," because climate change affects everyone [2]. Indeed, the expected impacts on Boston are concerning because they include increased frequency and severity of hot weather and heat-related illness and death, and increased rainfall and stormwater flooding. Combined with sea-level rise, these impacts will exacerbate coastal and river flooding that will impact about 15% of Boston's residents [1]. These impacts will fall disproportionately on Boston's most vulnerable populations, exacerbating historic marginalization among communities of color, women, youth, disabled people, elderly people, and people with limited English proficiency [1].

Buildings account for 71% of **greenhouse gas (GHG)**[1] emissions in Boston, and curtailing emissions is a formidable challenge to overcome in order for the City to reach its climate goals [1]. In its 2019 Climate Action Plan (CAP) update, the City committed to making all new construction **Zero Net-Carbon buildings**, and a Zero Net-Carbon Zoning Ordinance is in development that would require all projects going through approval by the Boston Planning and Development Agency to meet carbon neutrality performance standards. However, that still leaves about 80% of the 86,000 current structures to decarbonize [1]. Deep energy retrofits, which both electrify a building and achieve a significant reduction in its energy use through improved efficiency, can reduce citywide emissions by up to 40% [1]. Much of the remaining emissions reductions will come from further decarbonization of the New England electric grid, which currently generates about 39% of electricity from low-carbon sources such as solar, wind, nuclear, and hydropower [3].

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[1] All bolded terms are defined in the glossary.

The City is further addressing building emissions through its regulatory authorities. Building Emissions Reduction and Disclosure Ordinance (BERDO) 1.0, enacted in 2013, which required that all commercial and residential buildings that are 35,000 square feet or larger, or have 35 units or more, report their energy and water use to the city each year [1]. In addition to the reporting requirement, every five years the building owners must show they have taken action to reduce their energy use or emissions by 15%, or that they have conducted a detailed assessment of options to reduce their energy use. Over 2,200 buildings are covered by BERDO 1.0, accounting for over 258 million square feet, or 34% of Boston's total floor space, as well as a significant proportion of the City's carbon emissions [4].

In October 2021, BERDO 2.0 passed, which increased the scope of the buildings required to report to the City to include those that are at least as large as 20,000 square feet, and strengthened the Ordinance with new emissions-based performance standards [4]. In addition, BERDO 2.0 introduced: (1) *additional compliance mechanisms*, which allow building owners to address their emissions in ways other than direct energy use reduction and efficiency, such as municipal aggregation, Renewable Energy Certificates (RECs), and Power Purchase Agreements (PPAs); and (2) *alternative compliance payments*, whereby building owners who do not meet the performance standards pay to the City for contribution towards an Equitable Emissions Investment Fund based on how many tonnes of carbon are emitted beyond the required standards [4]. The price of the alternative payments is based on the average cost per metric tonne of **carbon dioxide equivalents** (CO_2e) to decarbonize buildings (the initial cost is $234/$tCO_2e$), and will be reviewed every 5 years by the BERDO board and the Environment Department. Money contributed to the fund from the alternative payments "shall be expended for the support, implementation, and administration of local building carbon abatement projects that benefit the City of Boston's emissions reduction goals" and "shall prioritize projects that benefit **Environmental Justice populations** and populations disproportionately affected by air pollution" [4].

The International Panel on Climate Change (IPCC) concluded that Carbon Dioxide Removal (CDR) must play a major mitigation role, and that numerous CDR methods could potentially reduce atmospheric GHG levels [5]. However, several of these methods, including **Direct Air Carbon Capture and Storage (DACCS)**, have not been tested or implemented on a scale sufficient to accurately assess their potential contribution. Thus, DACCS remains an unknown, but possibly useful, way for building owners in Boston to meet the requirements of BERDO 2.0.

This market report aims to assist the City in its potential consideration of CDR's role in its climate action plan. The report describes the emerging DACCS market and technologies, and then assesses whether they might play a role as a possible compliance pathway for building owners bound by BERDO 2.0, or perhaps as a recipient of funding from the Equitable Emissions Reduction Fund. The outline of this document is as follows:

1. *Carbon Dioxide Removal Strategies*: a broad overview of various CDR methods in development or in use today.
2. *Direct Air Carbon Capture and Storage*: a deep dive into the DACCS system, including the capture of CO_2, its compression and transport, and finally storage. This section also explores emerging technologies and the expected energy and resource usage of each method described.
3. *Current Status and Challenges*: describes projects underway and the challenges of DACCS including cost, verification, scale, and social and political considerations.
4. *Recommendations:* describes implications for the City of Boston and building owners bound by BERDO 2.0.

Carbon Dioxide Removal Strategies: an Overview

The Need for Removal

The Paris Agreement calls for "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels" [6]. Achieving deep reductions in GHG emissions is essential to meeting this goal. Decarbonization is the first step; however, as the IPCC Fifth Assessment Report (AR5) concluded in 2015, the majority of modeling to date assumes a significant global-scale deployment of **negative emissions** technologies in the second half of this century [5]. This conclusion is based on the observation that increases in CO_2 concentration in the atmosphere last up to 1,000 years, even after emissions cease, which means that climate change could still continue for several centuries if removal is not done at scale. Thus, we need *both* deep decarbonization *and* large-scale CDR. In the IPCC's **Integrated Assessment Models (IAMs)**, 101 of the 116 modeled scenarios with a 66% or better chance of limiting global warming to 2°C included CDR in the technology mix for the second half of the 21st century, on a scale of about 12 billion metric tonnes of CO_2 per year (or 12 gigatonnes), equivalent to more than 25% of current CO_2 emissions [5]. Even if global decarbonization moves as quickly as possible, keeping warming below 1.5° C will require removing gigatonnes of atmospheric CO_2 per year by the end of the 21st century. This is a daunting challenge.

Current levels of GHG emissions make it increasingly likely that we will surpass the key temperature targets. The IPCC's Working Group III contribution to the Sixth Assessment Report (AR6), released in April 2022, states that existing and planned fossil fuel infrastructure use up most of the budget for 2°C of warming, and warns that without stronger policies, we could be on track for 3.2°C by 2100 [7]. AR6 goes further than AR5, giving a total cumulative removal target of 380 $GtCO_2$ between 2050 and 2100, which the IPCC says will be required to return to below 1.5°C after an overshoot [7]. Thus, we have two global targets: 12 $GtCO_2$ of annual removal starting in 2050, and a cumulative total of 380 $GtCO_2$ by the end of the century if global average temperatures exceed 1.5°C.

The picture is no less urgent for the City of Boston, whose goal is to be net-zero by 2050. Because of significant contributions from residual emissions, the City will need to consider where, when, and how to incorporate negative emissions into its Climate Action Plan.

Natural vs Technological Methods

All CDR methods must include these general steps:

1. Capture
2. Transport
3. Storage

CO_2 removal methods generally fall into two categories: *natural* and *technological* (Figure 1). Natural methods involve the uptake of CO_2 in ecosystems by trees, soils, algae, mineralization, and other so-called **carbon sinks**. Natural CDR can be enhanced by human activities, for example by planting more trees, encouraging carbon sequestration of soils with no-till and composting methods of agriculture, farming kelp and algae, and weathering, among other options. For natural carbon removal systems, concerns include the potentially large administrative costs, the designation of large areas for carbon removal which may compete with other important land uses, the slow speed at which carbon sinks can absorb the CO_2, unintended impacts on the ecosystems themselves, and uncertainty in the permanence of storage.

Technological CDR is entirely anthropogenic. The broad technology classes include **Direct Air Carbon Capture and Storage (DACCS)**, which is explained in more detail in the next section, and **Point-Source Capture (PSC)**. The latter technology refers to the capture of emissions from point sources such as power plants. PSC systems are generally built as extensions of natural gas or coal power plants, which release CO_2 in concentrated streams (flue gas). Those concentrations of CO_2 are much higher than ambient air, and so less work is required to capture the same amount of CO_2 compared to DACCS, resulting in a cost advantage for PSC. However, PSC systems require the continued operation of fossil fueled power plants, raising concerns about whether development of these systems simply delays the important work of decarbonization.

Furthermore, PSC only addresses point-source emissions, whereas DACCS can theoretically be sited anywhere and can address **distributed emissions**.

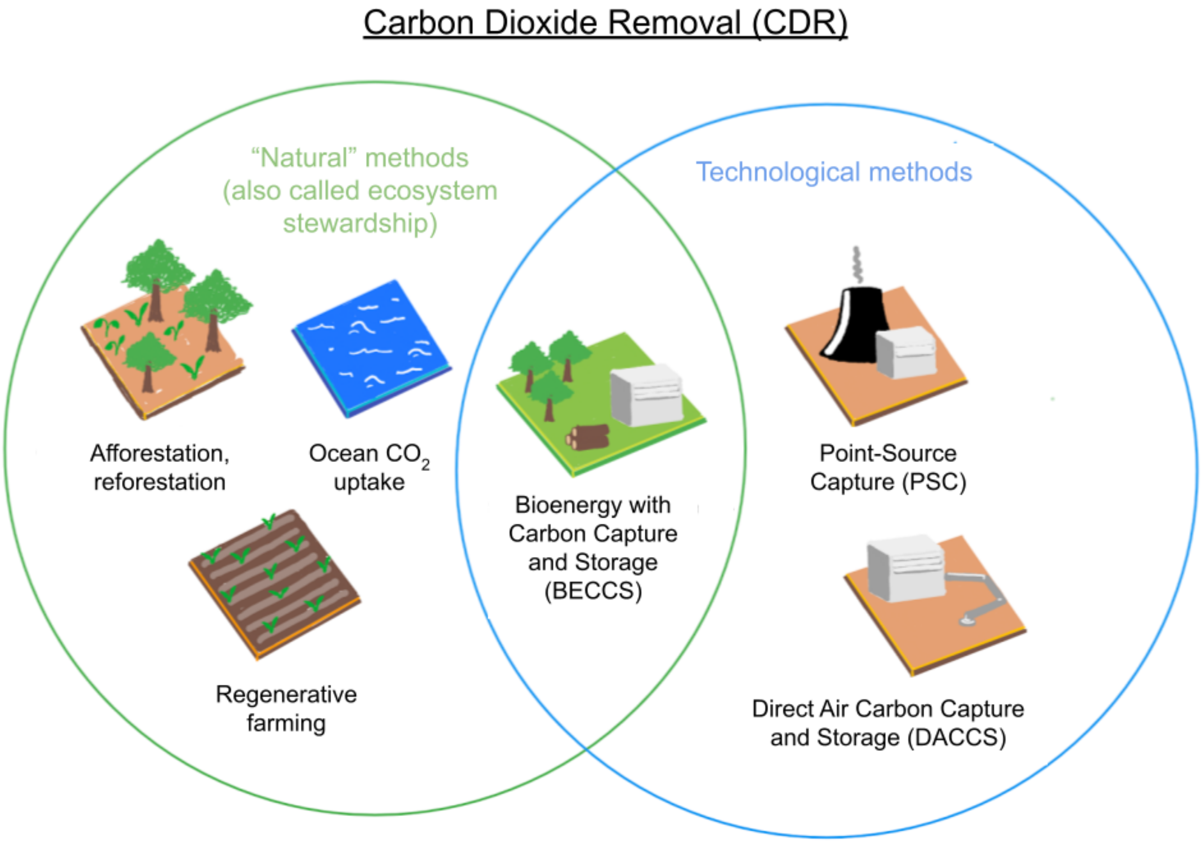


Figure 1: Some natural and technological methods of CDR.

Bioenergy with Carbon Capture and Storage (BECCS), is a CDR method that combines natural and technological processes. During BECCS, CO_2 is captured in biomass which is then combusted and converted into useful energy (e.g. biofuels, electricity, heat), and the CO_2 released from the combustion is captured and stored. BECCS is featured heavily in many IAMs, including in the IPCC's models, because it combines carbon capture with the production of useful energy. However, similar concerns arise with the large-scale deployment of BECCS as with afforestation and other natural CDR methods: competition with other land uses, rigorous carbon accounting, and the requirement of careful ecological stewardship.

This report focuses on DACCS. Note that in common usage, the term DAC sometimes refers to only the capture process itself, and sometimes encompasses the transport and storage steps as well. In this report, we will use DAC only when referring to the capture step of the process and DACCS to refer to the entire system of capture, transport, and storage.

Direct Air Carbon Capture and Storage (DACCS)

The DACCS System

A DACCS system encompasses three stages: (1) capture, isolation, and compression of CO_2; (2) transport of the compressed CO_2 to a storage site; and (3) sequestration or permanent storage of CO_2 (Figure 2). The capture step is summarized below, and a more technical description is given in Appendix A.

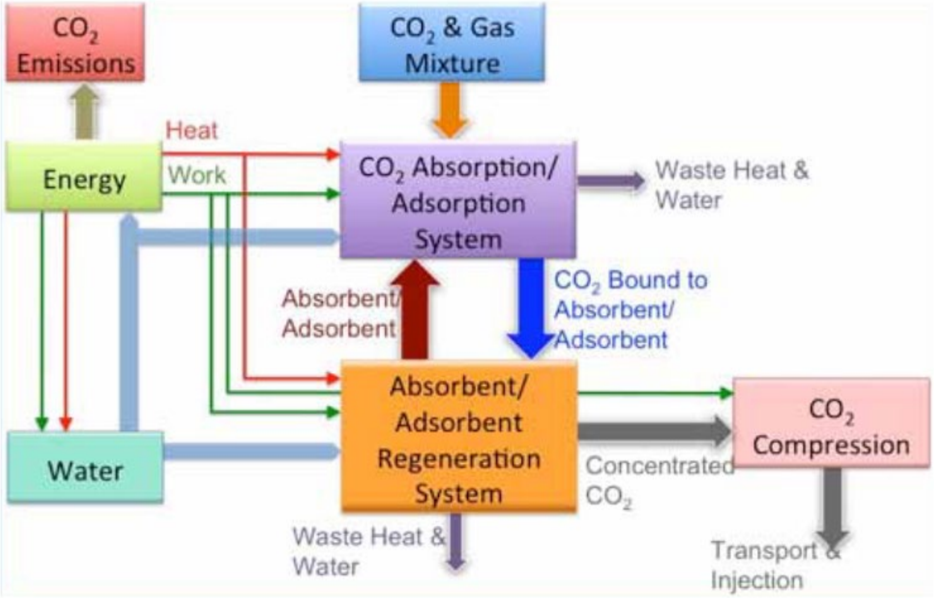


Figure 2: Flow diagram of a typical CO_2 capture system, with work and wastes.
Source: American Physical Society, 2011.

Capture

DAC, the capture and separation process of DACCS, is a method of removing CO_2 from intake air using chemical reactions, then compressing it for transport to a geological storage site. This process has been in development for about a decade and is showing promise as a way to capture carbon with relatively little land and water use than other methods, such as afforestation (see *Energy and Resource Use* for more on this). Several pilot plants have demonstrated its technical feasibility at the scale of millions of metric tonnes ($MtCO_2$) per year (Figure 3), but capital and operating costs are currently much higher than other emissions reduction methods (see *Cost Comparison* for more on this).

Many of these pilots use adsorption, a method of capturing carbon from intake air using CO_2-selective chemicals (or binding agents) on a solid sorbent material [8, 9, 10, 11]. Absorption of CO_2 in a solution and membrane capture of the CO_2 molecules are also methods of capture [8, 9, 10]. Once the CO_2 is bound, the agents are heated and go through a reverse chemical reaction to release the gas in a pure stream, which is then compressed for transportation to a storage site. Most of the energy needed for this reversal process, which is called regeneration, is thermal, usually provided by natural gas or waste heat from industrial processes [11, 12, 13]. Electricity is also used to power fans, contactors, and compressors.

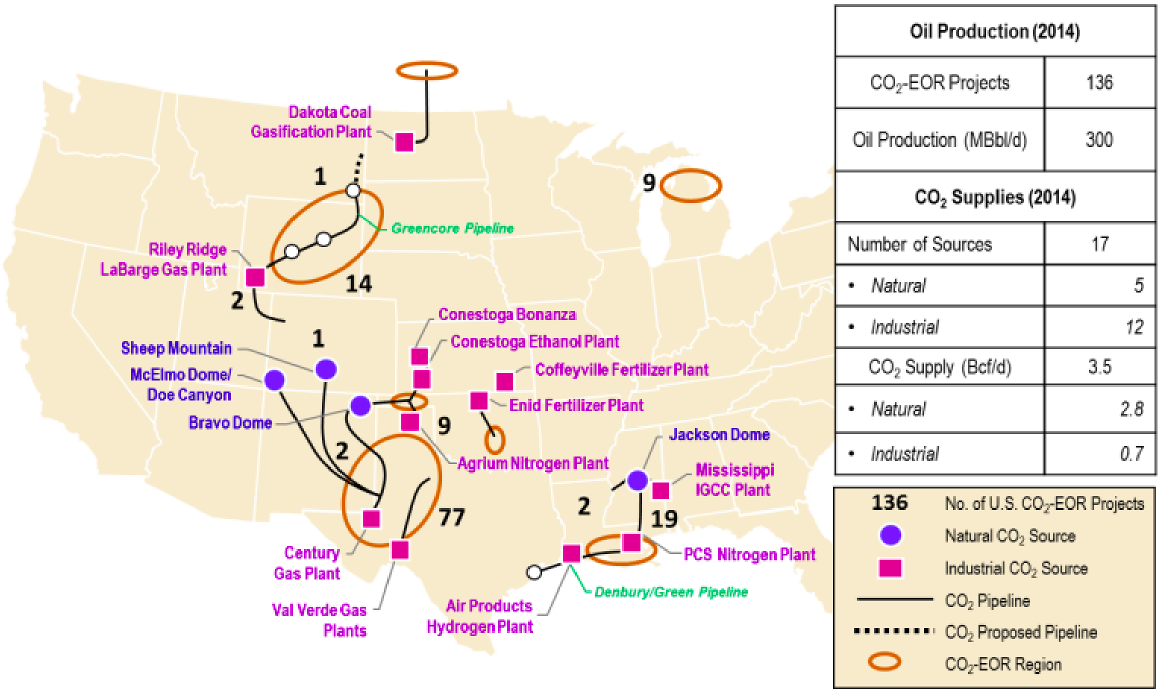
Figure 3: A rendering of Carbon Engineering's industrial-scale air contactor design for direct air capture. Source: Jeff Brady (NPR), 2018.

Compression and Transport

Depending on the method used for capturing it, CO_2 may contain impurities such as SO_x, NO_x, amines, NH_3, CO, H_2, N_2, O_2, and/or moisture. These impurities affect the properties of the output gas mixture, including its viscosity, compressibility, and fluid dynamics, as well as the corrosion and potentially hydrogen embrittlement of the transport vessel or pipeline [14]. Moisture is another concern: "dry" CO_2 (typically containing < 10 ppmv H_2O) is not corrosive to pipelines made of carbon-manganese steels that may also tolerate the presence of other contaminants, but moist CO_2 is highly corrosive even at moderately high temperatures and requires highly expensive corrosion-resistant alloys. Thus at the very minimum, the CO_2 gas mixture must be dehumidified before compression and transport, and, depending on the mode of transport and materials available, the other impurities must be removed.

There are various modes of transport such as rail, ship, truck, and pipeline, the latter of which is a technically feasible option for large-scale application and is already commercially deployed at a limited scale. Pipelines are currently the most common method for transporting large volumes of gas over long distances in the US, primarily for **enhanced oil recovery (EOR)** and natural gas infrastructure (Figure 4).

The optimum transportation method minimizes both energy and monetary transport costs. For a 500 MW plant located in the Midwest U.S., CO_2 transport costs vary widely from \$0.15/tCO_2 for a 10 km long pipeline to \$4.06/tCO_2 for a 200 km long pipeline [14]. Similarly, an analysis in China estimated the transportation costs for 4,000 tCO_2/day (or, 1.46 million tonnes/year) to be \$12.64/tCO_2 for railroad tankers, \$7.48/tCO_2 for ship tankers, and \$7.05/tCO_2 for a 300 km long pipeline [14]. These results suggest that pipelines are the most cost-effective CO_2 transportation modes for scaled CDR operations.



Oil Production (2014)	
CO_2-EOR Projects	136
Oil Production (MBbl/d)	300
CO_2 Supplies (2014)	
Number of Sources	17
• *Natural*	*5*
• *Industrial*	*12*
CO_2 Supply (Bcf/d)	3.5
• *Natural*	*2.8*
• *Industrial*	*0.7*

Figure 4: EOR operations in the United States in 2014, with existing and proposed CO_2 pipelines. Source: U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) Office of Fossil Energy, 2015.

Pipeline transport of CO_2 requires the gas to be compressed and then cooled to the liquid state or the supercritical state [9], that is at pressures above the critical point at which the distinction between gas and liquid vanishes and the CO_2 density increases greatly. Expectedly, there is an energy cost to achieve either state, because the transport vehicle or the pipeline must maintain at all times the pressure and temperature conditions required to keep the CO_2 in liquid or supercritical form. The most common type of compressor is the reciprocating positive displacement compressor, in which an inlet volume of gas is confined in a given space and then compressed by a reduction in the confined space [9]. At the elevated pressure, the gas is subsequently expelled into a discharge piping or vessel system. To decrease the cost associated with the compression of CO_2, advanced compression technologies must be pursued [9]. Several recent studies have modeled and tested the performance of multi-stage compressors for DAC, in which the CO_2 goes through multiple stages of compression and cooling, and they suggest that improved energy use efficiencies are possible [16] and may even be cost-effective [17].

The CO_2 pipeline between the capture and storage sites must be safe, reliable, energy-efficient, environmentally friendly, cost-effective, and have high local community acceptance. Large diameter pipelines lower the pressure drop and the associated pumping losses and hence may be more energy efficient, but they also cost more to build. The pipeline diameter is the primary design constraint when considering CO_2 pipeline transport, and the parameters that must be considered in its estimation are pressure drop, elevation change, intended CO_2 mass-flow rate, CO_2 compressibility, and viscosity. The extent of impurities in the CO_2 stream will also influence the extent of corrosion of the pipeline materials. Another important consideration in the pipeline design is appropriately spacing the isolation valves (e.g., closer together in populated areas) to limit leakage in case of a break.

In the U.S. alone, there are about 800,000 km of hazardous liquid and natural gas pipelines, in addition to 3.5 million km of natural gas distribution lines [18]. By contrast, only about 6,500 km of pipelines in the U.S. are used to transport 150 $MtCO_2$ for EOR purposes [14]. This existing infrastructure is not enough to support gigatonne-scale DACCS: the International Energy Agency (IEA)'s least-cost pathway to halve energy-related CO_2 emissions by 2050 estimates that roughly 100 times more CO_2 pipeline infrastructure will need to be built in the coming decades [18].

Storage/Sequestration

The greatest technical concerns for long-term CO_2 sequestration are (1) safety and (2) permanence. To mitigate climate impacts effectively, greenhouse gasses would need to remain in storage for at least 1,000 years [11], a timeline that is currently only supported by geological storage. Furthermore, the success of a sequestration project on the scale needed will be highly dependent on public opinion: people must be able to trust that the storage of CO_2 will be permanent enough and that the process will not endanger their lives, livelihoods, or the surrounding environment (see *Current Status and Challenges* for more on this).

Technical specifications for a sequestration site chosen for DACCS include: (1) capacity, (2) injectivity (i.e., the ease of fluid flow through the pores), (3) trapping mechanisms, and (4) confinement (i.e., the capability to contain CO_2 in the site). There are several

CO_2 sequestration methods that can meet these criteria with careful management, the most promising of which is storage in geological formations. Table 1 shows the theoretical worldwide storage capacity (in gigatonnes of CO_2) of several of these formations.

Table 1: Worldwide storage capacity in $GtCO_2$ of geological formations.

Formation	**Theoretical Worldwide capacity ($GtCO_2$)**
Saline aquifers	1,000 - 10,000 [9]
Sedimentary basins	5,000 - 25,000 [14]
Depleted oil and gas fields	1,000 [14]
Unmineable coal beds	100-300 [9]

A 2013 study by the National Research Council of the Academy of Sciences estimates the total geologic sequestration capacity, with a global "theoretical" capacity of 35,300 $GtCO_2$, an "effective" capacity of 13,500 $GtCO_2$, and a "practical" capacity of 3,900 $GtCO_2$ [19], highlighting the challenges both of assessing the capacity of different formations and also of being able to use them. A designation of "effective" or "practical" capacity is a function of constraints related to the location of the reservoir (eg. those near populated areas are not likely to be accessible), available equipment, and resource or cost constraints. Constraints aside, the global demand for CO_2 storage capacity (up to 380 Gt by 2100) is much smaller than even the most conservative estimates of available sites, which means that, in principle, DACCS will not be limited by storage capacity. Nevertheless, the National Research Council emphasizes the need for research, geological assessments, and, crucially, commercial-scale demonstration projects for the improvement of confidence in capacity estimates of individual sites [19]. In the US, 36 technically accessible (effective) geological sequestration resources are estimated to have a capacity of about 3,000 $GtCO_2$ [19], with saline aquifers being the largest resource (Figure 5).

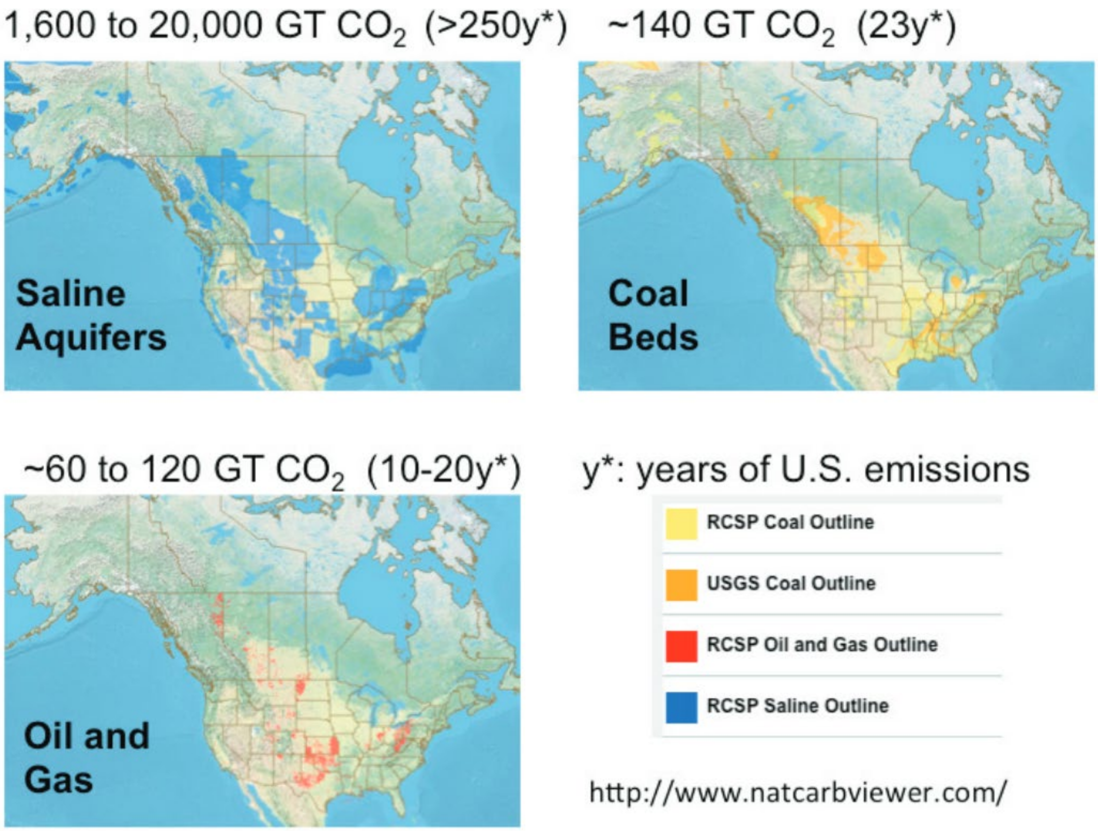


Figure 5: Opportunities in North America for CO_2 sequestration in saline aquifers, unmineable coal beds, and depleted oil and gas reservoirs. Source: National Research Council of the National Academies of Science, 2015.

Maximizing the potential of DACCS requires co-locating the steps of the process as much as possible and using low-carbon energy. DAC plants can, in theory, be located anywhere, provided they have a source of energy (heat and/or electricity) and sufficient land. However, citing a DAC plant near (<100 km of) a sequestration reservoir will reduce the costs of transporting the removed CO_2 [11].

Enhanced Oil Recovery and Carbon Sequestration

The technology required for storage of supercritical CO_2 in saline aquifers and depleted oil and gas fields is not new: the oil industry has long compressed and injected CO_2 and other gasses deep underground for enhanced oil recovery (EOR). This method is the most thoroughly characterized of all geological storage methods, and because of its already widespread use in the oil and gas industry, it is the most likely to be scalable in regard to cost and technological viability in the short run [20]. Estimates of the longevity of this storage are uncertain, but observations and modeling suggest that up to 25% of injected CO_2 is sequestered in carbonate minerals on the order of 10,000 years [20]. However, the majority of CO_2 used for EOR in one particular site is removed and re-utilized for a different EOR operation elsewhere, limiting effective storage in practice [19]. EOR technologies may serve as an on-ramp for DACCS, because the infrastructure and methods are already in use at scale. In fact, many oil and gas companies, industry coalitions, trade groups, and nonprofit organizations are exploring EOR as a method of CO_2 sequestration alongside continued oil and gas production [21]. However, in addition to concerns about the effective storage of CO_2 through EOR, there are important social and political challenges to greenlighting partnerships of DAC developers with fossil fuel companies.

During primary oil recovery, the natural pressure of the reservoir drives oil into the wellbore, combined with artificial lift techniques (such as pumps) that bring the oil to the surface. But only about 10% of a reservoir's original oil in place is typically produced in this way [22]. Secondary recovery techniques extend a field's productive life generally by injecting water or gas to displace oil and drive it to a production wellbore, resulting in the recovery of 20-40% of the original oil in place [22]. However, with much of the easy-to-produce oil already recovered from U.S. oil fields, producers have attempted several tertiary, or enhanced oil recovery, techniques that offer prospects for ultimately producing 30-60% or more, of the reservoir's original oil in place [22]. These techniques include fluid and gas injection, such as with CO_2 (Figure 6).

The first major concern arises from the sources of CO_2 used for EOR. Less than 20% of the CO_2 used in today's U.S. EOR operations is from anthropogenic sources such as gas processing, fertilizer, ethanol, hydrogen plants, and other industrial processes [22]. The remaining 80% comes from geological sources, mainly a few big natural CO_2 reservoirs under the Earth's surface [23]. Thus, the vast majority of the CO_2 used for EOR was already sequestered and is removed, then re-buried during the EOR process, at a loss of 5-10% that escapes to the atmosphere with the recovered oil. As a result, EOR in its current configuration does not remove carbon from the atmosphere as a bonus to oil production; in fact, it removes carbon in deep geological storage and emits a small but important quantity into the air.

By contrast, using geological storage for DACCS will necessitate capturing CO_2 from the air and using the infrastructure in place for transport and storage in EOR to permanently sequester it. Currently, only one such system is in construction globally: Oxy and Carbon Engineering are building the first joint DAC + EOR facility in the Occidental oil field in the Permian Basin of the southwestern United States, set to be operational in 2023 [24]. This is promising, however, the capacity of the facility is still small: just 1 $MtCO_2$/year.

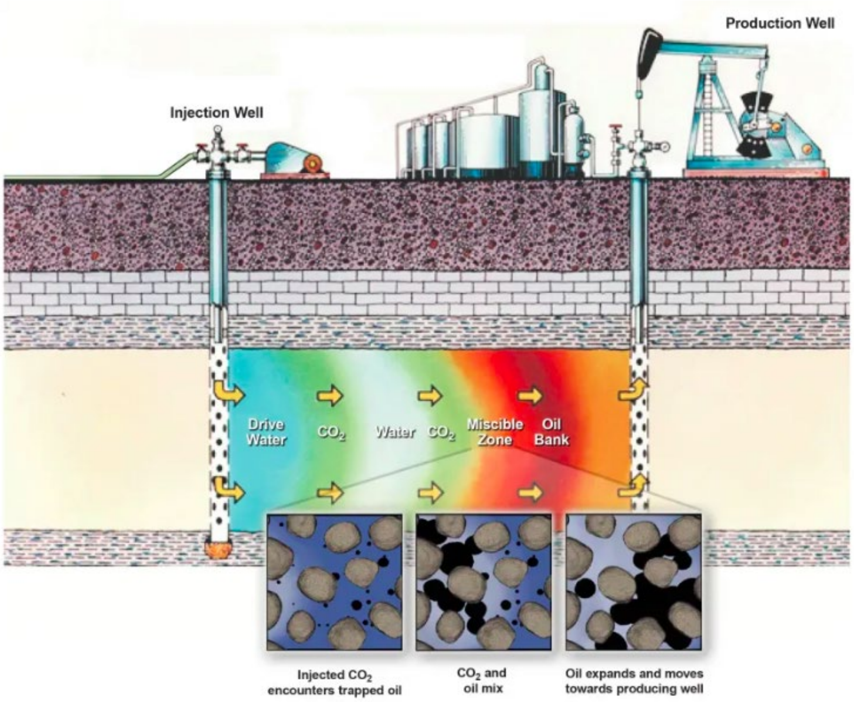


Figure 6: Diagram of the CO_2 enhanced oil recovery (EOR) process.
Source: U.S. Department of Energy (DOE) Office of Fossil Energy and Carbon Management.

The potential of EOR for carbon sequestration is further complicated by the fact that the oil and gas industry that has developed the technology is also (i) a large source of fugitive methane emissions, another potent greenhouse gas; and (ii) is in the business of selling fuels whose combustion accounts for 89% of all anthropogenic CO_2 emissions [25]. In order to effectively mitigate climate change, scalable CO_2 removal must be deployed *simultaneously* with reduced emissions, which necessarily means reducing the use of oil, gas, and coal globally during a just transition to low-carbon sources. Even if these industries delivered 'net-zero' oil, where the emissions released by its extraction and combustion were offset completely by CO_2 sequestration during EOR (as has been proposed by the Oxy and Carbon Engineering partnership [24]), *ceteris paribus*, atmospheric CO_2 concentrations would not fall. There are significant concerns that pursuing these methods without also reducing fossil fuel use will further entrench a dependency on oil in the economy and energy markets, and 'lock in' the resulting emissions for decades to come. Indeed, oil produced by EOR methods represents just 4% of the U.S. market, but it plays a central role in the industry's plans for *expansion* [15], which will only increase global emissions. Instead, effective climate action will require a combination of expanding renewable energy sources *and* CDR, perhaps with the infrastructure and industry expertise currently used for EOR.

Other Storage Options

A pilot project in the San Juan Basin by the Energy & Geoscience Institute of the University of Utah, which is in the Four Corners region of the American Southwest, will assess the feasibility of injecting CO_2 in coal seams to simultaneously sequester carbon and extract methane (CH_4) as a commercial fuel. The pilot project was not promising from a sequestration perspective [26], and it raised some troubling environmental and social concerns:

> [S]everal residents had to leave their homes due to methane and hydrogen sulfide contamination. Heavy truck traffic, contamination of drinking water, and depletion of underground aquifers continue to concern many residents. As production increased, natural geological seeps began emitting more methane. Stories of residents lighting their tap or creek water on fire – today infamously associated with fracking for oil and gas from shale – were already circulating in the 1990s in La Plata County due to coalbed methane production [27].
>
> The San Juan Basin (SJB) [has been categorized] as the biggest CH_4…"hot spot" in the United States. Over a 3-week period in April 2015, we conducted ground and airborne atmospheric measurements to investigate daily wind regimes and CH_4 emissions in this region of SW Colorado and NW New Mexico. The SJB…experienced elevated surface air pollution under low wind and surface temperature inversion at night and early morning. Survey drives in the basin identified multiple CH_4 and ethane (C_2H_6) sources with distinct C_2H_6-to-CH_4

emission plume ratios for coal bed methane (CBM), natural gas, oil, and coal production operations [28].

Methane (CH_4) is a more potent greenhouse gas than CO_2, with an 84-86 times greater global warming potential over 20 years, reducing to 28-34 times over 100 years [29]. Therefore, methane emissions associated with this method of sequestration will need to be weighed against the CO_2 sequestered, as well as the associated public health and environmental challenges. Pursuing DACCS through the production of methane in the natural gas industry raises similar concerns as doing so through EOR in the oil industry; experts do not recommend either as a path for CDR, since it would likely counteract emission reduction efforts.

A variety of alkaline waste materials from the mining, construction, and demolition industries possess significant potential to sequester large volumes of CO_2 [30]. Recent research has identified at least 12 types of waste material that can permanently capture CO_2 through **mineralization** or **enhanced weathering**, including ash, cement, and lime, among others [30]. A pilot project by CarbFix in Iceland showed that over 95% of the CO_2 injected into the mineralization site was permanently converted to carbonate materials in just 2 years, a much faster timeline than previously theorized [31], suggesting that mineralization could become a technically feasible method of CDR.

Emerging Technologies

In addition to DAC plants and different methods of CO_2 storage, there is interest in incorporating DAC technologies into so-called “CO_2 recycling” or **Carbon Capture and Utilization (CCU)** (Figure 7). The purpose of CCU is to use CO_2 as a feedstock in the manufacture of useful products such as plastics and synthetic fuels or to use it directly, for example to carbonate drinks [32]. An important distinction between CCU and CDR is that most CCU technologies do not include long-term storage of CO_2 because the gas is eventually released back into the atmosphere at the end of the product’s lifetime [32]. This temporary “storage” can last from days to weeks in the case of fuels, years for polymers, or even decades to centuries in the case of cement [32], however none is as effective as geological storage, whose timeline is >1,000 years. This limits the technology for permanent CO_2 reductions and creates a challenge for accurate carbon accounting. Not only is the "storage" of CO_2 in CCU temporally limited, but the technology also does not scale: even highly optimistic estimates assume that the total amount of CO_2 that could be utilized in this way is small, approximately 180 Mt for chemicals and 2 Gt for fuels [32], compared to the IPCC's goal of 12 $GtCO_2$ removed/yr or 380 Gt cumulatively by 2100. CCU may help us reach that goal alongside DACCS and other CDR methods, but is unlikely to play a large role.

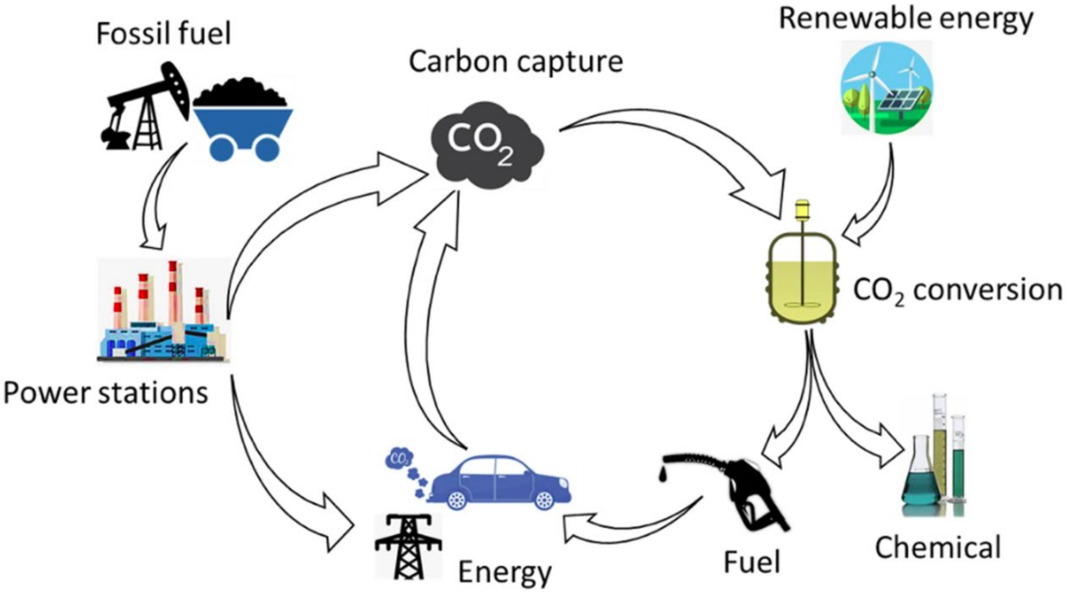


Figure 7: visual diagram of the CCUS cycle.
Source: Adamu et al., 2020.

A clearer environmental benefit of CCU comes from its potential to displace fossil fuels in some production processes. Life-cycle analyses (LCAs) suggest that CO_2-based polyols yield a 13-15% reduction in fossil resource consumption compared to petroleum-based polyols [32] that are used to manufacture polyurethane foams. Thus, CCU may be more effective as an emission reduction method than as a CDR method.

Process intensification (PI) is the modification of conventional chemical processes to make them more cost-effective, productive, greener, safer, and/or less resource intensive. One emerging PI technique for adsorption-based DAC is *photocatalysis*, wherein solar light irradiation is introduced to the agents bound to CO_2, accelerating the desorption (regeneration) step. Not only does this enable CO_2 separation to occur more quickly, but it can be done at room temperature, lowering energy requirements and perhaps eliminating the need for high thermal energy (natural gas) in the process [34]. Photocatalysis in the early stages of research and development.

Finally, development of modular on-site DAC technologies is growing. Carbon Reform, for example, has designed DAC devices that are small enough to install inside buildings when interfaced with existing building ventilation systems [35]. The DAC process of these modules is very similar to traditional adsorption technologies, but instead of producing a pure stream of CO_2 gas, the output is instead a limestone slurry that can be solidified and used in green construction. These devices, therefore, combine the benefits of DAC and CCU, and as a bonus, they reduce the energy use of building ventilation systems and improve indoor air quality: by reducing the CO_2 concentration indoors, there is less need for air exchange. Current configurations can capture up to 50 tCO_2 per year, per device, and each device is rated to cover about 20,000 sqft. An internal life-cycle analysis (LCA) of the process suggests that the net carbon benefit is high, even when taking into account emissions from production, energy use, and transportation of the limestone slurry, but the results are not public.

Current cost estimates from pilot projects are on the order of $\$400/tCO_2$ removed, including the capital cost of initial assessment and installation ($15,000), an annual lease ($5,000), and the operating costs of supplying the energy to power the devices (about 200,000 kWh/year for each 20,000 sqft). Carbon Reform claims a return on investment in the range of two to five years, as the energy savings and potential carbon removal credits lead the devices to begin paying for themselves. See the *Cost Comparison* section for how different DAC technologies and BERDO 2.0 compliance pathways compare in cost.

Modular on-site DAC is a promising alternative to remote DAC plants, but its effectiveness depends very much on the complexity of existing air ventilation systems within buildings: older buildings are likely to have much more complex HVAC systems that have been installed sequentially over the years, making interfacing a CO_2 removal device potentially costly or impossible. However, the devices may prove very attractive to building owners bound by public health requirements and emissions reductions ordinances like BERDO 2.0, since they can address the dual challenges of reducing energy and emissions, and improving indoor air quality.

Energy and Resource Usage

The potential for DAC to provide net reductions in atmospheric CO_2 is affected by the emissions from the fuel and electricity required to operate the facility. The monetary cost of this energy also affects economic viability.

Thermodynamics defines the minimum amount of energy required to separate one gas from another, a value that depends on the absolute temperature and the initial and final concentrations and pressures. For example, the thermodynamic minimum energy required to remove CO_2 from a mixture where its initial concentration is 0.04% (characteristic of ambient air) is about three times larger than the corresponding minimum energy when the initial CO_2 concentration is 12% (characteristic of coal flue gas) [8]. A techno-economic review of DAC suggests that an absolute lower bound for a plant's energy use (not including transport and storage) is just below 1 GJ/tCO_2 captured [36], the energy equivalent of about 7.6 gallons of gasoline. In short, separating CO_2 from ambient air, where it is dilute, requires a large amount of energy.

In practice, the energy usage of a DAC plant depends on the method of removal and its efficiency. Both absorption and adsorption technologies require large amounts of heat to regenerate the binding agents used to separate CO_2 from the intake air, and large amounts of electricity are needed to power fans, contactors, and compressors. The heat requirements are typically met by burning natural gas, but there are also configurations where DAC plants can be cited near other industrial facilities where sufficient amounts of waste heat can be recovered [37]. A reasonable range for the thermal energy requirements of DAC plants is 6-10 GJ/tCO_2 captured, with a middle value of 8 GJ/tCO_2. Similarly, the electricity requirements are likely between 1.1 GJ/tCO_2 and 1.9 GJ/tCO_2, with a middle value of 1.5 GJ/tCO_2 [36].

By 2100, gigatonne-scale DACCS could require around 50 EJ/year of electricity, equivalent to more than half of current global generation (about 10–15% of the global generation projected for 2100), and 250 EJ/year of heat, equivalent to more than half of today's final energy consumption globally [37] (Figure 8). Sourcing the energy required for such large-scale DACCS operations is likely to be a leading challenge in the coming decades, heightening the need for efficiency improvements and further development of the basic technologies.

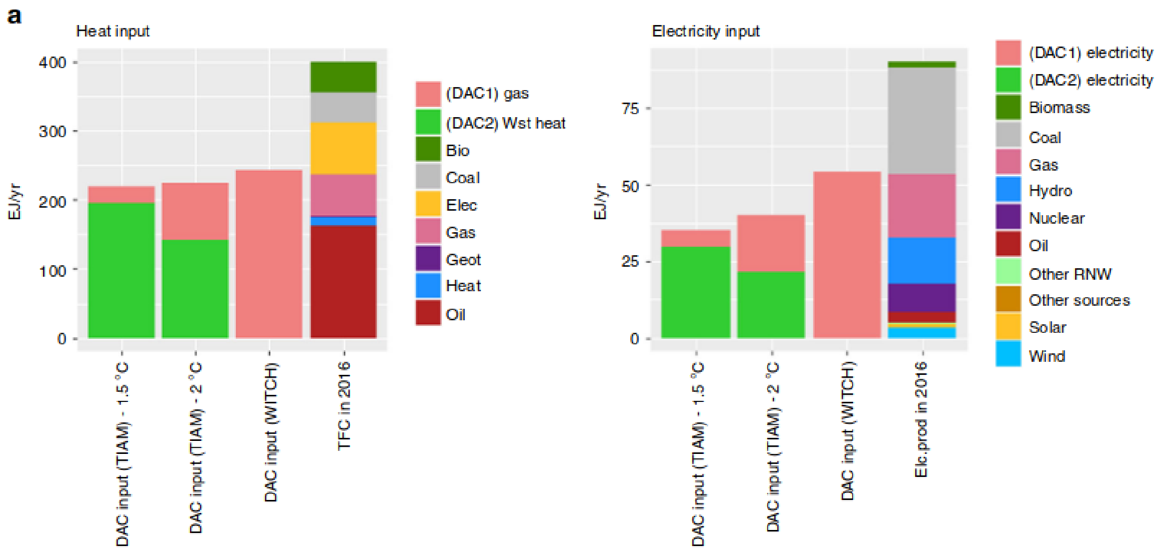


Figure 8: DACCS energy use, both electricity and thermal energy (natural gas or waste heat). TIAM and WITCH refer to the two Integrated Assessment Models (IAMs) used in the study to explore large-scale DAC deployment in order to meet Paris Agreement climate goals. DAC1 refers to absorption and DAC2 refers to adsorption. Source: Realmonte et. al., 2019.

The resource mix of the electricity powering a DAC plant will have significant effects on its realized emissions reductions. Some studies assert that it would be counterproductive to deploy DACCS if the source grid is dominated by fossil fuels [8, 9, 10, 19, 30, 37, 40]. Indeed, current configurations require thermal energy and electricity at scales of around 10 GJ/tCO_2. That is a gross estimate, meaning that it does not account for inefficiencies in the conversion of upstream primary energy to the final energy used in a DAC plant. [41]. Since the combustion of coal and methane release 9 to 11 GJ/tCO_2 and 20 GJ/tCO_2, respectively, currently configured DAC systems could not realistically rely on them as primary energy sources and yield significant realized reductions in atmospheric CO_2 [36].

Carbon Engineering reports a DAC plant with a capacity of 1 $MtCO_2$ removal/yr that requires 5.25 GJ of natural gas and 366 kWh of electricity per tonne of CO_2 captured. The natural gas input is burned on-site and the plant captures those emissions, so that the realized annual capture rate is 1 $MtCO_2$, assuming zero-carbon electricity. Figure 9 illustrates the emissions released by such a plant from its electricity use in different eGrid subregions of the US. There is an emissions penalty of up to 25% depending on the carbon intensity of the regional grid. For example, a 1 $MtCO_2$ per year plant connected to the coal-intensive SMRW grid in the midwest would realize 0.75 $MtCO_2$ per year. The same 1 $MtCO_2$ per year plant connected to the nuclear and hydro-intensive grid serving upstate New York would realize an annual net capture rate of 0.96 $MtCO_2$. If these plants were not capturing the emissions from burning natural gas, this penalty would be higher (Table 2). Note that these net emissions estimates do not include emissions from transport and storage of the captured CO_2. Source calculations for both the map and table can be found in Appendix B.

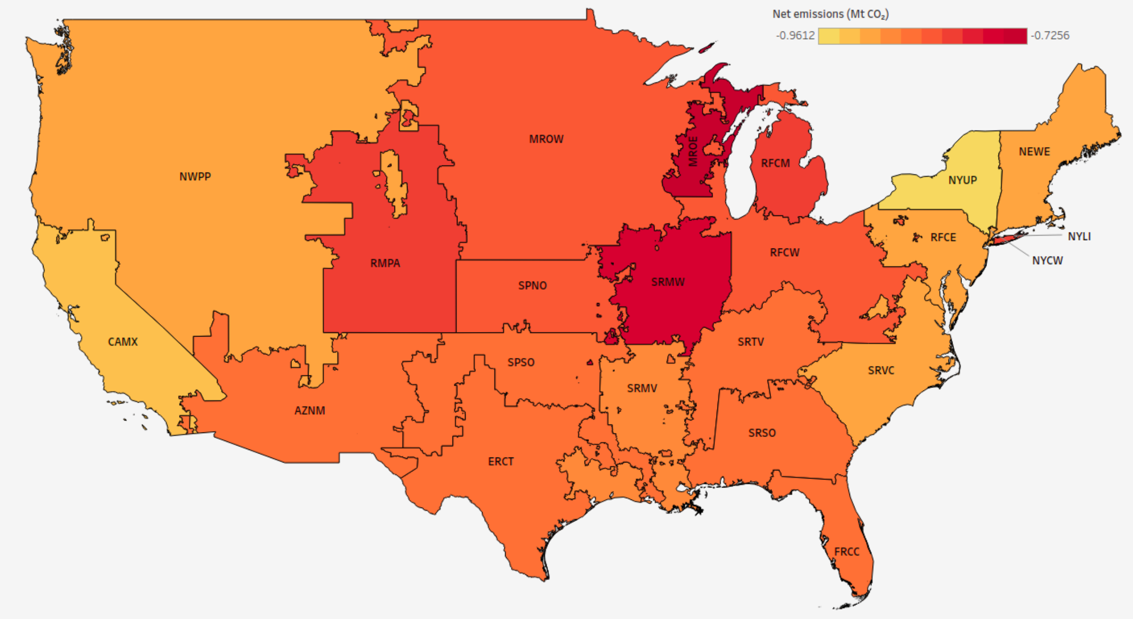


Figure 9: Map of realized carbon benefit from a reference Carbon Engineering DAC plant [13] by eGrid subregion in the contiguous United States [38]. Emissions sources include only the electricity used to power the plant and regenerate the binding agents, but not the natural gas used for thermal energy or emissions from transportation and storage. A full visualization with tooltips can be found in Appendix C.

Table 2: Realized carbon benefit of a DAC plant following Carbon Engineering's DAC plant if the natural gas burned on-site for regeneration is not captured. This plant has a capture capacity of 1 MtCO2/yr with an energy input of 8.81 GJ of natural gas, or 5.25 GJ of gas and 366 kWh of electricity per tonne of CO_2 captured [13].

Alternative energy mix configurations	**Annual Capture Rate ($MtCO_2$)**	**Emissions from fuel and electricity ($MtCO_2$)[2]**	**Realized Carbon Benefit ($MtCO_2$)**
Version 1: 8.81 GJ of natural gas per tonne captured	1	0.443	0.557
Version 2: 5.25 GJ natural gas + 366 kWh electricity per tonne captured	1	0.400	0.600

DAC plants demand large amounts of other resources besides energy. Aqueous solutions in absorption systems by definition also demand continuous water usage, and because of the capture and regeneration cycles, these systems are prone to potentially significant water loss via evaporation. Estimates range widely from 0-50 tonnes of water lost per tonne of CO_2 captured, but are likely to land between 5 and 13 tonnes during normal operation [36]. Land requirements vary, but the American Physical Society estimated that a 1 $MtCO_2$ annual capture facility would require a footprint of up to 1.5 km^2 [8]. Much of this footprint is attributed to the contactor because atmospheric CO_2 is in such low concentrations that large volumes of air must pass through the system.

At the gigatonne scale, the total land requirements of DAC plants may be significantly less than that required for other negative emissions technologies, such as afforestation or BECCS, and may also use less water (Figure 10) [37]. Thus DACCS may have

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[2] Average U.S. grid emissions factor from [38]; natural gas emissions factor from [39].

advantages over other CDR strategies, which because of their higher land and water needs, are more likely to compete with other important uses such as food and energy production.

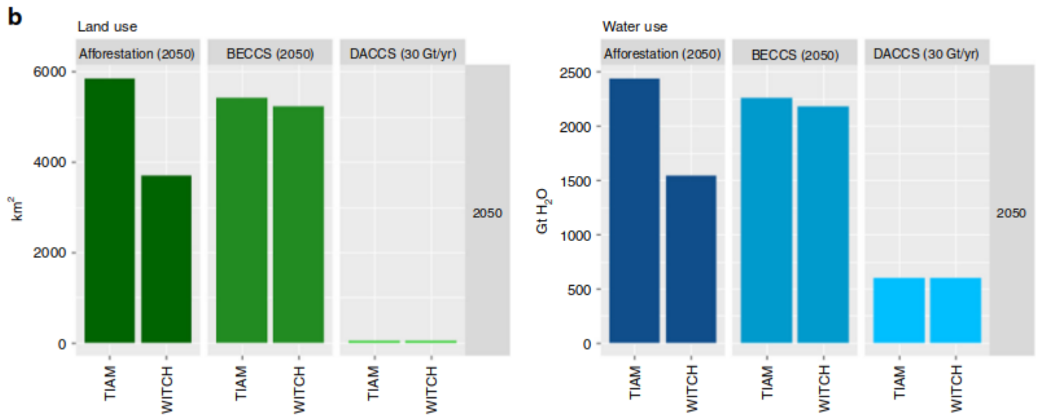

Figure 10: Land and water use of DACCS, compared to the same for other negative emissions technologies such as afforestation and BECCS. TIAM and WITCH refer to the two Integrated Assessment Models (IAMs) used in the study to explore large-scale DAC deployment in order to meet Paris Agreement climate goals.
Source: Realmonte et. al., 2019.

Current Status and Challenges

Projects in Action

The U.S. National Energy Technology Laboratory (NETL) maintains a database of nearly 300 worldwide carbon capture and storage projects, including those that are active or have been proposed or terminated [42]. Their summary states that “the 299 site-located projects include 76 capture, 76 storage, and 147 for capture and storage in more than 30 countries across 6 continents. While several of the projects are still in the planning and development stage, and many have been completed, 37 are actively capturing and/or injecting CO_2.” Of these, some of the most prominent active DAC plants have been developed by Carbon Engineering (Canada) [13] and Climeworks (Iceland), of which only one, by Climeworks, is a complete DACCS system (Orca) [12]. The Global Energy Assessment Report in 2012 also identified planned and existing CCS projects of varying sizes across the globe (Figure 11) [43]. Not all of these are DACCS projects, and many incorporate EOR or natural gas production.

Some cities in the United States have discussed CDR as a potential means to reduce emissions, or are currently in the process of doing so, though none use DACCS. These include: the Four Corners region of Boulder, Colorado [44, 45] and Flagstaff, Arizona [45, 46] (soil carbon sequestration, afforestation); Marin County in California [47] (soil carbon sequestration, regenerative agriculture); and Park City, Utah [48] (regenerative agriculture). The removal capacity of these projects is small: 2,500 tCO_2 (or 0.0025 Mt) planned in the Four Corners region, and up to 7,686 tCO_2 (or 0.0077 Mt) in Park City; Marin County values have not yet been published.

In Germany, the city of Bremen will become the site of the country's first CO_2 export terminal, built by the Norwegian management and technical consulting company CO_2 Management (CO_2M) AS [49]. The hub will function as a receiving station for industrial sources of CO_2, which will then be transported for storage elsewhere, such as to the North Sea. According to the company, the planning, approval, and construction of the CO_2 hub are still in their incipient stages, and as such operations at the terminal will not start for "several years" [49]. It is unclear what the business model or financial incentives for CO_2M are, but the company has called for "cooperation" from other industries to speed up development. It's possible that CO_2M is betting on investments from a funding directive that was announced by the German government earlier in the year [50]. At the time of the announcement in May 2022, there were no operational DAC or CCS plants, but the initiative has the potential to "establish networks and ties with countries like Norway that also plan ambitious carbon capture projects" [51].

For its part, Fortum Oslo Varme in Oslo, Norway is operating a joint BECCS and PSC project that captures 400,000 tonnes of CO_2 annually (or 0.4 Mt), transporting the gas for subsea storage in saline aquifers located in the North Sea [52]. The transport and storage components, along with one carbon capture facility, are fully funded by the Norwegian government, and the project is a joint venture of Equinor (a petroleum refining company), Shell (an oil company), and TotalEnergies (previously Total, an integrated energy and petroleum company) [52]. Additional funding is anticipated to come from other parties, such as the EU, or from individual countries like Germany who may use it as a storage solution for their own projects.

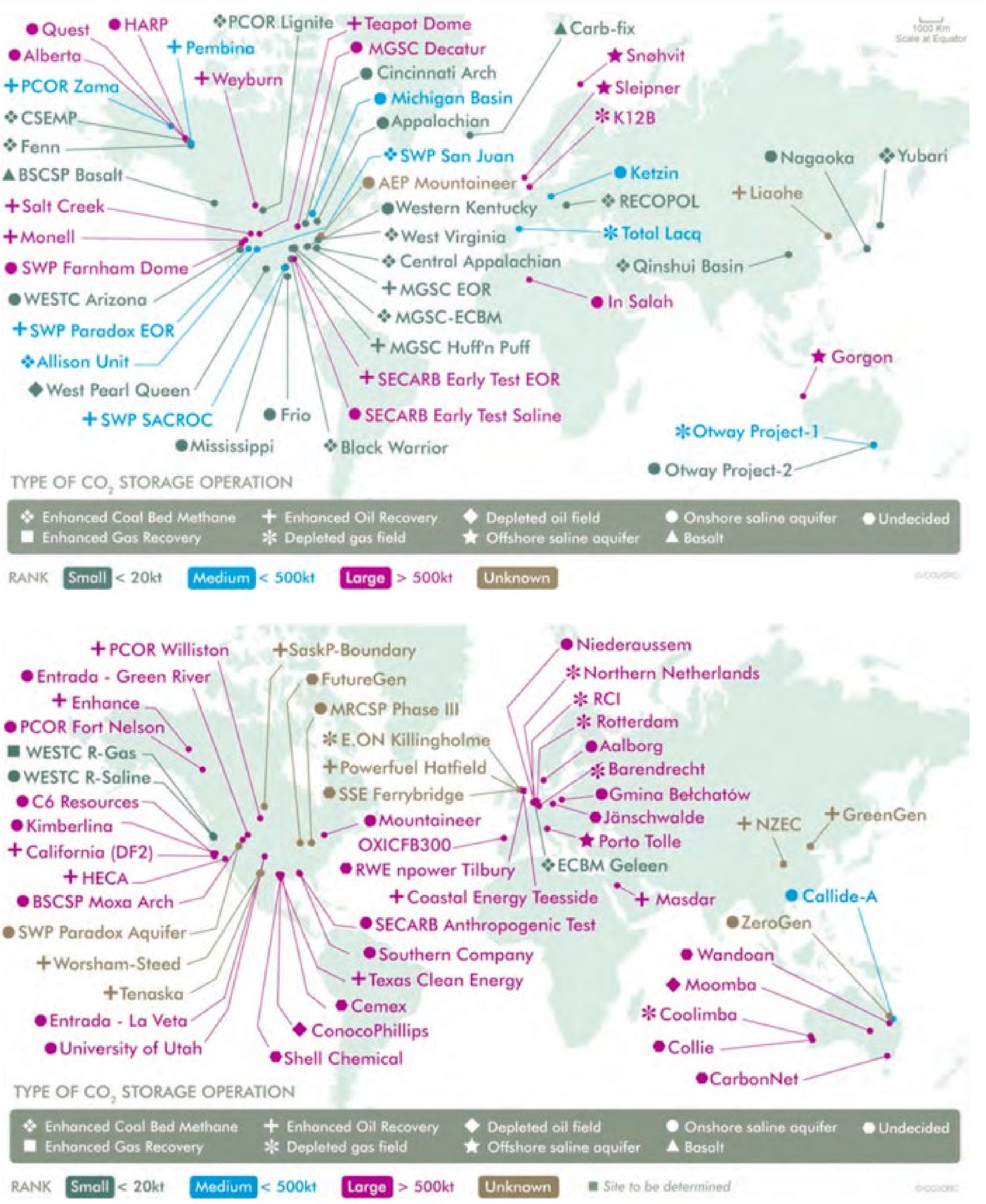

Figure 11: Location of existing (top) and planned (bottom) CCS projects, including commercial projects, pilot tests, and demonstration projects.

Source: Global Energy Assessment, 2012.

Cost Comparison: DACCS vs Alternative Compliance Pathways and Payments

The cost of CO_2 removal from DACCS compared to alternatives is a principal determinant of its potential as a climate policy instrument. Here we outline the estimated costs associated with DACCS and compare those costs with current alternative compliance pathways under BERDO, including PPAs, RECs, and alternative compliance payments.

The two principal cost categories for a DACCS system are:

1. **Capital cost**, which is the initial cost of building a DAC plant and the associated CO_2 compression, transport, and storage infrastructure; and
2. **Operating cost**, which is the recurring cost of running the system and includes fuel, water, sorbents and solvents, maintenance of parts, labor, overhead, etc. Included here is the cost of separating CO_2 from the intake air and compressing it for transport and storage.

In the literature, DACCS costs are also framed as **capture cost** (the cost of separating CO_2 from air and compressing it for storage) and **avoided cost** (the total capital plus operating costs across the entire process, from capture to permanent storage). The distinction is important because separation of CO_2 from the air is only part of the overall DACCS process. Table 3 briefly describes some of the factors that can influence the cost components of DACCS.

One techno-economic review suggested near-term (before 2040) capital costs in the range of $300 million and $3 billion, with a midpoint estimate of $1.6 billion, for a DAC plant with a 1 $MtCO_2$ capture capacity [36]. The same study estimated that cost reduction would eventually lead to a range of $20-200 million, with a midpoint of $100 million. Cost reductions come from economies of scale, technology improvements, and learning by doing. These learning and experience effects are well-documented in other industries such as solar panels and computer chips [54]. Note that 'near term' and 'long term' are often poorly defined.

Operating costs will be largely governed by fuel mix and energy prices, and can affect the capital cost as well as the capture and avoided costs in turn. A reasonable range for operating costs is \$10-200/tCO_2, with a middle value of \$100/t [36]. The wide range indicates great uncertainty, underscoring the need for more data from operational DAC plants. Operating costs are not likely to vary as much over time as capital or capture costs.

Table 3: Some factors affecting costs of DACCS.

Factor	**Capital cost**	**Operating cost**	**Capture cost**	**Avoided cost**
CO_2 pipeline diameter				X
Distance to a storage site				X
Fuel and electricity		X	X	X
Purchased equipment	X		X	X
Maintenance		X	X	X
Labor		X	X	X
Replacement of consumables (eg. chemicals, water)		X	X	X
Land lease and/or purchase	X		X	X

Table 4 summarizes various estimates of capture and avoided costs of DACCS and compares these to estimated costs of existing alternative compliance pathways and payments under BERDO 2.0. For comparison, the first row of the table also includes the capture cost of a PSC plant, to highlight the effect that CO_2 concentration can have on the economic viability of CDR systems.

Table 4: Cost comparison of DAC or DACCS with existing BERDO compliance pathways.

System or program	**Cost (USD)**	**Explanation**	**Cost(s) Included**
CDR methods and/or projects, with estimated costs:			
PSC plant, with an input stream from the flue gas of a coal-fired power plant.	\$80/tCO_2 captured [8] (2011)	CO_2 concentration in the flue gas is 300 times more concentrated than a DAC system, leading to higher efficiencies.	Only **capture cost**, i.e. missing cost of transport and storage.
"Benchmark" absorption-based DAC plant with a capacity of 1 MtCO_2/yr.	\$610-780/tCO_2 captured, with an upper bound of \$1,000/t [8] (2011)	Optimistic assumptions about some important technical parameters. Significant uncertainties result in a wide, asymmetric range associated with this estimate, with higher values being more likely than lower ones.	Only **capture cost**, i.e. missing cost of transport and storage.
Based on a survey of second-law efficiencies (the ratio of minimum thermodynamic work required vs actual	On the order of \$1,000/tCO_2 captured [40] (2011)	Analysis was done as an extension of "the Sherwood reasoning," referring to the well-known Sherwood plot which shows that the	Only **capture cost**, i.e. missing cost of transport and storage.

work expended) of existing trace gas separation processes and concentration factor.		cost to separate a given substance from a mixture scales inversely with the initial concentration of that substance. Such estimates have been accurate to the order of magnitude of the actual cost [27].	
Generic DAC system, if implemented in the 'short-term' (before 2040).	$100/tCO$_2$ (optimistic) $550/tCO$_2$ (pessimistic) $200/tCO$_2$ (middle) [36] (2015)	Based on a techno-economic review of DAC literature, with participating studies giving estimates ranging from $100-$1000/tCO$_2$.	Only **capture cost**, i.e. missing cost of transport and storage.
Generic DAC system, if implemented in the 'long-term' (after 2040).	$40/tCO$_2$ (optimistic) $140/tCO$_2$ (pessimistic) $95/tCO$_2$ (middle) [36] (2015)	Long-term total costs of DAC can be expected to fall due to the economies of scale, learning by doing, etc.	Only **capture cost**, i.e. missing cost of transport and storage.
Operational pilot 1 MtCO$_2$/yr aqueous absorption-based DAC plant. The energy input is 8.81 GJ of natural gas, or 5.25 GJ of gas and 366 kWh of electricity per tonne	$94-232/tCO$_2$ captured [13] (2018)	Estimated range is based on financial assumptions, energy costs, and choices of inputs and outputs.	Only **capture cost**, i.e. missing cost of transport and storage.

of CO_2 captured.			
Orca, Climeworks' largest (4 $\text{ktCO}_2\text{/yr}$) DACCS plant.	$\$1,200/\text{tCO}_2$ avoided (the price of purchasing a 'removal credit' from the company) [12] $\$600/\text{tCO}_2$ avoided (the price of purchasing bulk 'removal credits') [55] Goals: reach $200-300/t by 2030 and $100-200/t by 2045 (both avoided costs) [55] (2022)	Orca is Climeworks' only DAC plant that does not simply recycle carbon, but instead stores it for permanent removal in geological formations. In addition, these are the values published by the company as the price to purchase removal, which may not necessarily reflect the actual complete cost of DACCS for Climeworks.	**Avoided cost**, i.e. both **capture cost** and cost of transport and storage.
Alternative compliance pathways under BERDO 2.0:			
PPA	$50/MWh, or about $\$12/\text{tCO}_2$ avoided [38, 57]	According to the Lawrence Berkeley National Laboratory, most PPA markets in the nation have levelized PPA rates of $50/MWh or less. The NEWE grid, which includes Massachusetts, emits about 0.240 $\text{tCO}_2\text{/MWh}$. Note: under BERDO, PPAs can only be used to address emissions from electricity use, not fossil fuels for heating and cooling.	

Class I RECs	\$44 each, or about \$10.50/tCO_2 avoided [30, 38]	Eligible RECs under BERDO 2.0 are those that are generated by Class I non-CO_2e emitting renewable sources [4]. 1 REC = 1 MWh of renewable electricity. The NEWE grid, which includes Massachusetts, emits about 0.240 tCO_2/MWh. Note: like PPAs, under BERDO, RECs can only be used to address emissions from electricity use.
Alternative compliance payments	\$234/tCO_2e emitted [4]	This price may change over time, as the value is reviewed every 5 years by the BERDO Review Board and the City of Boston's Environment Department. Payments go towards the Equitable Emissions Reduction Fund, which supports projects to address emissions from Boston buildings and prioritizes benefits to Environmental Justice communities.

Clearly, the costs of various DACCS systems are still widely variable, and may not be comparable to other BERDO compliance pathways such as PPAs and RECs for some time. Optimistic lower estimates of per-tonne costs, especially those by [13, 36], suggest that DACCS might have costs on the order of the alternative compliance payments, which may incentivize the purchase of "removal credits" for emissions from heating and cooling, which often require the burning of fossil fuels (see *Verification, Carbon Accounting*).

Verification, Carbon Accounting

Assessments: Lessons from the Offset Market

The promise of DACCS is cost-effective storage of CO_2 on the order of thousands of years, effectively removing it from the atmosphere and reducing the concentration of GHGs. This will require both continuous monitoring of storage sites to verify their efficacy, and a careful, transparent accounting of both the lifecycle emissions of the system and the stored emissions. In the carbon offsets market, carbon registries track and evaluate offset projects via rigorous criteria in order to guarantee a verifiable carbon credit, which can be bought and attributed to an individual or an organization. With CDR gaining more attention and support for development, there is a growing need for creating a credit system for negative emissions, similar to the offset verification system. In April 2022, the American Carbon Registry launched one such registry infrastructure, which will provide removal credits for natural CDR methods such as afforestation and reforestation, and technological methods of CCS, such as DAC and PSC [58]. Other registries, including Verras and Gold Standard, are primarily focused on nature-based CDR over technological methods (see *Appendix D* for more detail on registries and other CDR industry players). A 2021 study in *Climate Policy* of existing and proposed carbon removal credit certifications revealed “ambiguity” in a large ecosystem with often competing standards for what constitutes carbon removal, and a “plethora of [removal] activities without standards” [56]. Such inconsistency is not likely to inspire confidence in carbon removal credits among regulators, buyers, and the general public. If certifications are not standardized, carbon removal credits are likely to repeat the mistakes - and garner the same resulting mistrust - as offset markets, which are notably absent from BERDO 2.0 and similar ordinances.

One issue is that reported values of avoided CO_2 (that is, CO_2 that has been both captured and stored in DACCS) must also account for the emissions from energy sources needed to run a DAC plant (Figure 12). As discussed above, DAC requires not just electricity, but also in some cases natural gas for thermal energy where waste heat or geothermal resources are not available. The map in Figure 9 quantifies the importance of indirect emissions. For this reason, projects should clearly differentiate between **captured CO_2** and **avoided CO_2**, similar to how the costs are separated. This can be done through an independent life-cycle analysis (LCA), such as that published in *Nature Energy* for two of Climeworks' DAC plants. The scope of the LCA includes all flows of energy and materials throughout the DAC plant life cycles, including construction of the plant, manufacture of materials and chemicals, and energy use. The study found that their carbon capture efficiencies are 85.4% and 93.1% [59], which means that the two plants re-emit 14.6 or 6.9 tCO_2 for every 100 tonnes captured, respectively. Similar LCAs should be carried out for all steps along the DACCS chain, including transportation and storage, to evaluate progress towards emissions goals.

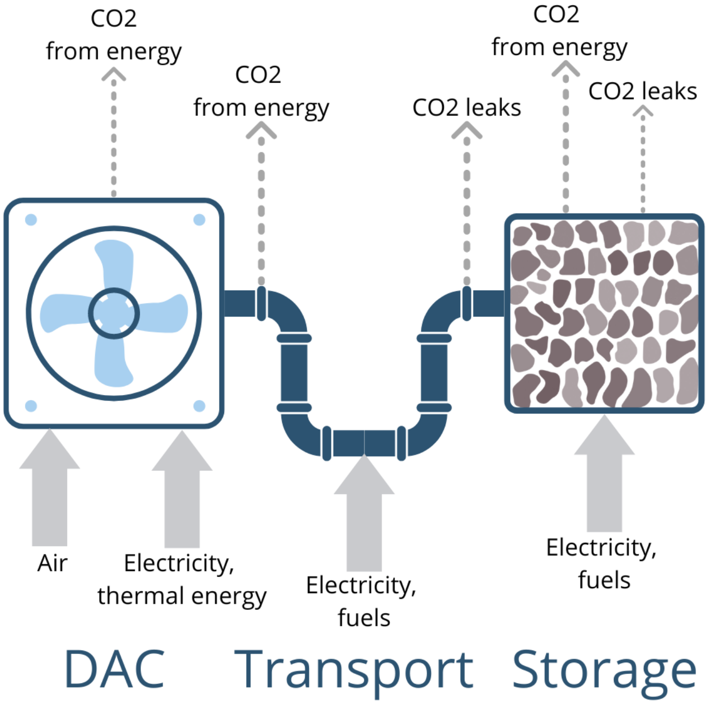

Figure 12: Diagram of energy and other inputs, and CO_2 outputs, of a DACCS system, from the DAC plant to pipeline transport to geological storage. Accounting for both the emissions from each step and the CO_2 removed is crucial to evaluating its effectiveness.

Ensuring Permanence of Storage

To minimize leakage, projects that incorporate geological storage must consider factors affecting the long-term integrity of the caprock that prevents CO_2 from exiting the reservoir. Geochemical reactions, pressure, and temperature can induce leakages from geological storage. Human factors include a poor sealing job (primarily done with cement) [60]. Moreover, CO_2 injection can induce earthquakes that can damage surface and subsurface infrastructure and reduce the integrity of the reservoir itself. For example, supercritical (high-pressure) CO_2 injection in the Cogdell oil field north of Snyder, Texas for EOR may be a contributing factor to seismic activity taking place in the surrounding area between 2006 to 2011: eighteen earthquakes of magnitude 3 or above have occurred there since operations began in 2004 [61]. Although earthquakes of this magnitude typically only cause minor damage, they can affect seal integrity, increasing the potential for CO_2 leakage [62].

A storage site must be carefully selected and monitored to ensure that reservoir pressures are kept low, thereby reducing the probability of leakage over time due to what are called secondary trapping mechanisms. Secondary trapping mechanisms include solubility trapping, where the CO_2 dissolves into brine already present in the porous rock, increasing its density and causing it to sink to the bottom of the formation over time, strengthening the trapping of the CO_2 [37]. Over longer time scales, the CO_2 can form carbonate minerals that are even a longer-lasting mode of storage (Figure 13). Experiences with projects having large amounts of monitoring data, such as the Sleipner natural gas processing Project in the North Sea (0.9 $MtCO_2$/year) and the Weyburn EOR Project in Saskatchewan, Canada (3 $MtCO_2$/year), have demonstrated a high degree of containment [43]. Generally, the risk of CO_2 leaking from a storage site is highest after injection begins, peaks when injection stops, and steadily declines over time [43].

A thorough risk assessment of storage candidate sites, particularly of the early stages of injection, will lead to proper site selection, characterization, and decision-making [60]. One example of a risk assessment, management, and communication framework for CO_2 storage, proposed by the International Energy Agency (IEA) is shown in Figure 14.

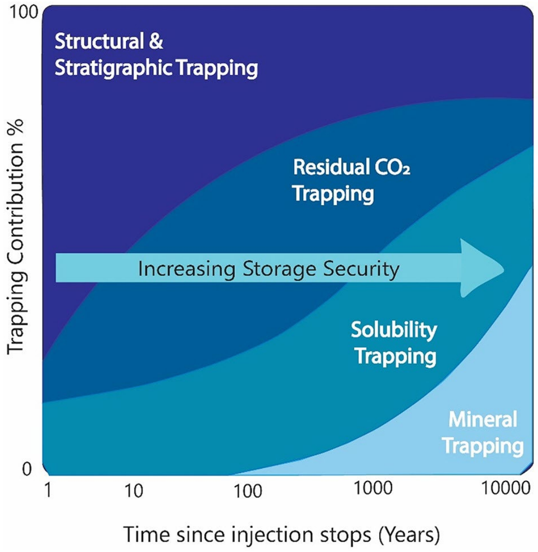

Figure 13: the role of secondary trapping mechanisms in increasing storage integrity.
Source: Gholami, Raza, & Iglauer, 2021.

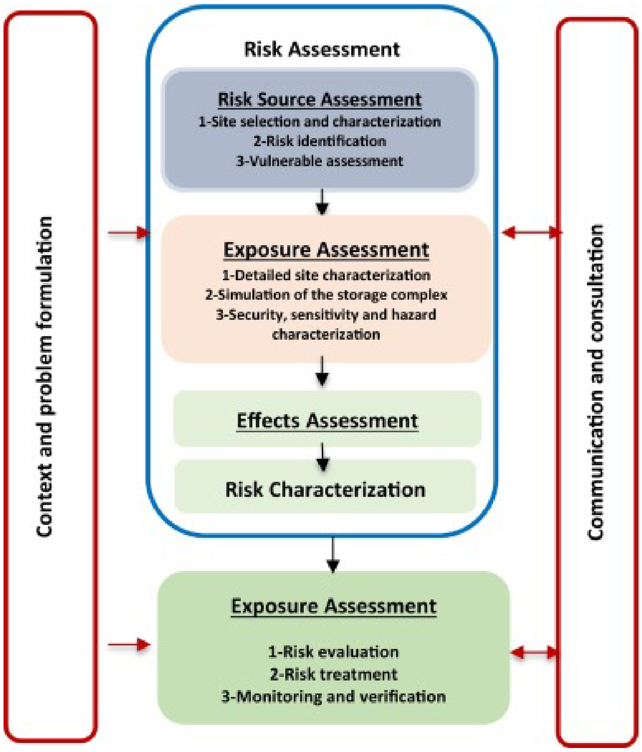

Figure 14: IEA GHG recommended risk assessment, management, and communication framework for CO_2 storage projects.
Source: Korre & Durucan, 2009.

Carbon Accounting

DACCS projects should be assessed by rigorous carbon accounting methods to measure and verify that the quantities claimed to be captured and stored are "real." It is especially important to distinguish "gross" from "net-negative" emissions [64, 65].

In addition, CDR should not be deployed and then used as a rationalization for reduced investment in emissions reduction. A study of 80 CDR stakeholders and experts, which included policymakers, business people, academics, and non-governmental organization representatives from nine countries, emphasized that CDR must deliver *additional* carbon removal, and should not be used as a substitute for cost-effective emissions reductions. Failure to do so could lead to the 'locking-in' of socioeconomic and technological configurations that sustain or encourage fossil fuel use, such as EOR [64]. As an example, consider the agricultural sector, which has great capacity to contribute to CDR but also significantly contributes to global emissions:

> [Agricultural emissions] (e.g., those related to meat production) are more politically difficult to reduce than technically (in that dietary change could deliver substantial reductions). Imagine then an agriculture sector, challenged to achieve net-zero, which invests in soil carbon management and perhaps some biochar or enhanced weathering, while continuing to produce large quantities of beef. Its emissions might be somewhat reduced by adoption of renewable energy and other changes in practice and management, and largely offset by its negative emissions from soil management. However, the same sector, pressed first to minimize emissions and supported by promotion of dietary change, could cut its residual emissions dramatically, and additionally free up land for biomass production, perhaps for BECCS. In this scenario the same sector makes a significant net-negative contribution to the national or global goal [64].

This scenario is not unique to individual sectors. It is easy to imagine an organization or a country with the capability to deliver substantial net-negative emissions, but that instead chooses the cheaper and politically more attractive route of net-zero. This route obviously leaves more CO_2 in the atmosphere. Separating emissions reductions goals from negative emissions targets, combined with evaluation by independent groups, could avoid these pitfalls and the "vested interests in continued emissions or in carbon removal technology" [64]. This has direct implications for climate justice: some advocates argue that high-income nations should assume responsibility for not just emissions reductions, but should also be investing in net-negative technologies. This would lessen the economic burden on low-income countries that have least contributed to historic emissions. Furthermore, a focus on emissions reduction while CDR methods develop and become more efficient, reliable, and the associated infrastructure and monitoring are built, lessens the burden on ramping up or inventing these systems quickly in order to undo emissions later. As a result, emissions reduction methods deployed now will be cheaper than relying wholly on negative emissions later [10].

Scale

The largest operational DACCS facility, Climeworks' Orca plant, captures and stores 4 ktCO_2 (or 0.004 Mt) annually. To give a sense of scale, removing 1 GtCO_2/year would require 250 billion similar plants to be built and operating globally. Removing 12 Gt, the annual removal needed starting in 2050 according to the IPCC, would need 3 trillion plants. Finally, the cumulative total removal of 380 GtCO_2 from 2050 to 2100, which will likely be needed to counteract an 'overshoot' beyond 1.5°C of warming, would require 950 trillion plants. The current state of the technology and infrastructure, coupled with the vast resources, development, and policies still needed to reach these targets, requires that the industry and policymakers begin thinking about scale now, in order to have thousands of DACCS plants operational and permanently storing carbon by 2050.

How do the plant-level cost estimates described previously translate into a scaled, global industry of carbon removal to meet a given emissions reduction target? First, consider that climate stabilization requires reducing the concentration of CO_2 in the atmosphere, which in July 2022 stood at 419 ppm. Limiting concentrations to 450 ppm is often associated with a target for a global average temperature change of 2°C [66], which means rapid emissions reduction/removal is needed now. Given global emissions rates even with some mitigation, the IPCC estimated that this budget would be completely spent by 2043, necessitating that carbon removal be operational by mid-century. The costs associated with these operations, assuming various per-tonne capture costs, range from hundreds of billions of USD [67] to $1 trillion [66, 68] per ppm. Despite the disagreement in order of magnitude, one thing is clear: scaled DACCS for climate mitigation will require significant and continued investment. For such vast investments to materialize, carbon capture must "be cost-effective and needs to create value that is bigger than its cost" [10].

The Task Force on CO_2 Utilization at the U.S. Department of Energy (DOE), presented a 2016 report outlining the RD&D potential and challenges of DACCS, including scale:

> To appreciate the magnitude of $GtCO_2$ per year, it is noteworthy that only a few industries match that scale today, such as steel, concrete, agriculture, as well as coal, oil and gas. These industries pervade our economy and have taken decades to develop. Hence, creating the infrastructure needed to manage $GtCO_2$ per year presents an unprecedented significant challenge....Furthermore, it is unlikely that a technology could be scaled to 1 $GtCO_2$/yr if it would be a stretch for the technology to be scaled to 0.1 $GtCO_2$/yr.
>
> Deployment for a 1 $GtCO_2$/yr scale requires capabilities and large-scale investments that can only be achieved by the private sector. It also involves regulatory compliance and business models, posing complex execution challenges. The choice of how scaling is achieved and how this landscape is navigated has implications for how rapidly the cost can be reduced down a technoeconomic learning curve and how risks are managed for large-scale investments.
>
> ...An endeavor at this scale will inevitably have consequences, intended and unintended, on our biosphere. Many of these consequences are difficult to predict a priori. It is critical that the RD&D has a continuous effort to understand the consequences of the $GtCO_2$/yr-scale of net decrease in emissions so as to minimize the ill effects and maximize the positive impacts. This will require a robust and widespread monitoring program of our climate and biosphere.

> Such an endeavor will require a continuous supply of skilled people, implying that education of a large workforce will be important.
>
> Finally, it seems inevitable that to achieve 1 $GtCO_2$/yr scale, there will need to be a charge on CO_2, either through a price or via regulations or a combination of both [67].

Many of the conversations surrounding CDR have been at the global level, for understandable reasons: the sheer scale of a coordinated effort to remove gigatonnes of carbon from the air, a range of incentives within individual countries, and the need for global cooperation, as climate goals such as the Paris Agreement, the Kyoto Accords, and others stress. In the end, however, individual actors deliver CDR [69], and there are potential political barriers to a scaled and cooperative CDR industry. The scale challenge is highlighted in this discussion of BECCS:

> [T]he BECCS supply chain may span several countries, requiring some harmonization in policies between countries to get incentives correct. It could be that biomass harvested in Cameroon would be exported to the UK for combustion and CO_2 capture, and then the captured CO_2 exported to Norway for permanent storage. The current method of reporting does not connect the bioenergy use in the UK with the biomass harvest in Cameroon, making it difficult to assess carbon neutrality. The CO_2 from bioenergy use, currently reported as a memo in the official GHG inventories under the UNFCCC, would need some form of payment to incentivize its capture. But this payment, perhaps from the UK government or a carbon trading system, would need a guarantee that Norway has permanently stored the carbon. An entity also needs to take the liability for a potential leakage from the geological reservoir, or if the biomass is not carbon neutral. The simple BECCS supply chain outlined here would require a detailed carbon accounting system spanning three countries, over a potential period of decades (biomass growth and permanent storage). This accounting system would need to be coupled to a system of financial transfers to incentivize behaviour. The entire system would require independent measurement,

> reporting, and verification. The accounting and financial system would have to be robustly applied across countries with vastly different motives and governance levels. Putting aside the technical and socio-political acceptability of BECCS, the governance challenges to incentivize BECCS would require resolving accounting and financial issues that remain sticking points in existing negotiations [69].

These challenges interplay with many of those already discussed: cost, energy use, and verification, as well as social and political issues described in more detail below. Each of these challenges will need to be addressed in order to scale DACCS to the level needed for gigatonne removal and permanent storage of CO_2 from the atmosphere.

Social and Political Considerations

Moral Hazard of Negative Emissions

DACCS faces significant social and political challenges. The most pressing of these is the '**moral hazard**' of negative emissions [69], which describes a "[license for] the ongoing combustion of fossil fuels while ostensibly fulfilling the Paris commitments." The concern, which has been raised by scientists and environmental justice experts, is that development of DACCS will be used not only in place of emissions reductions, but will also hinder those efforts. Examples include facilitating the growth of the oil industry because of its promises of geological storage of CO_2, when in fact fossil fuel combustion must be minimized in order to meet global climate goals. Allowing this moral hazard is a risky gamble: if DACCS and other CDR methods are unable to deliver on their promises, an oversized focus on negative emissions at the expense of actual emissions reductions today could have dire consequences that have a highly inequitable distribution of risk. If large-scale carbon removal fails or underperforms, the impacts will fall on historically low-emitting communities that are geographically and financially vulnerable to climate change [69].

Public Acceptance Challenges

DACCS cannot thrive in areas where it does not have a social license to operate. Acceptance must come from '**fenceline communities**' (those living in the vicinity of pipeline infrastructure or storage locations) [70], and from the general public, who may be mistrustful of the verifiability of removal. A focus group study of California communities that are potential sites for the pilot DOE-funded West Coast Regional Partnership project, WESTCARB, found that "communities want a voice in defining the risks to be mitigated as well as the justice of the procedures by which the technology is implemented" [71]. This sense of empowerment is key to understanding the range of CDR options and their siting opportunities and includes the "ability to mitigate community-defined risks of the technology" and protection against "the downside risk of government or corporate neglect," which are rarely identified in technical risk assessments but are crucial to securing the public acceptance of projects [71]. Germany is an example where these community-focused risks were not properly assessed: a report by the country's largest industry association specifically calls out strong public resistance as a limiting factor to development [72]. Across Europe, similar issues have deterred the development of parts of the CCS supply chains, such as pipelines for CO_2 transportation and storage in the North Sea [73].

Gaining social acceptance requires clear communication about the 'moral hazard' described above, according to a multidisciplinary group of global DACCS experts: "'People, when you talk to them about DAC, yes, they can accept it, but with reservations, and it tends to be A, 'Well, are you using this as an excuse to not do what you should on emissions reduction?' And B, it is not dealing with the root cause'" of emissions [70]. Further, potential projects will be "'in trouble if we think we can just rush forward without including local communities'" because "'once trust is lost, it is hard to rebuild....all it takes is one project going awry. That will be amplified in news and social media and can sour other projects, as well'" [70]. DACCS proposals should therefore clearly communicate plans for monitoring the permanence of storage, local co-benefits such as job creation, integration with fence-line communities, and a clear and explicit emphasis on removal as only part of a climate action plan, not as a replacement for direct emissions reductions. The issue of public acceptance demands that considerations of equity and justice be brought to the forefront of policy and private development of DACCS, by ensuring that one group or geographic region is not overly burdened by the costs or risks and by promoting a "more globally and societally equitable sharing of risks as well as benefits" [70].

Despite these challenges, there is growing support for CDR among American voters across party lines [74]. However, it is clear that a large proportion (almost half) "do not know enough about carbon removal technologies to form an opinion," and a majority incorrectly identified measures such as protecting biodiversity and recycling as carbon removal methods [74], highlighting the need for more effective communication from trusted messengers not only about what CDR is but also its potential benefits and challenges and what role it may play in climate action strategies. Perhaps this communication initiative will be a requisite first step to equitably scaling DACCS and other CDR methods, whether with publicly run DAC plants or using economic incentives for private developers.

Policy and Economic Instruments

There have been meaningful discussions among experts about what an effective DACCS policy could look like. Some advocate for carbon being treated as a pollutant in order to reduce its occurrence and encourage its removal from the atmosphere - which would necessitate, like other wastes, that its removal be viewed as a public good. According to this recommendation, "DACCS deployment, therefore, demands a suitably high carbon price to provide a signal to markets and encourage innovation, upscaling, and economies of scale; such activities and aims must be underpinned by strong government funding, incentives, and regulation" [70]. This view also calls for a shift in perspectives about carbon and carbon removal, from the current "technological innovation problem" view of CDR and carbon as a commodity to a "sociotechnical system" of "social actors and infrastructure that includes institutions and regulators; individual users; and finance; as well as the pipes, land, soil, and material infrastructure that will do the work of moving carbon around and storing it" [75]. This vision of community control of public carbon removal projects is one where "local cooperatives elect leadership" and can emphasize environmental justice and public health concerns or direct ownership of CDR plants by municipalities.

Some policy examples exist. New York State introduced the NY Carbon Removal Leadership Act in 2021, a law that established a carbon removal procurement program through which the State purchases "verifiable, durable and equitable carbon removal services from private providers via a reverse auction" and establishes the state as a hub for carbon removal [76]. Finally, the act calls for 15% of New York's net-zero emissions plan to be accomplished either by carbon offsets or by CDR, an amendment that attempts to decrease the state's reliance on carbon offsets, which it says "may serve to further dependence on fossil fuels in hard-to-decarbonize sectors and [do] not address the issue of legacy carbon already in the atmosphere" [76]. Thus, this legislation not only creates a path for New York to more effectively meet its climate goals but also positions itself as the hub of a nascent CDR industry through investments that will help to further development and innovation. More specific details, for example which carbon accreditation registry the state will use, were not included in the bill.

Similar draft legislation by the European Union, proposed in late 2021, institutes a plan to capture 5 $MtCO_2$ annually by 2030 through both natural and technological methods [77]. This draft legislation supports The European Climate Law, which firmly sets the goal of climate neutrality by 2050 and highlights the necessity of reducing by 95% the use of fossil fuels in the EU's energy consumption. Carbon removal would help the EU meet its carbon neutrality goal, and also meet the target of 55% emissions reduction by 2030, based on 1990 emissions levels [78]. Fundamental to this plan is (1) putting in place "a regulatory framework for a clear and transparent identification of the activities that unambiguously remove carbon from the atmosphere and can decrease the atmospheric CO_2 concentration, therefore developing an EU framework for the certification of carbon removals" and fostering (2) "a new industrial value chain for the sustainable capture, recycling, transport, and storage of carbon" [78].

There is momentum towards emitting entities being responsible for carbon removal through a **carbon tax** or **cap-and-trade** system, where CDR could be incorporated as credits [79] or as a recipient of funds from the revenues, such as in the Regional Greenhouse Gas Initiative (RGGI) of the Eastern US. Both carbon tax and cap-and-trade systems encourage companies to alter their production processes to reduce emissions, and they affect consumers' decisions by causing the prices of carbon-intensive goods to rise relative to other goods. Australia and New Zealand already have national cap-and-trade systems, as do British Columbia in Canada and seven cities in China [80]. Carbon tax programs exist in various European and Scandinavian countries [80]. The main theoretical attraction of these measures is their potential to achieve emissions reductions at lower costs than direct regulations such as performance standards for vehicles and power plants. Goulder & Schein [80] find that both carbon tax and cap-and-trade policies, if properly designed, have “equivalent potential” in the dimensions of: achieving a fair distribution of the policy burden between polluters and consumers; preserving international competitiveness; and avoiding problems associated with the verification of “emissions offsets.” Both would also help avoid “problematic interactions” with other climate policies and large wealth transfers to oil-producing nations [80]. However, it is important to note that there is still debate on whether a carbon tax, cap-and-trade, some combination, or another policy altogether would be more effective economic strategies to address emissions. Perhaps most importantly, new taxes face significant public and political opposition in many countries, notably the United States.

Recently, a team of economists has argued that leaders must create an artificial market for carbon removal, through what are known as **advance market commitments**. Such commitments by governments or NGOs would set a price on carbon removal and commit billions of dollars to the cause, “specifying how much they are willing to pay to private companies for a given amount of carbon removed from the atmosphere” and driving innovation and development [81]. Advance market commitments have demonstrated success: in the early 2000s, pneumococcal diseases were killing millions of people annually around the world, and though vaccines could have been easily developed, pharmaceutical companies did not see enough financial incentive to invest in RD&D to do so. An advanced market commitment by Canada, Italy, Norway, Russia, the UK, and the Bill & Melinda Gates Foundation in 2007 promised to purchase the vaccines at a set price, thus creating a market where there wasn’t one. Three pharmaceutical companies then created the necessary vaccines, resulting in 150 million children being immunized against pneumococcal disease and saving an estimated 700,000 lives [81]. Proponents of advanced market commitments argue that the same success could be extended to CDR, because unlike a prize, which is not a business model, “an Advance Market Commitment creates a real market, with all of the benefits that come with it" [81]. Not only would this create economic incentives for carbon removal, but companies could also then get private funding and loans from banks and investors, compete with each other, and then the best technologies and methods would rise to prominence. Many companies and foundations are already beginning to fund DACCS. More and larger commitments from a coalition of governments, NGOs, and private companies can help advance the development and innovation of DACCS and other CDR technologies, driving scale and bringing costs down.

Clearly CDR, and in particular DACCS, are still new to policymakers. DAC plants that do exist are largely discrete, relatively small private projects operating in isolation from each other and other initiatives. Moreover, there is no city or municipality currently using DACCS as a policy instrument in their climate action plan. However, new federal initiatives could accelerate the process in the United States: H.R.133, passed by Congress in late 2020, authorized nearly $450 million over five years solely for CDR, including the first-ever federal program dedicated to carbon removal RD&D across various agencies and departments including the EERE and DoD [82]. The total funds set aside for negative emissions, including research into storage, amount to $65,500,000, and $43,000,000 for DAC. In addition, the Inflation Reduction Act (IRA) of 2022 promises credits of $180/metric ton specifically for DACCS projects using geological storage [83]. The act also increases incentives in Section 45Q of the Internal Revenue Code, which provides tax credits for companies to inject CO_2 for geological storage. Importantly, Section 45Q has been criticized for subsidizing EOR projects [84], which have limited carbon benefits as described above.

Whichever policy mechanism, or combination of mechanisms, is favored to drive DACCS development and implementation as a climate recovery method, three criteria will ensure success: (1) establish and verify that removal is taking place at the projects' intended levels; (2) ensure the long-term security of the carbon storage site; and (3) minimize collateral socioeconomic, health, and environmental damage to communities [79]. Given these challenges, and the complexities, uncertainties, and interactions between factors, appropriate policy frameworks must "include opportunities for regular review" and "iterative learning," which suggest introduction on a modest and gradual scale that "allows careful assessment of difficulties, adjustment to regulatory frameworks, and time for societal debate about the implications of different choices to mature" [79]. Furthermore, prudency in scaling up DACCS infrastructure highlights the need to not view it as a replacement for direct emissions reductions given the urgency of the climate crisis.

Recommendations

BERDO 2.0 or any policy that contemplates DACCS a compliance mechanism will benefit from the following “best practices” checklist:

1. **Transparent protocols for third party verification and monitoring** of storage and removal, through every step of the DACCS process (capture, transportation, and storage).
2. **Controls on carbon removal credit sellers**, including some characterization of high vs. low quality credits and an explanation of these categories, similar to RECs.
3. **Complete life-cycle assessments** of each DACCS process being used for pathway compliance to quantify realized negative emissions.
4. **Careful monitoring of the per-tonne avoided costs** of DACCS in order to gauge when it may become financially attractive to building owners.
5. **Thorough consideration of the social and political challenges** such that the deployment of DACCS infrastructure does not exacerbate existing energy, climate, and environmental inequities in vulnerable and marginalized communities.
6. **Recognition that DACCS should not be used in place of cost-effective emissions reduction** methods such as energy efficiency and electrification, perhaps as part of the hardship clause in BERDO 2.0.

Equally important to the question of *how* to incorporate DACCS into a regulatory mandate like BERDO 2.0 is *whether* it should be done at all. Here we return to the moral hazard argument, and to point 6 above. There are many parallel situations in climate policy where two competing methods purport to address the same problem, but one is pursued over the other. For example, rather than developing renewable natural gas for household use, some municipalities have instead invested heavily in home electrification that obviates the need for gaseous fuel. One can view DACCS and the range of alternative methods of addressing emissions in a similar way: directly reducing those emissions, whether by decreasing fossil fuel combustion and/or increasing energy efficiency, may be cheaper and more effective than investing in a costly new technology that demands complex infrastructure and new regulations. DAC plants, transport pipelines, and injection facilities largely do not exist, and all would need to be built, coordinated, and monitored at very large scales. On the other hand, low- and zero-carbon energy alternatives exist, with costs that increasingly out-compete the cost of electricity generated by natural gas and coal power plants; electric heat pumps are already on the market and gaining uptake through tax incentives; and deep retrofits can increase energy efficiency and save building owners money.

That being said, climate experts including the IPCC warn that negative emissions will be increasingly needed as we approach mid century, especially if emissions do not fall quickly enough. We can, and should, continue to investigate and develop CDR methods for use at scale if and when the time comes, perhaps to return to 1.5°C after an overshoot.

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Appendix A: DAC Capture Step Technical Details

Capturing CO_2 follows three sub-steps that occur in a continuous cycle:

1. Intaking air (a gas mixture containing CO_2) into the facility;
2. Separating CO_2 from the gas mixture via binding agents; and
3. Regenerating the binding agents.

Air intake is done by fans that blow the air into a contactor, where separation occurs. As the gas mixture flows through the contactor, CO_2 binds to capture agents while the rest of the gasses pass through and leave the system. The capture agents, which may be a water-based solvent, a synthetic sorbent, or a membrane structure, contain chemicals that bind to CO_2. In the regeneration stage, the CO_2 is extracted from the saturated capture agents, which enables the process to begin again. The result is a somewhat pure stream of CO_2 (up to 90% [9]), which can then be purified and compressed for transport and eventual storage.

1. Air Intake

Fans push air through *contactors*, large structures modeled after industrial cooling towers (Figure 4). Here, the gas mixture meets the binding agents, CO_2-reactive chemicals such as amines and hydroxides). As the air passes through the contactor, CO_2 collides with and binds to these agents, while nitrogen and oxygen continue to move through the system and return to the atmosphere. Structures within the contactors control airflow to maximize CO_2 uptake by the binding agents in the next step.

Figure 3: A rendering of Carbon Engineering's industrial-scale air contactor design for direct air capture. Source: Jeff Brady (NPR), 2018.

2. Separating CO_2

Separating CO_2 from gas mixtures is a well-established technology in hydrogen, ammonia, and natural gas purification plants [8]. There are two primary separation methods: *absorption* of CO_2 through water-based solvents, and *adsorption* through a synthetic sorbent. Membrane separation has also been studied but is less common. Each method has advantages and disadvantages and is applied in different situations depending on the desired capture rate, the surrounding environment, energy and resource availability, capital cost budget, and available materials.

In **absorption**, the CO_2 is transferred from the gas phase to the liquid phase in a column, which contains an aqueous solvent in which the CO_2 dissolves (Figure 15). Other gasses in the intake air (primarily N_2 and O_2) pass through the column undisturbed and are returned to the atmosphere. The solvent must have high CO_2 solubility, such as ionic liquids or basic catalysts (OH^-, NH_3) [9]. After CO_2 is dissolved, the solvent is regenerated to be used in the next capture cycle.

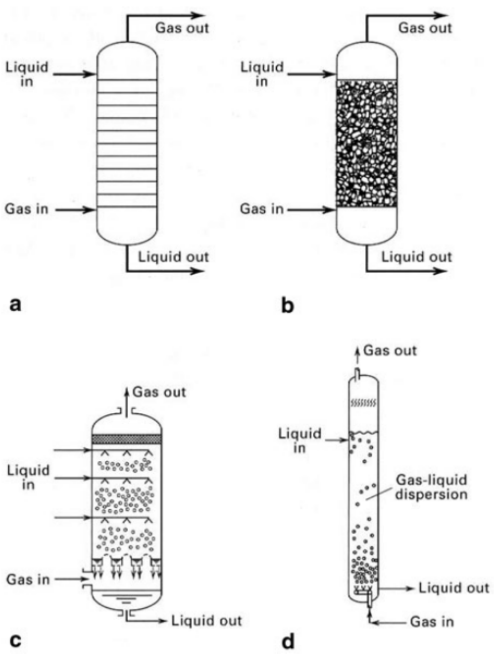

Figure 15: Industrial equipment for absorption and regeneration: (a) trayed column; (b) packed column; (c) spray tower; and (d) bubble column.
Source: Jennifer Wilcox, 2012.

Adsorption is the adhesion of atoms, ions, or molecules from a gas, liquid, or dissolved solid to a surface. In the case of carbon capture, the intake gas mixture contacts small porous particles that selectively adsorb or bind to CO_2. Both Climeworks and Carbon Engineering's DAC systems use adsorption processes, demonstrating that the technology is feasible at the kt and $MtCO_2$/year scale, respectively.

Adsorption can occur in either physical or chemical forms. In physical adsorption, or *physisorption*, the bonding forces are physical and defined by surface interactions between the sorbent and CO_2 molecules. These surface interactions are caused by differences in polarity or surface reactivity. In chemical adsorption, or *chemisorption*, on the other hand, the bonding forces are chemical, or covalent. These reactions generate heat, which can influence sorbent uptake.

There are two general types of systems associated with separation via adsorption on a large scale: fixed-bed and moving-bed adsorption processes (Figure 16). In fixed-bed adsorption, the feed gas is transported through one of the beds while the other bed is regenerated. The valves are switched so that the feed passes through the second bed, and regeneration occurs in the saturated bed when the concentration of adsorptive in the exiting gas reaches a certain point, or at a scheduled time [9]. Due to the pressure drop associated with fixed beds and the scale of CO_2 capture that is required for any significant mitigation, moving beds offer the advantage of reduced pressure drop, but do suffer from sorbent attrition, or loss, in addition to mechanical complexity associated with the equipment involved [9]. Pressure drop in an adsorption process is important as it determines the cost of blowers or fans required to pass the gas through the sorbent material.

Adsorption is particularly known for its effectiveness in the separation of dilute mixtures, which makes it an intriguing candidate for DAC, where the concentration of CO_2 in ambient air is low [9]. As in the absorption process described above, adsorption also requires regeneration (or desorption) of the sorbent used to capture CO_2.

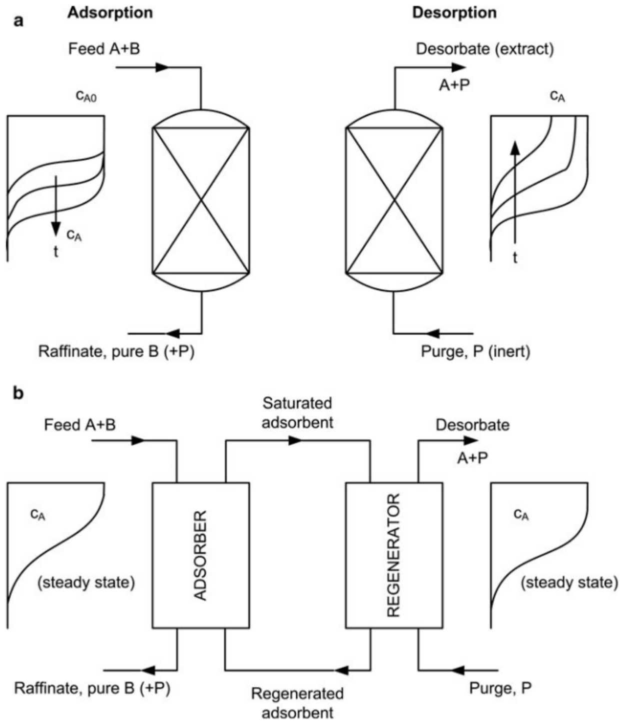

Figure 16: Adsorption and desorption (regeneration) process schematics, with (a) fixed-bed and (b) moving-bed designs. Source: Jennifer Wilcox, 2012.

Finally, CO_2-selective **membranes** can also be used in DAC. In theory, these processes have many advantages over absorption and adsorption processes, including no regeneration, ease of integration into a power plant, process continuity, space efficiency, and absence of a phase change, which can lead to increases in efficiency [9]. However, the technology has drawbacks for DAC applications. Membranes require a sufficient driving force for effective separation, especially in gas mixtures where the target gas (in this case, CO_2) is dilute. Furthermore, CO_2 has similar molecular diameters (0.330 nm) to N_2 (0.364 nm) and O_2 (0.364 nm), making size-selective separation of CO_2 by membranes ineffective for ambient air [10]. No commercially viable plant or pilot project for membrane-based DAC exists, but membranes still show promise as a method for PSC.

3. Regenerating Binding Agents

Both absorption and adsorption separation methods require regeneration of the agents that are bound to the carbon in the intake air in order to produce a somewhat pure stream of now-separated CO_2 and reuse the agents for the next capture cycle (some impurities in the CO_2 stream may remain; see *Compression and Transport*). Regeneration of the solvents used in absorption processes is a reversal of the CO_2 separation process: CO_2 is transferred back to the gas phase from the liquid phase, using heat and catalysts, thereby removing it from the solvent so that it can be used again in the next capture cycle [9]. In absorption processes, the regeneration (in this case, also referred to as desorption), also requires heat to release the CO_2 from the sorbent. Thus regeneration is the most energy-intensive step of the DAC process. The regeneration temperature is higher for the solvents used in absorption than for the solid sorbents used in adsorption: 900°C vs 100°C, respectively [11]. The high temperature requirements limit the solvent-based system's available heat sources to fossil fuels such as gas, whereas sorbent-based systems can utilize low-carbon energy sources such as geothermal heat, concentrated solar, and even some waste heat [11]. Climeworks' Orca plant uses waste heat from a municipal waste incineration plant for its desorption process [12]. On the other hand, Carbon Engineering uses on-site combustion of natural gas to meet its thermal heat requirements [13].

Both the solvents used in absorption and the solid sorbents used in adsorption degrade over time, requiring replacement. This challenge presents opportunities for research on agents with both high CO_2 uptake and longer lifetimes to improve on the current processes and limit frequent replacement [11].

Appendix B: DAC Plant Energy Use Calculations

Calculations of net emissions of Carbon Engineering DAC plant, based on 1 $MtCO_2$ annual removal and reported energy input mix [13]: link.

Appendix C: DAC Plant Emissions Visualization

Visualization can be found here.

Appendix D: CDR Industry Players

Tabel 5: CDR industry players, including private companies providing CDR, investment firms, NGOs, and nonprofits. Source: Merchant et. al., 2022 [85].

Name	**Location**	**CDR Type**
CDR Providers		
Carbon Engineering	Vancouver, B.C., Canada	DAC
Heirloom	San Francisco, California, U.S.	Mineralization
Mission Zero Technologies	London, England	DAC
Climeworks	Zürich, Switzerland	DAC, DACCS
Noya	San Francisco, California, U.S.	Retrofitted cooling towers for DAC
Charm Industrial	San Francisco, California, U.S.	BECCS
Carbo Culture	Walnut, California, U.S. Helsinki, Finland	Biochar
Carbofex	Nokia, Finland	BECCS
Running Tide	Portland, Maine, U.S.	Ocean CO_2 uptake
Climate Foundation	Seattle, Washington, U.S.	Marine permaculture
Ocean-Based Climate Solutions	Santa Fe, New Mexico, U.S.	Ocean CO_2 uptake
Carbon Cure	Dartmouth, Nova Scotia, Canada	Mineralization
Carbon Built	Manhattan Beach, California, U.S.	CCUS in cement
FutureForest	Darlington, England	Afforestation
Neustark	Bern, Switzerland	CCUS in cement

Carbix	Quincy, Massachusetts, U.S	CCUS in cement
System Actors, NGOs		
Carbon180	Washington, D.C., U.S.	All types
CarbonGap	Oxford, England	All types
ClimateWorks	San Francisco, California, U.S.	All types
Breakthrough Energy Ventures	Kirkland, Washington, U.S.	Ecosystem management, DAC
Grantham Foundation	Boston, Massachusetts, U.S.	Soil carbon, afforestation, ocean CO_2 uptake
Additional Ventures	Palo Alto, California, U.S.	Ocean alkalinity
Lowercarbon Capital	Jackson, Wyoming, U.S.	CCUS in cement, ocean CO_2 uptake

Glossary

Advance market commitments are binding contracts, typically offered by governments or financial entities, used to guarantee a viable market for a product once it is successfully developed. Generally, advance market commitments are used when the cost of developing a product is too high to be worthwhile for the private sector without a guarantee of a certain quantity of purchases in advance.

Avoided CO_2 is the net CO_2 that does not enter the atmosphere due to a carbon-capture system being in place. Avoided CO_2 is equal to the captured CO_2 minus the CO_2 emitted by the system itself.

Avoided cost is the cost per tonne of avoided CO_2 in a carbon-capture system, and must include the costs of CO_2 capture, compression, transport, and storage. In an energy system that uses fossil fuels, there will be indirect emissions associated with these stages.

Bioenergy with Carbon Capture and Sequestration (BECCS) is a “hybrid” (natural and technological) method of CDR in which dedicated crops are used both as fuel for a power plant and to capture and sequester the CO_2 emissions from that plant.

Cap-and-trade policies function on a system of tradable emissions allowances. They have two dimensions: a cap on GHG emissions to limit pollution, and a market on which to trade emissions allowances. The cap, or emissions limit, typically lowers over time [86].

Capital cost is the initial cost needed for a system to operate, after which there are only operating costs.

Captured CO_2 is the gross CO_2removed by a carbon-capture system. This does not include the CO_2 emitted by the system itself, only what it captures from the atmosphere or from a concentrated gas stream.

Capture cost is the cost per tonne of captured CO_2 in a carbon-capture system. This cost represents only the cost of capturing a tonne of CO_2, and is always less than the avoided cost in an energy system that directly or indirectly uses fossil fuels.

Carbon Capture and Utilization (CCU) is a “carbon recycling” technology that uses captured carbon in the production of fuels or materials, such as cement. CCU is not a permanent method of storing CO_2, since the utilized carbon is eventually released back into the atmosphere at the end of the product’s lifecycle, which may range from days to weeks or even years to centuries, depending on the product.

Carbon Dioxide Removal (CDR) is an umbrella term that encompasses various methods of removing carbon dioxide from the atmosphere. Some methods combine removal with storage, whether in living beings, in geologic formations or underground, or in products. Broadly, CDR is done in two different ways: “natural,” such as through forests and soil carbon sequestration, and “technological,” through chemical processes of separating carbon dioxide from ambient air or from the air produced by power plant outputs.

Carbon taxes are levies on the carbon content of fossil fuels. Because virtually all of the carbon in fossil fuels is ultimately emitted as CO_2, a carbon tax is equivalent to an emission tax on CO_2 emissions. A carbon tax is paid “upstream,” i.e., at the point where fuels are extracted from the Earth and put into the stream of commerce, or imported into the U.S. Fuel suppliers and processors are free to pass along the cost of the tax to the extent that market conditions allow. Placing a tax on carbon gives consumers and producers a monetary incentive to reduce their carbon dioxide emissions [87].

Direct Air Carbon Capture and Storage (DACCS) is a technological method of CDR that removes the gas from the atmosphere using chemicals. It involves a DAC (direct air capture) 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. The captured CO_2 must then be transported and stored in a sequestration site.

Distributed emissions, such as those from vehicles and household heating, are difficult to capture at their source, compared to point-source emissions, which can be.

Enhanced weathering refers to the preparation (grinding, milling, etc.) of substrates for the specific goal of accelerating natural weathering processes, in which CO_2 is transformed into aqueous bicarbonate ions. As the name suggests, enhanced weathering accelerates natural weathering processes, which are chemical reactions between rocks, water, and CO2. Weathering, like mineralization, is a permanent CO_2 sequestration method.

Enhanced oil recovery (EOR) is the process by which oil companies inject high-pressure CO_2, sometimes alternated with water, to push oil closer to production wells, where it can be recovered. Close to 90-95% of the CO_2 used in EOR remains underground, prompting many oil companies, researchers, and industry coalitions to push EOR as an effective carbon sequestration method. Note: EOR differs from fracking, which releases great amounts of gas stored underground by fissuring the land.

Environmental Justice populations, as defined in BERDO 2.0 and by the Commonwealth of Massachusetts, means a neighborhood that meets 1 or more of the following criteria: (i) the annual median household income is not more than 65% of the statewide annual median household income; (ii) minorities comprise 40% or more of the population; (iii) 25% or more of households lack English language proficiency; or (iv) minorities comprise 25% or more of the population and the annual median household income of the municipality in which the neighborhood is located does not exceed 150% of the state annual median income [4].

Fenceline communities, also called frontline communities, are those that are immediately adjacent to a company or industrial center and are directly affected by noise, pollution, traffic, odors, chemical emissions, parking, waste, or operations of the company or center.

Greenhouse gasses (GHGs) are gasses that absorb and emit radiant energy, causing the greenhouse effect. GHGs include carbon dioxide, methane, nitrous oxide, and ozone. The primary GHG emitted through human activities is carbon dioxide.

$GTCO_2e$, or billion metric tons (tonnes) of carbon dioxide equivalents, describes the amount of carbon in billion metric tonnes that are equivalent to the gas in question, by warming potential. By definition, one billion metric tonnes of CO_2 is equivalent to itself, that is: $1 GTCO_2 = 1 GTCO_2e$.

Mineralization of carbon is the process by which CO_2 becomes a solid mineral, such as carbonate. The chemical reaction that results in mineralization occurs when certain rocks are exposed to CO_2. The reaction is not reversible, which means that the CO_2 cannot escape back into the atmosphere; thus, mineralization is a permanent form of carbon sequestration.

Mitigation, when referred to climate change, is a human intervention to reduce the sources or enhance the sinks of GHGs.

Moral hazard is an economic term for a situation where an agent has an incentive to increase its exposure to risk because it does not bear the full consequences of that risk. When applied to anthropogenic climate change, economic incentives encourage delaying action to reduce emissions, the consequences of which are felt most by poor people and countries globally who are least responsible for historic emissions.

$MTCO_2e$, or million metric ton (tonnes) of carbon dioxide equivalents, is a common unit of measure for GHGs, and describes the amount of carbon in million metric tonnes that are equivalent to the gas in question, by warming potential. By definition, one million metric tonne of CO_2 is equivalent to itself, that is: $1 MTCO_2 = 1 MTCO_2e$.

Negative emissions describe a decrease in the atmospheric CO_2 concentration. This differs from simply reducing or avoiding emissions, which decreases the rate at which atmospheric CO_2 concentrations increase.

Operating costs are the recurring costs associated with the regular operations of a system.

Point-Source Capture (PSC) is a technological method of CDR that removes CO_2 from a confined stream of effluent at emissions sources, for example coal power plants. The concentration of CO_2 in the intake air is higher than in ambient air, therefore PSC systems can capture more absolute carbon than generic DAC systems for the same energy used by the system. As a result, PSC systems tend to have significantly lower operating and per tonne CO_2 costs than DAC systems.

Process intensification (PI) is any chemical engineering development that leads to a substantially smaller, cleaner, safer, and more energy-efficient technology.

Residual emissions are any GHG emissions that remain after technologically and economically feasible changes have been made to reduce emissions.

Sequestration of CO_2 is a process in which the gas is injected underground into geological formations, ocean storage, or mineral storage.

Sinks of carbon dioxide store or sequester gasses so that they are no longer present in the atmosphere.

Zero Net-Carbon (ZNC) Buildings are highly energy efficient buildings that produce on-site, or procure, enough carbon-free renewable energy to meet building operations energy consumption annually. In a ZNC building, carbon-based energy consumption is reduced first through building design strategies and efficiency measures, then through on-site renewable energy generation where possible, and finally through procurement of locally produced off-site renewable energy.

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