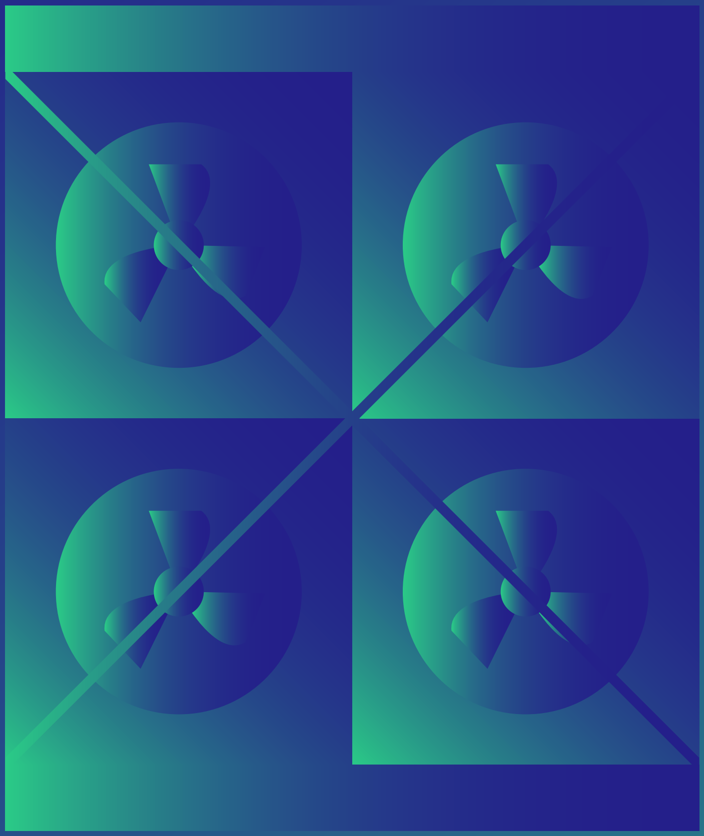
Carbon Capture

Prime Movers Lab
July 2020



Prime Movers Lab

The growing resources available to support carbon capture technologies along with domestic and foreign policy changes and increasing levels of private sector support tell us that we will see significant commercialization of carbon capture technologies in the next 10 years. Carbon capture technologies fill one of two roles: 1) reducing CO_2 emissions from industrial processes, making them more carbon neutral, or 2) removing CO_2 from the air, acting as a negative emissions technology (NET).

Two key things are happening: markets for CO_2 capture are being created, and a few CO_2 capture technologies are moving down the cost curve. A 2018 amendment turned California's Low Carbon Fuel Standard (LCFS) into a $2.5B potential market for CO_2 capture and sequestration. Clarifications on the federal "45Q" tax credit will unlock several projects for CO_2 capture from industrial facilities, specifically from ethanol production. Food and beverage, new CO_2 utilization technologies, possibly enhanced oil recovery offer growing markets for pure CO_2 (albeit small relative to total emissions).

Dave Johnson coal-fired power plant, central Wyoming / By Greg Goebelipsum

Simultaneously, new CO_2 capture technologies are being demonstrated at increasing scales. Early in 2020, Occidental Petroleum partnered with Svante to capture industrial emissions, and Carbon Engineering for a direct air capture engineering study. Another leading direct air capture startup Climeworks raised another $75mm and received a contract from tech company Stripe to offset emissions.

Looking forward, large projects (>1 million tonnes of CO_2 per year) such as the Oxy-Carbon Engineering collaboration and other projects led by the oil & gas sector will be a steady but slow area of growth, given long project timelines and the large quantities of capital required (>$500mm). With the existing state and federal tax credits to incentivize carbon capture, specifically the LCFS market and 45Q credits, most projects will be led by large corporate entities (likely oil & gas majors), who sell transportation fuels or can monetize the tax credits. A significant unknown is if big tech companies like Microsoft and Amazon, who have launched climate-related funds, will put resources towards deploying carbon capture technologies.

At a carbon tax level of $50–60 per metric tonne of CO_2, *removing CO_2 from the emissions of large industrial facilities* could be cost-neutral with today's technologies. Liquid amine scrubbing systems will likely remain the technology of choice for CO_2 capture from large industrial sources, unless there is significant process innovation around solid adsorbents or membranes. Svante, a leader in carbon capture process innovation, is a possible disrupter, and research continues into fluidized beds and other types of processes that could make CO_2 capture with solid materials more cost effective for gases with high CO_2 contents (5–30% CO_2).

The cost of *directly capturing CO_2 from air* (0.04% CO_2) will fall significantly due to innovations in solid materials for CO_2 capture, process innovations leading to more efficient material heating and cooling strategies, and optimization of carbonation technologies. This field is currently led by new companies rather than large established ones: specifically Climeworks and Carbon Engineering are currently deploying carbon capture plants. Business model innovation may enable “crowdsourcing” or corporate funding of capturing CO_2 directly from the air if capture costs can be reduced to $100 per metric tonne or less. In all cases, the ability to site carbon capture systems near pipelines, storage sites or other CO_2 users is critical.

Small scale CO_2 capture plus utilization or chemical conversion technologies mature, CO_2-to-products plays at smaller scales of 10,000–100,000 metric tonnes of CO_2 per year could become an area of rapid growth. These technologies require either very low capture costs ($40/tonne or less), or the ability to use non-pure CO_2.

Prime Movers Lab is excited about the growing opportunities for CO_2 capture, specifically in the direct air capture space. We have invested in Idealab’s “Carbon Capture” a new carbon capture startup led by Bill Gross to develop a low cost system for direct air capture that can be rapidly scaled. The growth of a US negative emissions industry will create enormous economic opportunity, create hundreds of thousands of jobs (consistent with the solar industry), and change billions of lives for the better.

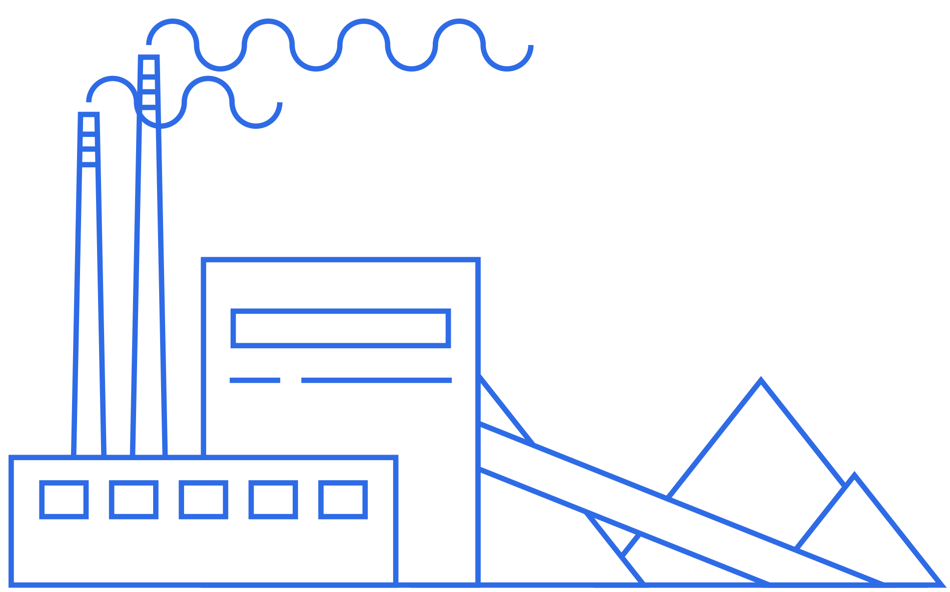
Introduction

The discussion around climate change and possible solutions is evolving rapidly. In the US, an increasing number of large companies (Microsoft, Delta, Nestle, and Stripe to name a few) have made public announcements supporting renewable energy and climate change solutions. Tree planting, regenerable agriculture, and CO_2 capture from the air receive significant attention in the mainstream media. We believe that CO_2 capture is poised to become a huge economic opportunity if carbon markets develop.

For carbon capture technologies to make a significant impact on global CO_2 emissions, they would need to capture gigatonnes of CO_2 per year scale (1 gigatonne = 1 billion tonnes = 1 trillion kilograms.) The scientific community estimates that the world's yearly CO_2 emissions (attributed to humans) are roughly 35 gigatonnes per year (Gt/yr). [1] Emissions from the US energy sector alone account for 5.3 Gt/yr. [2]

How does the scale of impactful CO_2 removal compare to the scale of money that might flow into this area? If a carbon tax appeared overnight at the level of Microsoft's recently publicized internal carbon tax — $15 per metric tonne of CO_2 — removing a gigatonne of CO_2 per year would be a $15B opportunity. (For context, Microsoft estimates that their direct and indirect activities produce 20mm metric tonnes (mt) of CO_2 annually, which means that offsetting their current emissions would cost them $300mm/yr.)

Why is **now** the right time for this technology? The amount of capital funding for climate-related technologies has increased dramatically, as has the level of public attention (which corporations are increasingly leveraging for branding and other reasons). California recently changed regulations to extend fuel credits to carbon capture. Research and development (R&D) programs under the US Department of Energy (DOE) and Advanced Research Projects Agency-Energy (ARPA-E) that began in the late 2000s and early 2010s have invested billions of dollars and raised the level of technical readiness of several technologies to the stage where they can be demonstrated at large scale in the real world. [3] The situation is similar in Europe where the European CO_2 Test Centre Mongstad (TCM) is also testing many new technologies.



Regulatory bodies in Europe are signalling that carbon pricing is around the corner (and already exists for the airline industry). The stage is set for a few companies who are able to rapidly scale and execute to break out and gain significant traction if the cost of CO_2 capture from power plants and industrial sources can be reduced to \$40/mt CO_2. [4] (This assumes the current \$50/mt CO_2 "45Q" tax credit for sequestration, and that there are some areas where transportation and storage costs are less than \$10/mt.)

The range in costs for capturing CO_2 is huge: from nearly pure industrial sources of CO_2, costs can be as low as \$20/mt of CO_2 captured. The cost of capturing CO_2 from power plant emissions is currently \$80–100/mt of CO_2, and a small-scale Climeworks facility that currently captures CO_2 directly from air reports costs less than \$600/mt of CO_2. With the exception of industrial capture from pure sources (a very mature technology), these costs will fall as additional facilities are built and scale increases. Due to regional variations in regulatory environments, demand for CO_2, and existing infrastructure, pockets exist where even direct air capture of CO_2 may be commercially viable. This is illustrated by the recently announced engineering study between Oxy Petroleum and Carbon Engineering to capture CO_2 from air and combustion gases in the Permian Basin, where it can be used directly for enhanced oil recovery (EOR). [5]

Markets and Drivers

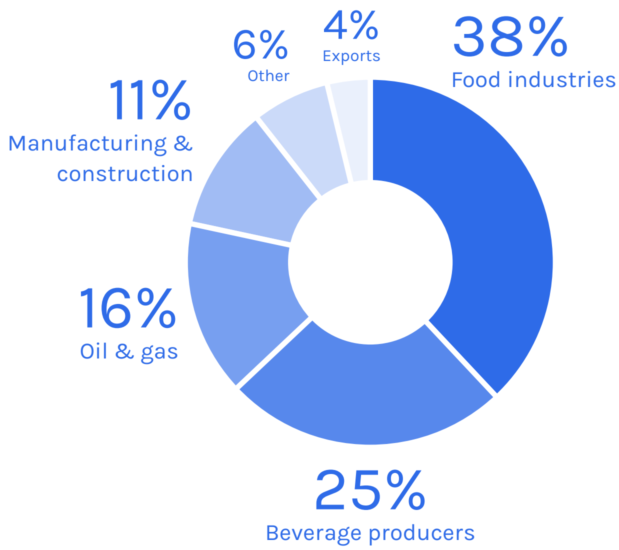
The primary challenge for carbon capture companies today is the lack of markets for these technologies. Current monetary incentives to capture and sequester CO_2 don't cover the costs in most cases, and markets for supplying CO_2 are not only difficult to break into, but are orders of magnitude too small relative to global CO_2 emissions. What incentives will create a market (and sufficient confidence) for large-scale development and deployment of carbon capture technologies, and on what timescale could this happen?

The two primary use cases for CO_2 today are enhanced oil recovery (pumping CO_2 into existing oil wells to increase oil production), and the food and beverage industry (freezing, storing and transporting food; carbonated beverages). Unlike the food and beverage industry, the oil & gas sector can reasonably expand CO_2 use and sequestration if the economics become favorable.

To actually make an impact on CO_2 emissions, we need to use or store over 100x more CO_2 than we use today.

The existing global merchant market for CO_2 is roughly 20–23 million metric tonnes (mm mt) of CO_2 per year [6]—tiny compared to the 35–40 BILLION metric tonnes of CO_2 emitted globally.

In the US, the total revenue generated by the merchant CO_2 market was $723mm in 2019. This implies that the maximum revenue potential for carbon capture companies from these markets (absent incentives) is a few hundred million per year. [7] Of this, 38% from food industries, 25% from beverage producers, and 16% from the oil and gas sector.



Percent revenue by sector within the merchant CO_2 market

In the US, the total revenue generated by the merchant CO_2 market was $723mm in 2019. This implies that the maximum revenue potential for carbon capture companies from these markets (absent incentives) is a few hundred million per year. [7] Of this revenue, 38% came from food industries, 25% from beverage producers, and 16% from the oil and gas sector.

Prices for CO_2 are highest in the food and beverage sector due to strict purity requirements. Across these markets, long-term contracts between larger CO_2 consumers (food processors, oil and gas and industrial users) and the largest industrial CO_2 suppliers are a major barrier to entry. Often, the cost of delivering CO_2 to customers is greater than the cost of producing the gas; existing distribution networks owned by large CO_2 suppliers drive profitability.

The CO_2 sold in the US is often extracted from natural underground reservoirs of CO_2 [8], but may also be collected from ethanol plants, ammonia plants, and other industrial sources that produce fairly pure CO_2 gas. Prior to 2018, the total amount of CO_2 captured from industrial processes in the US (not extracted from underground CO_2 reservoirs) was estimated to be 21 mm mt/yr. Of this, 8mm mt/yr went to the food & beverage industry and other uses that do not create any long term CO_2 storage.

The remaining 17 mm mt/yr was injected underground for enhanced oil recovery (EOR) and is considered stored;

In 2018, the US captured 17 million tonnes of CO_2 from industrial processes and stored it underground.

Underground storage of captured CO_2 is something we know how to do at the million tonnes a year scale- could it be expanded to a hundred million or billion tonnes of CO_2 per year, if there is a "demand" for storage?

In the near term, enhanced oil recovery (EOR) operations are the best option for sequestering additional captured CO_2. Over 15mm mt/yr of CO_2 is currently captured from industrial processes and used for EOR, mostly in west Texas. EOR operators also used an additional ~50mm mt of CO_2, extracted from underground CO_2 deposits in the midwest and transported through existing CO_2 pipelines (the US has over 3000 miles of dedicated CO_2 pipelines). [9, 10] Experts estimate that the industry can absorb an additional 300 million mt/yr with operations as usual. To store additional CO_2 up to 1 billion mt/yr, a storage fee of $5–15 per mt CO_2 would likely be implemented (versus the current situation with EOR facility operators paying for CO_2). [11] However, storage in EOR-like geologies is currently economically limited to CO_2 capture facilities that are near an oil or natural gas reservoir or existing CO_2 pipeline.

If government or private incentives develop, there could be an incentive to store CO_2 in other geologic formations that include unmineable coal seams and deep saline reservoirs in addition to oil and gas reservoirs. Currently only a few permits have been issued for drilling operations to store CO_2 in saline reservoirs [12], but since this has been demonstrated, this number could quickly increase. One of these operations is ADM's carbon capture project at their Decatur bioethanol plant, which captures and injects over 1mm mt CO_2/yr into a saline reservoir in Illinois. This could quickly be replicated if clarity around incentives (specifically 45Q) develops.

Government Incentives and Regulatory Pressures

The most effective incentives, policies and regulatory pressures have so far come from state and national governments. Internationally, the United Nations "Framework Convention for Climate Change" (responsible for the Paris Agreement) and the Intergovernmental Panel on Climate Change (IPCC) provide forums for international collaboration and concerted action. The IPCC is a global assembly of scientists that assess the scientific knowledge that exists and makes recommendations accordingly. While these organizations are relevant, they do not have a direct impact on the adoption of carbon capture technologies. Globally, the use of carbon pricing and emissions trading systems is increasing; governments raised approximately US$44 billion in carbon pricing and emissions trading revenues in 2018. [13]

US Government

Reformed 45Q. The reformed 45Q tax credit is the strongest incentive for carbon capture in the US. In 2018, the US expanded and enhanced section 45Q of the US tax code to give a tax credit of $35 per metric tonne of CO_2 or CO captured and used to either make useful products or for enhanced oil recovery. [14] The credit amount is $50/mt CO_2 if the CO_2 is stored in geologic formations (and not used for EOR). To qualify for the credit, power plants must capture at least 500,000 mt/yr and other industrial facilities must capture at least 100,000 mt/yr. New guidance on requirements to receive the credit was released by the IRS in early 2020, but ground must be broken by 2024. One source estimates that $250mm in ethanol production and similar projects are in the pipeline, awaiting clarification on 45Q.

DOE and Other Grant Programs. The US government also directly funds research and development (R&D) of carbon capture technologies through the DOE and ARPA-E. DOE began funding related R&D activities in 1997; over $5B has been invested by the DOE in public and private sector projects related to carbon capture since 2010. [15]

California and other US States

California's Low Carbon Fuel Standard (LCFS) clearance market has effectively become a CO_2 "X-Prize" and offers an immediate $2.5B market for the CO_2 capture. In 2019, the value of credits solid was roughly $2.5B dollars, and reduced the emissions of California vehicles by the equivalent of 13mm tonnes of CO_2. LCFS credits traded near $200 per tonne of CO_2 mitigated in early 2020; even during the oil crisis in March, the LCFS credit price remained above $180 per tonne CO_2.

The LCFS market works by requiring anyone selling transportation fuels in California to purchase credits to bring the average "carbon intensity" (CI) of their fuels below CA's targeted level. The California Air Resources Board (CARB) is responsible for certifying the fuel's CI score. The size of the LCFS market depends on California's demand for transportation fuels, and a multiplier that increases each year. Even if fuel demand goes down, the demand for credits increases. In 2019, the volume of fuels sold in California was 13.8B gallons of gasoline equivalents (GGEs). The LCFS model has already expanded to Oregon (for a 10% increase in market size), and Washington and New York have similar bills in their state legislative process.

Together with the federal 45Q tax credit, these programs create revenue streams of $215-250 per tonne of CO_2 captured.

State Pledges. California has pledged to reduce greenhouse gas emissions 40% below 1990 levels by 2030, which requires emissions to decrease from the equivalent of 424 million mt CO_2/yr in 2017 to below 260mm mt CO_2/yr in 2030. [16] Accomplishing this will likely require some level of carbon capture.

State Renewable Portfolio Standards (RPS) could also become a vehicle for carbon capture incentives in the future. In addition to California, twenty-nine US states have RPS targets, which require that a specified percentage of the electricity that utilities sell comes from clean or renewable resources. [17] Under these standards, utilities must obtain renewable energy credits (RECs); the REC structure and cost varies from state to state, with most having cost caps in their RPS policies to limit increases in ratepayers' bills to a certain percentage.

Corporate Entities

While the motives and extent to which Oil & Gas majors fund carbon capture are frequently questioned, some have a long history of technology development in this area. Equinor (formerly Statoil), Shell, and Chevron have already built and operated commercial-scale carbon capture facilities. Equinor captures and re-injects CO_2 from natural gas production at the Sleipner and Snovit fields in the North Sea. Shell has been involved in two major CO_2 capture projects: the "Quest" project at an H2 plant in Alberta and the Boundary Dam project on a coal-fired power plant in Saskatchewan. In Aug 2019, Chevron began CO_2 injection at its Gorgon Liquified Natural Gas (LNG) plant in Australia, which can inject 3.5–4mm CO_2/yr.

The industry also funds external development of new carbon capture and other emissions-related technologies. A major vehicle for this is the Oil and Gas Climate Initiative (OGCI), a $1B+ investment fund backed by thirteen of the largest oil and

The Sleipner field in the North Sea, where CO_2 is captured from natural gas production.
(Photo: Harald Pettersen / Equinor ASA)

gas companies. Outside of this fund, Exxon and Occidental Petroleum recently announced collaborations with startups in the carbon capture space — Exxon with Global Thermostat, Mosaic Materials, and FuelCell Energy, and Occidental Petroleum with Carbon Engineering and Svante. Chevron has also invested in Carbon Engineering and Svante through Chevron Technology Ventures and their Future Energy Investment Fund.

Companies in other sectors have recently announced direct funding, changes to supply chain, or other initiatives that are potentially relevant to carbon capture. Microsoft's announcement in January 2020 has been the broadest and most detailed; the company has pledged to go carbon *negative* by 2030, and remove all carbon emissions produced since 1975 by 2050. They simultaneously published their estimated current emissions: currently 16mm mt/yr CO_2, including both direct and indirect emissions.

Microsoft will start by gradually extending its \$15/mt CO_2 internal carbon tax on direct emissions to supply chain (Phase 2) and indirect emissions (Phase 3) as well, and create a \$1B climate innovation fund (no details yet on what this fund will be used for).

Jeff Bezos has responded by announcing a \$10B “Bezos Earth Fund” in February 2020 (no details of what it will fund or how have yet been released) and a \$2B venture fund investing in companies to cut greenhouse gas emissions. Previously in September 2019, Amazon set a goal of 100% renewable energy by 2030; so far the company has initiated 15 utility-scale wind and solar renewable energy projects that will generate 1.3 GW capacity. Amazon has also announced \$100mm for reforestation projects, and pointed to a purchase order for 100,000 E-delivery vehicles from Rivian, which they estimate will avoid 4mm mt CO_2/yr.

Tech company Stripe announced it’s first “negative emissions” purchases in May 2020, which include 332 tonnes from Climeworks at a price of \$775/tonne (\$250k total). Other prominent examples in the transportation sector include Delta, British Airways, Cathay Pacific and other airlines, who have committed to becoming carbon neutral in the future. These announcements come on the heels of the International Civilian Aviation Organization (ICAO) enacting a program called CORSIA (the Carbon Offsetting and Reduction Scheme for International Aviation), to prevent increases in total CO_2 emissions from international aviation above 2020 levels. Airlines operating within Europe are particularly affected, and will need to buy carbon neutral jet fuel or offsets. Additionally, Tesla promised last year to run on 100% renewable energy and assessed it’s current carbon impact (282kt/yr).

In summary, the US government and California have provided credit-based incentives that may make some carbon capture projects border on economically viable for oil & gas majors, if the regulatory risk is acceptable and the price of oil justifies EOR. Several billion dollars have been committed by other corporate entities, but much of this will likely go to lower cost offsets (planting trees, land use modification, methane capture from landfills) rather than carbon capture technologies. CO_2 capture from industrial sources would be enabled at a massive scale would be enabled by reliable subsidies from governments at the \$50–\$60+ per metric tonne level (which looks, if not likely, increasingly possible).

Alternatively, substantial investment in an emerging technology at initially high costs per tonne CO_2 could help reduce the cost of capturing some emissions below \$50/mt CO_2. The next section discusses the current costs of CO_2 capture from different sources, and the impact that a \$1B investment might have in different areas.

Applications and Key Metrics

The cost of capturing CO_2 is affected by the source of CO_2, size of the facility (scale), and the technology maturity level.

These three of these factors are key to understanding the current landscape, and the impact of future investments in carbon capture

technologies. Capturing CO2 from gases with a higher CO2 content will cost less. Larger facilities will have lower costs per tonne of CO2 captured than small facilities, up to a point. Finally, the first facility built is always significantly more expensive, for a host of engineering and financial reasons. For emerging technologies, the first few facilities built will initially appear less cost competitive until the associated construction and manufacturing processes are standardized.

Carbon capture technologies are typically benchmarked by the cost (or expected cost) of capturing one metric tonne (1000kg) of CO_2 at commercial scale (\$/mt of CO_2). This cost should include both the capital cost of purchasing the equipment and building the facility (CapEx), and operating expenses like utilities, labor, etc (OpEx).

The qualifier "at commercial scale" is critical because the per unit cost of capturing CO_2 (and producing most commodity products) falls as the facility size increases. As a first approximation, engineers often use "The 6/10ths Rule": as size increases, costs generally increase by the size ratio raised to a factor of 0.6. For example, if a 100,000 mt/yr carbon capture facility costs \$100mm to build, a 1 million mt/yr facility will cost \$390mm. [18]

The cost of CO_2 capture also depends strongly on the source and CO_2 content of the gas. Some industrial processes (like ethanol production) produce nearly pure CO_2 that can currently be captured and utilized economically (at less than \$20/mt CO_2). However, the vast majority of CO_2 produced by industrial processes is released to the atmosphere at 4–30% CO_2. Moreover, additional clean up steps are required for capturing CO_2 from some sources like burning coal, due to the sulfur content and nitrogen oxides that must also be removed.

Finally, the projected cost of carbon capture depends greatly on the technology maturity and underlying economic assumptions. To help ensure apples-to-apples comparisons, the National Energy Technology Laboratory (NETL) maintains a standardized methodology and reference cases for estimating ***the cost of point-source CO_2 capture at commercial scale,*** reducing CO_2 emissions from a specified coal and natural gas power plant by at least 90%. NETL funds the bulk of carbon capture research and development in the US, with a target of demonstrating technologies with an at-scale cost of \$40/mt CO_2 or less in the 2020–2025 timeframe. [19]

Cost estimates for capturing CO_2 from the air (negative emissions technologies) are significantly more uncertain, and are highly sensitive to the assumed cost of electricity (in addition to design-specific assumptions). The most mature direct air capture company, Climeworks, has reported a cost of capture of \$600/mt CO_2 for its plant in Switzerland, which captures 900 tonnes of CO_2/yr (pilot scale). A 2019 report from the National Academy of Sciences estimates costs of \$147–228/mt CO_2 for direct air capture, once these technologies have reached the 1 million tonne per year scale and been deployed repeatedly. [20]

Energy Requirements and Life Cycle Assessment

Both government incentives (California's Low Carbon Fuel Standard) and private efforts are requiring greater transparency around how much CO_2 is generated and emitted during the "carbon capture" process.

This starts with the amount of **energy consumed per tonne of CO_2 captured**, generally expressed in gigajoules per tonne CO_2 (GJ/mt CO_2). The source of the energy used to power the carbon capture process has a large impact on another key metric, the **cost of CO_2 avoided**, which considers the CO_2 captured vs the additional CO_2 emitted (directly and indirectly) as a result of the carbon capture process. Using the National Academy of Sciences study on direct air capture [20] as an example, the cost of CO_2 avoided is 35% higher than the cost per tonne of CO_2 captured: \$199–357/mt CO_2.

Building on these simple metrics, **Life Cycle Assessments (LCAs)** are increasingly important for businesses in the CO_2 mitigation space. An LCA goes beyond determining the cost of CO_2 avoided to estimate the total impact of the project on other emissions, water, and land use over the project lifetime. For credit-based incentives such as California's Low Carbon Fuel Standard (LCFS), an LCA is required to determine net emissions that result from making and burning the fuel.

Sources of CO_2

The source of CO2 significantly affects the cost and type of carbon capture technology used, so it's worth additional discussion.

Sources of CO_2 vary widely in composition, from the low quantities found in air (400 parts per million, ppm) to greater than 90% produced in fermentation processes (e.g. making beer and bio-ethanol production). The typical CO_2 content of different gases and estimated cost of capture are shown in Table 1. [21]

Source	CO_2 Content	Cost of Capture	Maturity
Ethanol & Ammonia Production	>90%	<$20/mt	Commercial
Cement Production	20-30%	$55-65/mt	Pilot Scale
Power Plant, Coal	12-15%	$55-65/mt	Demonstration Scale
Power Plant, Natural Gas	3-4%	>$70/mt	Pilot Scale
Air	0.04% (400 ppm)	>$200/mt	Pilot Scale

Table 1. Sources of CO_2 [21]

To visualize why carbon capture from concentrated sources like cement production and coal-fired power plants is cheaper than capturing it from a more diluted source like air, think about how much easier it is to pick a pint of blueberries when there are tons of blueberries on a bush, versus at the end of the season when very few are left. Capturing CO_2 from a concentrated source is like picking berries on a farm, where you are likely limited by how fast you can pick, rather than searching a large area for blueberries.

Likewise, a key difference between capturing CO_2 from air versus a concentrated source like a power plant is the amount of air you need to gather, process to gather a single tonne of CO_2. The concentration of CO_2 in air is 100 times lower than the exhaust from natural gas power plants, and 300 times lower than the exhaust from burning coal. [22] Direct air capture systems must handle hundreds of times more gas, requiring much larger equipment and more energy to capture the same amount of CO_2.

Existing carbon capture facilities in the US capture CO_2 from sources with high CO_2 contents. Of the 17 million metric tonnes (mm mt) of CO_2 captured in the US in 2018, 14 mm mt came from low-cost, almost pure CO_2 sources such as ethanol production, natural gas processing, and excess CO_2 at ammonia plants, with costs less than \$20/mt CO_2. [21] Since the gas from these sources already contains >90% CO_2, it is more cost effective to remove the other components (mostly water) rather than "capture" the CO_2 — this is why the cost is so low. An additional ~1mm mt/yr is captured from bioethanol production at ADM's Illinois Carbon Capture and Storage project and sequestered in an underground saline reservoir rather than being sold. The remaining 2–3mm mt/yr came from true carbon capture facilities, including NRG's Petra Nova project (1.4mm+ mt/yr), and the Port Arthur hydrogen plant project operated by Air Products (1mm mt/yr). All received significant grants from the DOE's National Energy Technology Laboratory (NETL).

A notable non-point source project on the horizon is the proposed engineering study and collaboration between Carbon Engineering (a direct air capture company) and Occidental Petroleum to determine if a 1mm mt CO_2/yr facility in the Permian Basin of TX is economically viable. The facility would be powered by cheap surplus natural gas, the captured CO_2 would be used for EOR, and Occidental could potentially claim a "carbon negative barrel of oil" eligible for LCFS and 45Q credits.

This example underlines the value of co-locating carbon capture with a) transport or storage infrastructure and b) cheap energy. For any CO_2 captured to be monetized, it must be transported to where it can be utilized, stored or sequestered. Storing and sequestering CO_2 is a major logistical challenge; if there are not enough "cheap tonnes" of CO_2 in a given region to justify a pipeline, storage facility, or utilization facility, more expensive sources of CO_2 may come into play.

Looking ahead, many experts think that carbon capture from dilute sources (and particularly direct air capture) will not see significant traction until after more concentrated sources are exhausted, given the higher cost of capture. However, there are some cases where public incentives, environmental regulations, transportation considerations, and business plan innovation can create opportunities for seemingly less cost-effective technologies.

CO_2 Capture Technologies

Current State of the Art

Today a handful of first-of-a-kind, commercial-scale carbon capture plants have been built for point-source CO_2 capture, generally using liquid amine technologies. Examples include NRG's Petra Nova coal retrofit project in South Texas, Shell's Quest project in Saskatchewan, and Norway's Snohvit project in the Barents Sea. The installed costs of the amine systems themselves are typically in the range of $80- $100/mt CO_2. The Boundary dam plant, which uses Shell's CanSolv amine technology, is able to capture 1mm mt/yr of CO_2. For several reasons, the project went over budget, and the long-term economics were hurt by falling natural gas prices. [23] Currently, NRG's Petra Nova project is the largest operational carbon capture facility in the US, capturing over 1mm mt CO_2/yr for EOR. [24] Norway has ambitious plans to develop a CO_2 transportation and sequestration hub for Europe under the "Northern Lights Project", building on Equinor and other North Sea operators' extensive experience reinjecting the CO_2 produced from oil & gas production.

In the US, a large number of additional point-source pilot and demonstration projects are moving through the pipeline, supported by DOE funding from the past 10–15 years. [25] The companies developing these technologies estimate costs of $40–60/mt CO_2 for point-source capture from a coal-fired power plant at commercial scale (4mm mt CO_2/year) [26] and an expected time to commercial deployment of roughly 3–7 years if partners are found and project economics are favorable.

Many organizations receiving DOE funding for point-source carbon capture are research institutions or early stage companies that are not in growth mode. One exception is Svante (formerly Inventys), a Vancouver-based company that recently completed a 10,000 mt/yr pilot system at a Husky oil sands facility in Alberta, Canada. A possible larger project with Occidental Petroleum (Oxy) and Total to capture CO_2 from a Colorado cement plant is in the feasibility study stage.

At present, the direct air capture area ecosystem includes fewer large companies, though this may change if funding from public and private entities increases. Three companies have publicly deployed pilot or demonstration systems to date: Climeworks (Switzerland), Carbon Engineering (Canada), and Global Thermostat (USA). There is significant room for growth and additional technology development if additional resources enter this space.

The challenges associated with cost-effectively removing the small amount of CO2 in air require process designs and adsorbents that are very different from point-source technologies. This generally leads to higher capital and operating costs to capture CO_2 from air. Estimated costs of $90–250/tonne CO_2 for DAC systems at commercial scale were published in a 2019 report from the US National Academy of Sciences.

However, direct air capture (DAC) facilities have the advantage that they can be located anywhere, including next to cheap energy sources, CO_2 utilization facilities, or sequestration sites. Unlike point-source carbon capture technologies, which reduce industrial emissions (bringing them closer to carbon neutral), DAC technologies are negative emissions technologies (NETs). Analyses from numerous groups, including the International Panel on Climate Change (IPCC), indicate that NETs and specifically carbon capture and storage will be required to limit global temperature rise to <2 degrees C. [27] The capture costs at the low end of the NAS range may be economically viable with a sufficient market price for CO_2 coupled with growing public or private incentives.

Overview

Before diving into specific technologies, here is a brief overview of carbon capture approaches that have seen significant traction. The most mature technologies are **liquid absorption** processes that are similar to the CO_2 removal systems used in the oil and gas industry. The gas containing CO_2 is bubbled through a liquid (called a "solvent"), which absorbs CO_2 and lets the rest of the gas pass through. Many liquid-based technologies use a family of chemicals called "**amines**" that react strongly with CO_2. Other liquid-based approaches use liquids that dissolve the CO_2 but don't chemically react with it (**physical solvents**).

Other technologies utilize solid materials called "adsorbents" (note the "ad-" for solids vs "ab-" for liquids) to trap and later release CO_2 in a similar reversible process. The gas or air is passed through a container of solid material (much like an air filter) that traps CO_2.

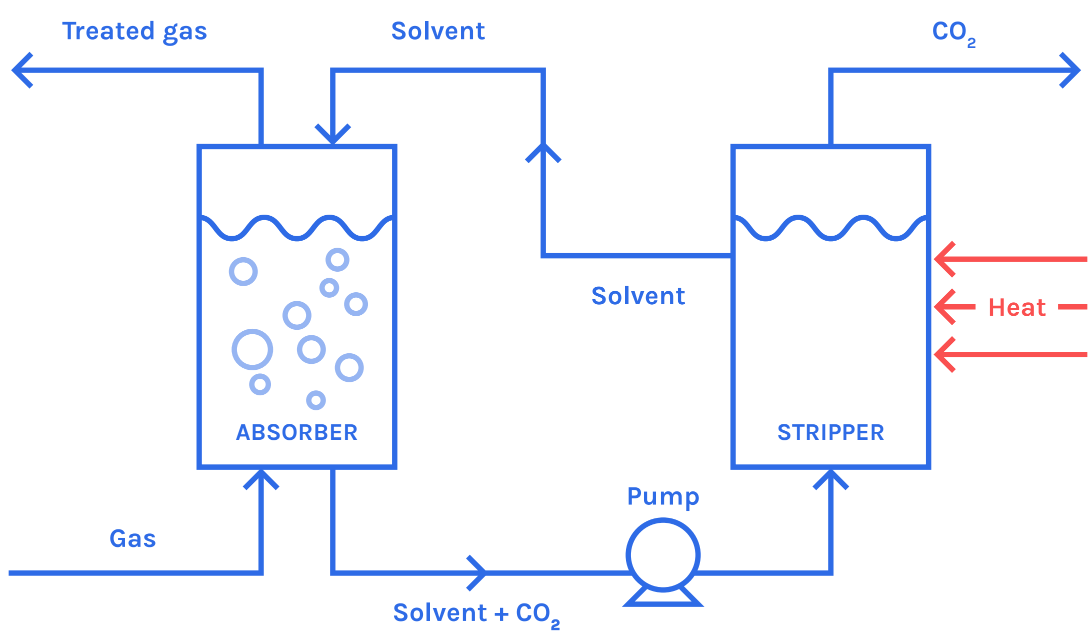
Advances in **membrane technologies** over the last decade have led some teams to include membranes in their carbon capture designs, particularly for gases with high CO_2 contents. Membranes are thin sheets of material which only allow certain gases to pass through, in this case CO_2.

Some companies combine carbon capture and storage with **mineralization** technologies. In these technologies, CO_2 is permanently converted to a mineral: limestone (a component of concrete), baking soda, or other useful inorganic products. These technologies avoid many of the challenges of gas pre-cleaning and CO_2 purification, but may be limited by the demand for the final product.

CO_2 capture companies generally focus on either capturing CO_2 from point-sources (emissions from power plants, chemical plants, cement production, etc.), or on capturing CO_2 directly from the air (DAC). Liquid absorption processes and membranes are used almost exclusively for point source CO_2 capture. Most companies developing DAC systems are using solid adsorbent or carbonate formation approaches, although these approaches have been used for point source capture as well.

Liquid Absorption with Amines

The oil and gas industry has been using **liquid** "**amine scrubbers**" to remove the CO_2 present in natural gas coming up from oil and gas fields since the 1930s. The process of capturing CO_2 from emissions is not the same as removing CO_2 from natural gas for several reasons. The pressure of the natural gas is 20–100 times higher and different contaminants are present. Still, much of the engineering and equipment design is the same, and this is by far the most mature carbon capture technology. A large number of companies including oil majors (Equinor/Statoil, Shell), established technology providers (e.g. Fluor), and startups (ION Engineering, Carbon Clean Solutions)



Basic overview of a liquid absorption process are pursuing this approach to capture CO_2 from point-sources like cement, coal and natural gas power plants.

Liquid amine scrubbing systems remove CO_2 by bubbling the gas through water that contains 20–50% amine, a liquid chemical that strongly binds to CO_2 but not other molecules. The gas leaving the top of this “absorber” is essentially CO_2-free, and the liquid (with the amine and trapped CO_2) is pumped to a separate large metal tower known as the CO_2 “stripper”. The stripper heats the liquid water-amine-CO_2 solution to force each amine to release its CO_2 molecule. The liberated CO_2 gas (plus some water) leaves the top of the stripper, and the liquid amine-water is recycled back to the absorber to trap more CO_2.

To bring down carbon capture costs, companies using liquid-based processes try to create **better liquid solvents** that 1) absorb more CO_2 per liter of solvent, 2) react with CO_2 faster, or 3) produce less heat when they react with CO_2. By trapping more CO_2 per liter of liquid solvent, the equipment can be smaller, reducing the upfront capital cost. Heating the water-amine-CO_2 liquid to release CO_2 also uses a large amount of energy, so reducing the amount of liquid needed reduces the energy consumed (a primary driver of operating costs). It is also important that the amine solvent doesn’t degrade over time.

An example of metal “packings” / Source: Joeravo (Creative Commons)

Often, the amount of CO_2 absorbed by the liquid is limited by how fast the CO_2 reacts with it, rather than how much CO_2 the liquid can theoretically hold. To make the CO_2 react faster, extra chemicals can be added, or the absorber can be filled with more elaborate shapes, bars, or other forms to mix the gas and liquid better. Some common absorber “packings” look like metal packing peanuts or steel wool. **Improving absorber packing design and materials** for liquid-based carbon capture is an important area of technical innovation.

To make things even more complicated, CO_2 gives off heat when it reacts with amines: this heat is called an “exotherm”. At higher temperatures, less CO_2 can be absorbed (remember that the liquid is heated to release CO_2.) Finding ways to cool the liquid during CO_2 absorption or otherwise **manage the heat released** is another important area for process optimization.

Companies active in this area include CanSolv (Shell), Mitsubishi Heavy Industries (MHI), ION Engineering, Carbon Clean Solutions Limited, Stanford Research International (SRI), and the Gas Technologies Institute (GTI)

Liquid Absorption with Physical Solvents

The processes for liquid absorption of CO_2 with physical solvents vs amines are very similar. However, physical solvents dissolve the CO_2 without a chemical reaction. As a result, less heat is released when CO_2 is absorbed, and less heat is needed for physical solvents to release CO_2 in the stripper.

The trade-off is that physical solvents are generally less selective for capturing CO_2 — they also dissolve other gases (e.g. nitrogen and methane) at low levels. For gases with high CO_2 contents (>15%), physical solvents may offer a less energy-intensive approach. Examples of physical solvents for CO_2 removal include Rectinol and Selexol, which were developed to remove CO_2 from natural gas but have seen limited adoption in the industry.

Membrane Systems

Membranes are also being explored to capture CO_2 from gases with a high CO_2 content. In a membrane separation process, gas is fed to one side of a long sheet of membrane material (typically wound into a cylindrical tube). As the gas travels along the membrane, some components of the gas (in this case, CO_2) pass through the membrane and exit through a separate “permeate” outlet, while the remainder exits at the end of the tube (the “retentate” outlet).

An advantage of membrane systems is that they are easy to scale up or scale down for different applications. Unlike liquid absorption systems, which need to be redesigned for each new facility, the size of a membrane facility can be increased by adding more membrane cartridges. The disadvantages of membrane systems are that they are prone to fouling (dirt and contaminants build up), and the level of CO_2 purity achieved by a single membrane is often low (so a series of membrane modules might be needed).

Companies active in this area include: Membrane Technology Research (MTR) and the Gas Technologies Institute (GTI).

Mineralization

CO_2 can also be converted into minerals including sodium bicarbonate (baking soda, NaHCO3) and limestone ($CaCO_3$), a common ingredient in concrete. In these processes, CO_2 is first dissolved in water to make carbonates. The carbonate + water solutions then undergo a "mineralization" step, where the liquid is cooled slowly. As the solution cools, the carbonate in solution "un-dissolves" and forms solid rocks around a starter material (similar to the process of making rock candy). The mineralization process can be adjusted to make rocks of different sizes, from powders to small boulders. This material can be used to make concrete, which is a mixture of rocks, sand, and cement (cement acts as the glue to hold everything together).

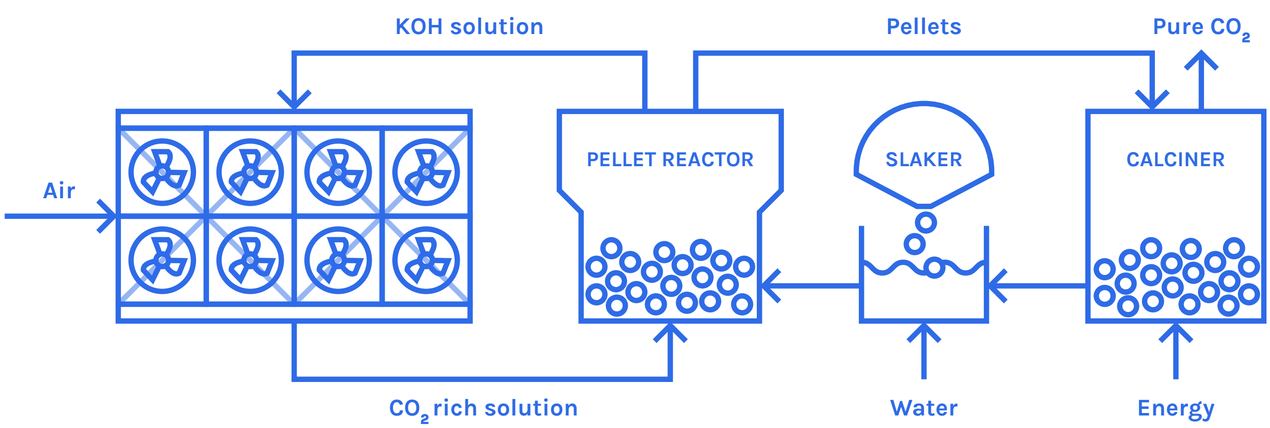
Rock candy, another mineralization process / By Evan Amos

Concrete and cement are controversial products because the process of making cement is highly CO_2 intensive (1 tonne of CO_2 is emitted for every tonne of cement produced). Companies taking this approach cite increasing demand for concrete and cement, and the need for less carbon-intensive cement (or cement-like) materials. Blue Planet claims that each ton of CO_2-sequestered limestone (not cement) traps 440 kilograms of carbon dioxide.

Companies active in this area include: Blue Planet, Carbicrete, C-Crete, Carbonfree Chemicals, Solidia, CarbonCure

Carbonate Formation

An alternate approach to direct air capture first converts CO_2 to carbonate ions (CO_{32}-) by dissolving CO_2 in a water-salt solution, similar to the mineralization process discussed earlier. However, once the CO_2 is dissolved, this process recovers pure CO_2 through several additional steps. The first step, carbonate formation, is similar to liquid scrubbing systems, but uses water and potassium hydroxide rather than an amine solution. Potassium hydroxide (KOH) is cheaper, less toxic and less corrosive than amines. Large fans draw air into the absorber, where the gas passes over thin plastic surfaces that have the liquid water+KOH flowing over them. The KOH plus CO_2 produces a carbonate salt (KCO_3) that stays with the liquid.



The liquid containing carbonate ("CO_2 rich solution") is used as an input into a series of chemical processes to purify and convert it back into pure CO_2 gas for use or storage. This involves separating the carbonate salt out from the liquid into small solid pellets and then heating the pellets to 900 degrees C in a third step, a calciner, to release pure CO_2 in gas form. This step also leaves behind solid salts that are redissolved in water in a slaker (like sugar in coffee) and recycled back to the absorber.

The main company active in this area is Carbon Engineering, although others use a related process to produce concrete and other products.

Solid Adsorbent Systems

Note that because we think that carbon capture with solid adsorbents is a particularly exciting area, this section is longer than the other technology descriptions. Solid adsorbent processes are exciting because they are applicable to removing CO_2 from a wide range of sources, from air (0.04% CO_2) to cement plants (20–30% CO_2). Compared to liquid absorption processes, systems with solid adsorbents are more easily customized, modularized and scaled for different use cases. From an investment standpoint, breakthrough innovations in solid adsorbents and process technology are also more likely to have additional applications beyond carbon capture, for example in other gas separations and catalysis.

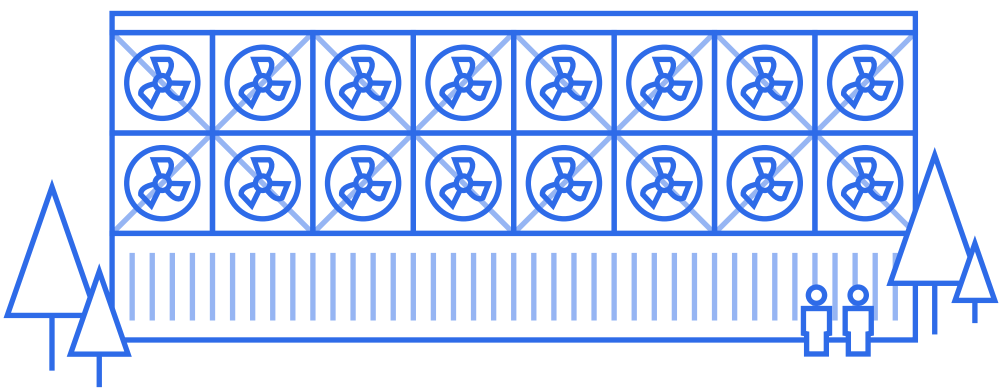
What is an adsorbent? Solid materials have long been engineered to reversibly capture and release CO_2 or other gases, acting like a selective sponge. These materials are called adsorbents. The little “do not eat” bags of material you find in packaged foods and shoes are examples of adsorbents that really like to capture water out of air. An even more relevant example are the CO_2 scrubbers used by NASA and featured in the Apollo 13 movie. If you zoom in on a typical adsorbent, it would look like an endless network of connecting tunnels, or holes. **Physical** adsorbents rely on the size of holes (called pores) in the material to trap CO_2 but not other gases. They include activated carbon, zeolites, and some metal-organic frameworks (MOFs). **Chemical** adsorbents form chemical bonds with the gas they capture (e.g. CO_2). Like liquid solvents, solid materials for CO_2 capture that rely on chemical adsorption generally include a type of chemical called an amine. Examples include aminated silicas, polymers with amines, and other families of MOFs.

Designing an effective carbon capture system starts with the adsorbent. A good carbon capture adsorbent has a **high CO_2 capacity** while being very **selective**, meaning it will take up (“adsorb”) a lot of CO_2 but not other gases. [28] The adsorbent needs to be cheap, last a long time, and continue to work if it encounters water, NOx, or other pollutants. The amount of CO_2 that a certain adsorbent will hold changes with the amount of CO_2 in the gas, the pressure, and the temperature. Because of this, one adsorbent may be good for capturing CO_2 from cement plants, while another may be better for capturing CO_2 from air.

A good adsorbent alone is not enough. Systems that use solid adsorbents for carbon capture act like filters for CO_2. In a Brita water filter, gravity causes water to flow through the filter cartridge. For gases, a fan or gas compressor is needed to push the gas with CO_2 through the filter (or through the liquid in absorption systems).

The amount of energy it takes to force CO_2 through the capture system can be very large, especially for capturing CO_2 directly from air, where more than 1650 tonnes of gas must be processed to capture 1 tonne of CO_2. [29] A major area of innovation for direct air capture systems is reducing the amount of energy needed to move air through the system. A key metric for this is the change in gas pressure (pressure loss) across the carbon capture system. **Reducing the pressure loss** across the system reduces the cost of carbon capture. [30]

Carbon capture systems with solid adsorbents typically have multiple filter containers or "beds" of the solid material that act like rechargeable batteries. There are two ways that adsorbents filled with CO_2 are generally recharged. The first way is to heat the material (a "temperature swing"). The second way is to expose the filter to a lower pressure or vacuum to pull off the CO_2 (a "pressure swing"). In a typical process, the gas containing CO_2 is pushed through one or several of the beds, while beds that have already been filled with CO_2 are recharged offline.



Based on renderings from Climeworks and Carbon Engineering. A colleague commented that these technologies look like giant HVAC systems, which is exactly what they are! These systems take in air, process it, and return it.

The speed of filling and recharging the adsorbent is important, because the faster you fill and recharge the adsorbent, the less adsorbent and housing you need. Less adsorbent means a smaller system to capture the same amount of CO_2, which reduces cost. The total amount of time to fill a bed of adsorbent with CO_2 and recharge for the next use is called the **cycle time**. For capturing CO_2 from point-sources (cement and power plants), these times are a few hours or less. [29]

For direct air capture processes, using a bed more than twice a day is an accomplishment. It can take hours to completely fill the adsorbent with CO_2 by blowing air over it. The time to fill the adsorbent depends on how fast you blow gas through the bed.

However, at high gas velocities the CO_2 won't have time to stick. (Imagine playing putt-putt golf and you putt too hard. The golf ball [CO_2] may skip over or bounce out of the hole.) The energy needed to push CO_2 through the bed also increases with the speed of the gas, incentivizing moderation.

Decisions about how the CO_2 is removed from the adsorbent to recharge it strongly affect cost. Generating enough heat to remove CO_2 is generally much cheaper than pulling vacuum to remove it. Heating a solid is much slower than removing CO_2 by lowering the pressure, which creates a trade-off with cycle time. The fastest way to heat and regenerate a solid adsorbent is to flow steam through it, but this may cause some adsorbents to adsorb water instead of CO_2 or possibly degrade. Electric heaters could in theory be used to take advantage of renewable energy, but heat from electricity is typically more expensive than steam due to conversion losses.

As with liquid absorption, solid adsorbents that require less heat to regenerate reduce the energy requirements and cost, but with the trade-off that they are less selective about capturing CO_2 but not other gases. Overall the design of carbon capture systems is a fascinating optimization problem, which is why the cost of capture varies so widely between applications.

Companies actively developing solid adsorbent technologies for carbon capture include:
Point Source: Shell, Svante, Innosepra, Mosaic Materials, TDA Research, GTI
Direct Air Capture: Climeworks, Global Thermostat, Skytree, Svante, Mosaic Materials, Infinitree, Klaus Lackner/ASU, Idealab's Carbon Capture

Summary of Carbon Capture Companies

The current landscape of carbon capture companies is summarized in the following table. While it is too soon to tell which companies will reach significant deployment first, expect significant growth in this sector. Government incentives will likely drive the first deployments for both point-source capture technologies (receiving up to $50/tonne CO_2 in tax credits from 45Q) and for direct air capture technologies (with potential revenue of ~$240/tonne through LCFS credits and 45Q).

Company	Primary Technology
Climeworks	Amine-functionalized filter
Global Thermostat	Amine-functionalized monolith
Carbon Capture (Idealab)	Physical adsorbent
Skytree / Giaura	Amine-functionalized porous plastic beads
MOFWorx / CSIRO	Airthena system (MOF-based CO2 capture)
Svante (fka Inventys)	Rotary adsorbent bed (wheel) with proprietary filter structure
Mosaic Materials	Amine-functionalized metal-organic framework
TDA Research	Many; it's a research institute
Gas Technology Institute (GTI)	Many; it's a research institute
InnoSepra	Physical adsorbent
Shell, CO2 Abatement Group	Various, incl. fluidized bed with solid adsorbent
Exxon Mobil	Various
Carbon Engineering	Potassium hydroxide solution / calcium carbonation
SRI	Various research projects
Gas Technology Institute (GTI)	Many; it's a research institute
ION Clean Energy	Proprietary amine solution; contactor / regenerator design
Carbon Clean Solutions Ltd (CCSL)	Propriety amine-salt mixture
CanSolv (acquired by Shell)	Proprietary amine solution; contactor / regenerator design
Mitsubishi Heavy Industries (MHI)	Proprietary amine solution; contactor / regenerator design
Membrane Technology Research (MTR)	Membranes for partial CO2 capture
Gas Technology Institute (GTI)	Many; it's a research institute
Carbonfree Chemicals	Mineralization
Verdox	Electroswing Adsorption

Notes

[1] Source: 2019 National Academy of Sciences Consensus Study Report

[2] Source: US EIA reported CO_2 emissions in 2018

[3] Since FY2010, Congress has provided more than $5 billion total in appropriations for DOE carbon capture and storage (CCS)-related activities through the Fossil Energy Research and Development (FE R&D) program, with a focus on coal-fired power plants. The annual amount going to CCS-related R&D each year has increased since 2017; Congress appropriated $727 million for FY2018, and both House- and Senate-passed bills for FY2019 to match or increase this. Source: a Congressional Research Service report (2018).

[4] This assumes CO_2 transport costs of less than $10/mt CO_2 and that companies are able to receive the 45Q tax credit of either a) $35/mt CO_2 while avoiding a $5–15/mt CO_2 purchase cost for EOR, or b) $50/mt CO_2 sequestered.

[5] Carbon Engineering press release, May 2019

[6] This number reflects the merchant market, which does not include CO_2 generated and used by the same company, or that is transferred through private off-market agreements. In North America, size of the merchant market for CO_2 is about 13mm mt of CO_2/yr. Source: "ICIS Market outlook: Europe CO_2 shortage highlights critical uses" by Al Greenwood

[7] Source: IBISWorld Industry Market Report OD4929, "Carbon Dioxide Production in the US," April 2019.

[8] The major underground sources of CO_2 used in the US are the Jackson Dome (MS), the Sheep Mountain and McElmo Dome sites (CO), and the Bravo Dome (NM). Source: NETL report on "Carbon Dioxide Enhanced Oil Recovery" (see page 10)

[9] Source: US EPA Greenhouse Gas Reporting Program (GHGRP)

[10] Why is this 50 million tonnes of CO_2 larger than the size of the merchant market? Many CO_2 transactions in the oil and gas industry are effectively internal transfers between Occidental Petroleum, Kinder-Morgan, Denbury, and others who manage both extraction of CO_2 from natural deposits and EOR activities, and therefore aren't listed.

[11] Source: Working Document of the National Petroleum Council Study, "Meeting the Dual Challenge: A Roadmap to At-Scale Development of Carbon Capture, Use, and Storage", Topic Paper #1, December 12, 2019.

[12] For contrast, there are over 180,000 UIC Class II oil & gas related injection wells in the US, and 6 Class VI wells for geologic sequestration of CO_2. Source: Clean Water Action report on EOR, Aug 2017.

[13] The World Bank Group's June 2019 report, "State and Trends of Carbon Pricing 2019" provides a comprehensive guide to carbon pricing initiatives around the world.

[14] Prior to the 2018 reform, section 45Q gave tax credits of $10 and $20 per mt CO_2 used for EOR or stored, respectively. The credits were also limited to 75mm mt CO_2 cumulatively, which created significant risk that the credits would be unavailable after a project began. This limitation was also removed in the reformed version.

[15] Source: Congressional Research Service Report R-44902, April 2018.

[16] Source: "Insights from the California Energy Policy Simulator" by Chris Busch and Robbie Orvis, Jan 2020. (see "Summary for Policy Makers")

[17] Source: National Conference of State Legislatures website, Dec 2019.

[18] In this example, $100mm x (10)^(6/10) = 390mm. To estimate the cost of other equipment at a larger scale from the cost of smaller equipment:
[Cost of big equipment] = [Cost of small equipment] x ([Size, big]/[Size, small])^{0}.6. For the aspiring engineering student, an online explanation: https://www.pdhonline.com/courses/g127/g127content.pdf.

[19] Source: NETL Carbon Capture Fact Sheet

[20] Source: National Academy of Sciences, "Negative Emissions Technologies and Reliable Sequestration: A Research Agenda" 2019, Ch. 5.

[21] Source: National Petroleum Council Study, "Meeting the Dual Challenge: A Roadmap to At-Scale Development of Carbon Capture, Use, and Storage", Topic Paper #1, December 12, 2019. See Table 2.1.

[22] Assuming that both direct air capture (DAC) and point-source systems remove 90% of the CO_2 in the incoming gas stream; some DAC systems remove <50%, so even more air must be handled.

[23] The Boundary Dam project retrofitted a small, and outdated coal plant with an amine scrubber for an initial capital cost on the order of $800 million per million tonnes of CO_2 captured per year (very high). However, the "capture costs" included revamping the entire plant site's water systems, rebuilding the 50-year old boiler, rebalancing the steam turbine, and other activities. The plant would have been shut down anyway, and was a low-risk place to experiment. Complications like these make it difficult to project the true cost of future facilities.

[24] The total cost of this project was roughly $1B, which was funded through a $190mm grant from the US DOE, $600mm in equity from NRG and JX Nippon, and $250mm in project finance loans. Source: 2018 JX Nippon presentation

[25] For more information on DOE funded projects in carbon capture and sequestration, see the National Energy Technology Laboratory (NETL) program summaries and conference proceedings for the Carbon Capture Program.

[26] Based on the DOE/NETL "baseline" for CO_2 capture from coal fired power plants: a 550 MWe supercritical coal-fired power plant with carbon capture produces roughly 4mm mt CO_2/yr.

[27] There are many negative emissions technologies, and that many are technically simpler than building large carbon capture facilities. Each has distinct advantages and disadvantages in terms of cost, time for deployment, land use, water use, and energy use to name a few. To have a chance at meeting the 2 deg C goal set by the Paris Accord, "all of the above" will be required. Source: Center for International Climate Research

[28] Alameda, CA-based startup Mosaic Materials has developed a MOF adsorbent with a high capacity for CO_2 even at the low CO_2 content of air.

[29] This assumes that the carbon capture plant removes 100% of the CO_2 in the incoming gas. In reality, removing 30–90% of the CO_2 is more likely.
Fun fact: to capture 1 tonne of CO_2 from air, the volume of air needed is 1.2x the volume of the Empire State Building.

[30] Emerging DAC company Global Thermostat has developed a monolith (honeycomb-like) adsorbent that leads to very low pressure losses.

[31] A key innovation of one growth stage startup, Svante, is a wheel-shaped bed design that rotates the adsorbent through filling and recharging in 60 seconds (this is an example of a solid adsorbent used for point-source carbon capture).