Direct Air Capture: Startup and Market Environment

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Introduction

To mitigate global risks associated with climate change, communities and companies around the world must accelerate decarbonization. With the rapidly declining costs of wind and solar energy, the first step is to meet all new energy demands with renewable power sources. However, worldwide emissions reductions are moving too slowly to hit critical climate targets of 2 degrees Celsius (let alone 1.5 degrees). Direct removal of CO_2 from the atmosphere is required. Over half of the models cited in the Intergovernmental Panel on Climate Change's (IPCC's) Fifth Assessment Report (published 2013 - 2014) required carbon capture to stay within 2°C of global warming compared to pre-industrial temperatures.[1,2] While some capture can come from natural solutions such as planting trees, this strategy comes with inherent risks such as increased soil disturbance, fires, and changes in light absorption.[3] Growing forests also takes time, land tenure and land-use rights must be handled, and it is difficult to estimate CO_2 sequestered by trees.[4,5] Engineered solutions to carbon capture have different risks and benefits, making them an essential part of a CO_2 removal portfolio.

Carbon capture can be deployed on industrial sites to remove CO_2 directly from the flue gases, reducing annual emissions. On the other hand, direct air capture is completely decoupled from any particular industrial process, and removes CO_2 from the atmosphere itself, making it a negative emissions technology. Whether from the air or industrial flues, the gas stream is passed through chemical compounds, which can be either fluid solvents or solid sorbents that grab the CO_2. The gas stream, after CO_2 removal, is then released into the atmosphere. To keep the process going, heat is commonly used to eject CO_2 from the capture medium (solvent, sorbent, etc). The regenerated capture medium is then returned to the job of capturing more CO_2 from incoming gases. The CO_2 ejected by the regeneration process is sent to pipelines for permanent underground storage. Both carbon capture from industrial flue gas and direct air capture result in carbon being permanently stored in underground geologic reservoirs, but they differ in the source of CO_2. Traditional carbon capture separates CO_2 from other gasses resulting from power generation, such as from coal or natural gas power plants, or from industrial facilities, such as steel and cement factories. Direct air capture (DAC) removes CO_2 directly from the atmosphere.

IPCC reports state that both technologies are critical; however, the challenges faced by each are somewhat different. When capturing carbon from industrial gas, emissions from power plants are emitted directly from a pipe (AKA flue), so it is somewhat straightforward to install a system directly onto the source of emissions. On the other hand, DAC uses more energy as it requires fans to pull in air from the atmosphere. Typical CO_2 concentrations in the atmosphere are around 412.5 parts per million (ppm), or around 0.04125%.[6] CO_2 concentrations from flue gas, while still low, are relatively high compared to atmospheric air, typically coming around 8-10%.[7] With higher CO_2 concentrations from flue gas, traditional carbon capture systems filter through much less gas to capture the same volume of CO_2, making the process more efficient. Finally, differences in ownership and responsibility of GHG make DAC more challenging. Power plants and industrial facilities are held responsible for their emissions, so they are motivated to construct carbon capture systems. On the other hand, there is no clear party responsible for elevated CO_2 concentrations in the atmosphere, so there is no clear entity to sell DAC plants to. Due to this difference in difficulty, flue gas capture has been scaled to multi-million ton/year capture capabilities with costs often hovering around $70 - 100/ton.[8] Direct air capture's largest facility is ORCA with a capacity of 0.004 million tons/year at costs of around $1000/ton.[9]

This paper focuses mainly on direct air capture plants and the capture and utilization phases of the process. The carbon removal process can be split into three main categories — capture, storage, and utilization. In the capture phase, carbon is extracted from the atmosphere using chemicals. This requires relatively large plants and fans, requiring significant energy and construction time. Once the carbon is captured and pushed into pipelines, it can be either stored or utilized. Most of it is stored underground by carbon storers, in which it is sequestered permanently underground through capillary forces in porous rock formations or chemical forces in basaltic rocks and saline aquifers. The other option for permanent storage is to utilize the carbon and turn it into actual products. For example, carbon can be turned into concrete, plastics, biomaterials, feedstocks, and even diamonds and furniture. This paper provides an outlook on the industry for carbon capturers and carbon utilizers.

Carbon Capturers

Carbon capturing companies require a large number of capital expenditures since CCS plants (whether for power plant/industrial flues or direct air capture) are very capital intensive, which may lead to the market ultimately being dominated by a few key players. For example, ORCA cost Climeworks between $10M - $15M to build, and Carbon Engineering’s 1PointFive will require an $811M investment.[9,10] Traditional early-stage venture capital investors are often hesitant to invest this much money, especially since the path to profitability/returns is unclear and likely far away. For carbon capture plants, scaling often requires significant capital, various strategic and community partners, and iterative deployment and testing. On the other hand, investors prefer to invest in companies and projects when there are clear precedents since this reduces risk. Additionally, many private funds (venture capital/private equity) have a timeline such as 8-10 years and at the end of this period, investments must be sold to get liquidity and return capital to investors.

Table 1. Types of funding sources and their goals.
Green: great match for CCUS; Yellow: some match; Red: poor match

DAC Funding Requirements	Traditional Private Funds	Specialized Infrastructure/ Energy Funds	Strategic Corporate Partners
Long Timelines	🟥 Most VC/PE funds must return profits to investors within 8-10 years	🟩 Specialized funds are set up with a suitable time horizon for infrastructure	🟩 Investing own money, so no obligation to return to investors within 10 years
Strategic Partnerships	🟥 Traditional generalist funds do not need offsets; industry connections don't justify risk	🟨 Fund has advisors, connections, and Portfolio Companies within industry	🟩 Corporate has connections and strategic interest in partnership/offsets/ deployment/etc.
High R&D Tech Risk	🟥 Capital investment is too high for ample diversification, causing concentrated risk	🟨 Fund's investment mandate covers infrastructure risk	🟩 Risk is offset by desire for product, and corporates do not answer to fund investors

Since DAC companies often have long R&D and construction periods, their longer timeline limits some equity investors like generalist venture capital funds. Investors in DAC startups are therefore more likely to be strategic investors like corporations that demand carbon reductions, specialized funds in the infrastructure space, or governments. For example, Svante has raised money from Chevron Technology Ventures (strategic corporate), Carbon Direct (specialized investor in CCUS companies), and Canadian government entities.[11] Strategic investors (as opposed to financial investors) would not have a restricted timeline to return funds to investors and are interested rather in strategic value such as company synergies. Smaller specialized funds are often better partners for early-stage start-ups, who need a network and advice along with funding. Governments also provide fundraising for CCUS startups, though their funding often comes as a grant rather than an equity investment. Governments also have a public duty to reduce the nation's GHG emissions and support public infrastructure, and providing funds for DAC startups helps support federal or state net-zero commitments and emission reduction targets. Therefore, specific bills and departments like the Infrastructure Bill and the Department of Energy can provide funding for DAC startups.

Startups must achieve large production volume to find economies of scale through lower costs, especially as average fixed costs decrease with additional production. Also, DAC startups must pass approvals and regulations and demonstrate successful pilots before operating at scale. Finally, the industry appears unprofitable, which deters additional competitors from entering the market versus pursuing profitable opportunities. Overall, the carbon-capturing industry has high barriers to entry that can prevent some companies from obtaining a foothold in the market.

The DAC industry may be dominated by a few key players in the future. This may happen as unsuccessful DAC companies become bankrupt and there are acquisitions and partnerships between the ones that survive, which leads to industry consolidation. For example, large mergers in the oil and gas industry have contributed to the industry's status as an oligopoly.[12] Notably, more mergers in the oil and gas industry have happened during the downside of the business cycle when oil prices are lower.[12] This is because as oil prices fall, profits have fallen, which has motivated cost reductions and restructuring through consolidation. Oil and gas companies combine to reduce overhead costs and optimize portfolios with the most competitive and efficient projects. For example, Exxon and Mobil merged in 1998, expecting \$2.8B in savings.[12] Together, they achieved \$10B in synergies through job cuts, more strategic capital expenditures, and increasing control over functions and technology across the postmerger company.[12] A similar trend could emerge with DAC companies, as larger companies acquire smaller ones to gain access to their technology or expand their portfolios to diversify across regions and plant types. Similar to how oil and gas mergers are affected by oil and gas prices, DAC mergers may also be tied to a business cycle based on carbon prices.

Carbon capturers must operate at a large scale and build huge plants to be successful. To effectively make a tangible impact on carbon concentrations in the atmosphere, DAC plants must filter through a lot of air. For example, the 1PointFive plant is 100 acres, or approximately 0.15 square miles, and is designed to capture 1,000,000 tCO$_2$/year.[13] This comes out to a rate of

$$\frac{1{,}000{,}00\ tCO2/year}{100\ acres} = 10,000\frac{tCO2/year}{acre}.$$

Orca is much smaller than 1PointFive; it is designed to capture just 4,000 tCO$_2$/year. It consists of eight collectors, which are each the size of a 40-foot shipping container, which has dimensions 40' x 8' x 8'6".[14] Visually, the plant seems to have dimensions approximating 2 collectors x 1 collector plus around 10 feet of space surrounding each collector.[15] This comes out to

$$120' \times 60' = 7200\ ft^2 = 0.165\ acres.$$

This leads to a carbon capture rate of

$$4,000\frac{tCO2}{year} \div 0.165\ acres = 24,000\ \frac{tCO2/year}{acre}.$$

To put DAC plants' carbon capture rates into perspective, the rate of carbon capture through these DAC plants can be compared to the rate of carbon capture from trees. One acre of a 50-year-old forest can be assumed to capture 30,000 pounds of CO_2 per year.[16] This is a rate of

$$30,000\frac{lbs\ CO2/year}{acre} \times \frac{1\ ton}{2{,}000\ lb} = 15\frac{tCO2/year}{acre}.$$

These estimates vary by source. Another source suggests that at their most productive stage of carbon storage of 10 years, trees can absorb about 9.2 tCO_2/year/acre.[17] An article from Yale praises California redwoods for their carbon storage abilities and states that redwoods can store 6,240 tCO_2/acre.[18] Assuming an average lifespan of 600 years, redwoods would store 10.4 tCO_2/year/acre.[19] Assuming a forest can capture around 10 tCO_2/year/acre, this means that 1PointFive will be about 1,000x and Orca is about 2,400x more efficient at capturing carbon.

For the last decade, three main startups have tackled the initial development of large DAC plants. These three companies, which were founded between 2009 - 2010, are Climeworks, Carbon Engineering, and Global Thermostat. Of these three, Climeworks and Carbon Engineering have had the most success, while Global Thermostat has struggled and fallen behind due to mismanagement by founder Graciela Chichilinisky.[20] Climeworks's ORCA was launched in Iceland in September 2021 and is designed to capture 4,000 tCO_2/year, while 1PointFive, which licenses Carbon Engineering's technology, is expected to capture 1,000,000 tCO_2/year starting in 2024. Climeworks's technology is made of CO_2 collectors that contain a filter with solid sorbent. The collectors are modular and each unit can capture roughly 50 tCO_2/year. The modularity is advantageous because units can be mass-produced and allows for flexibility in the size of the plant without having to redesign each one. However, a disadvantage of the system is that it is run with a vacuum, which is very energy-intensive. The modularity helps minimize upfront CapEx risk by preventing overbuilding, but the vacuum harms the potential for economies of scale due to the way energy intensity scales with vacuum demand.

Carbon Engineering uses a liquid solution of potassium hydroxide in water and moves the air using a fan. The liquid solution is more scalable than a solid filter since it is easier to add more liquid than construct additional filters. Its technological advantage is that it does not require a vacuum. Carbon Engineering has two main types of plants. First, it creates standard DAC plants that bury CO_2 underground with secure geologic storage. Second, AIR TO FUELS plants capture atmospheric CO_2 and convert it into synthetic crude that can be processed into gasoline, diesel, and jet fuel that work in existing vehicles and transportation infrastructure without any modifications. This process is not new; it was used widely in World War II as Germany created more than 92% of aviation gasoline and half of its total petroleum from synthetic fuel.[21] Creating a marketable product through fuel can help Carbon

Engineering gain traction and expand. Per an article published in 2018 by the Carbon Engineering team, the company aims to price captured carbon between \$94 - \$232/tCO_2 once the technology reaches commercial scale.[22] Compared to more expensive technologies such as Climeworks' Orca, which prices carbon at \$600 - \$1200/tCO_2 removed, Carbon Engineering has a clearer path to economic viability.[9]

Climeworks and Carbon Engineering have achieved several milestones including DAC plants, partnerships, and purchasers of their carbon credits. Climeworks has carbon removal agreements with fintech and tech companies including Microsoft, Block, and Swiss Re. Climeworks also supplies captured carbon to carbon utilizers such as Aether, and Coca-Cola Switzerland carbonates beverages using captured CO_2. Carbon Engineering's strategy is different because they use captured carbon for enhanced oil recovery and fuel. Although this is not the best use from an environmental perspective since it enables the continuation of fossil fuels, it has a clearer path for demand and profitability. Oil companies that work with CE have a higher demand for captured carbon to reduce their carbon intensity, especially with increasing regulation and scrutiny. Meanwhile, Climeworks supplies CO_2 to cleaner utilizers like Coca-Cola, which has both a lower demand quantity and willingness to pay. Whereas the beverage industry uses 10M tCO_2/year, enhanced oil recovery used approximately 63M tCO_2 in 2012 (the figure has definitely grown by now).[23,24] Additionally, fossil fuel companies have a higher willingness to pay for captured carbon. Coca-Cola sources cheaper CO_2 commercially, while fossil fuel plants are faced with greater regulatory and shareholder pressure to decarbonize, which increases their willingness to pay for captured CO_2.[25] Therefore, there is a tradeoff between gaining fossil fuel customers eager to partner with DAC plants to reduce their carbon footprint vs. using captured CO_2 for "cleaner" uses like carbonating beverages (instead of supporting oil and fuel production).

Finally, Global Thermostat uses fans with steam to regenerate the system and passes the air through amine panels. Using steam is generally more scalable than a vacuum and does not have the size limitations that are inherent to a vacuum system. Global Thermostat has lost momentum while its peers have continued to innovate and build projects, so it will have to work harder to recover and gain market share than younger startups in the space.

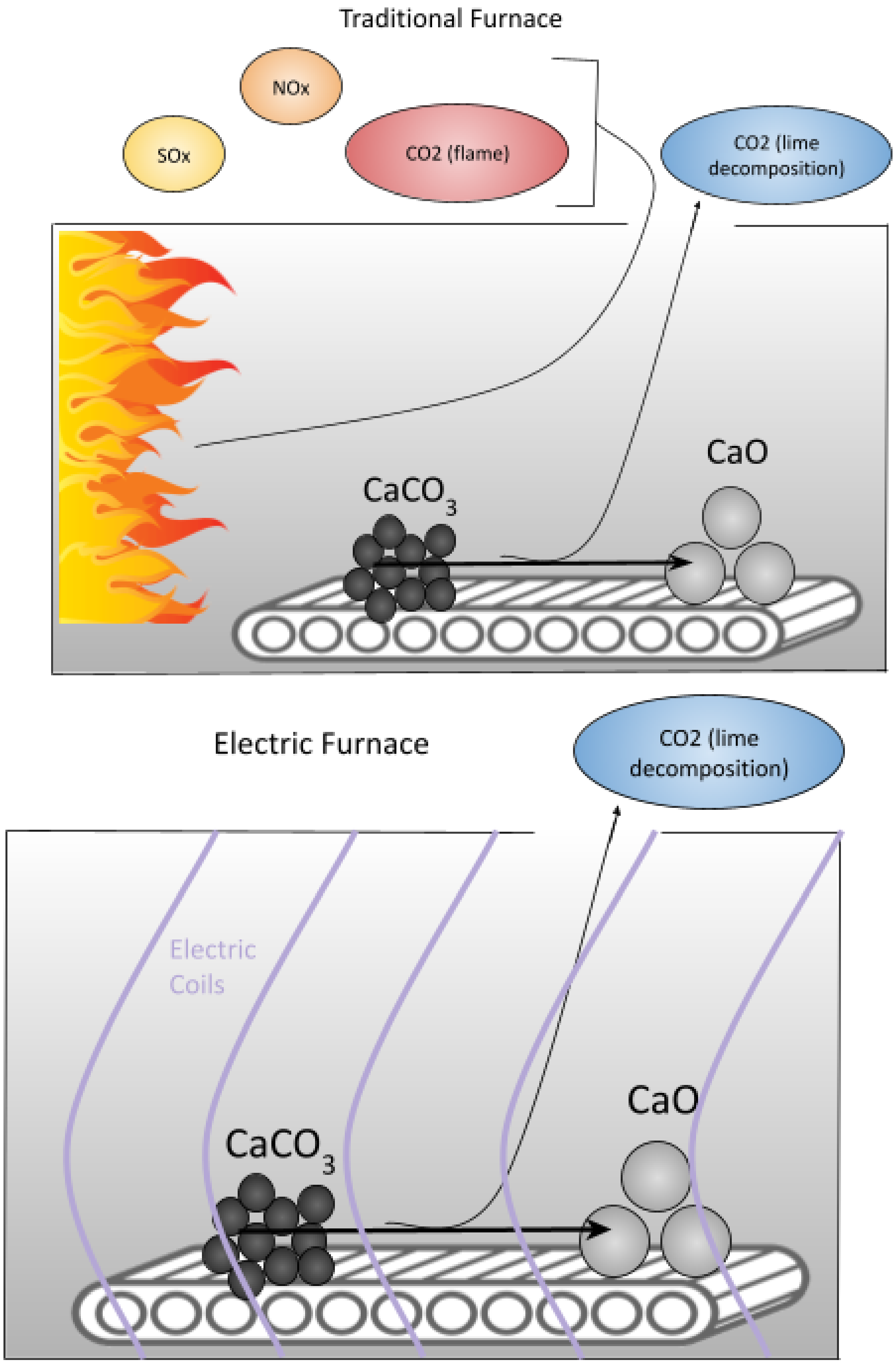
Although initial capital expenditures to create a carbon-capturing company are high, younger startups are able to move faster than more established ventures. Since a decade has passed since the founding of capture companies like CE, Climeworks, and Global Thermostat, new companies have begun to enter the market, sometimes with new technological advantages, like Svante, CarbonCapture, and Heirloom. Svante developed a mechanical rotary mechanism that provides a new way for ultraporous membrane adsorbents (i.e., resembling those used by Climeworks) to capture CO_2 rapidly, allowing them to even work with industrial flue gases.[26] Svante has a rotary mechanical unit that captures flue gas on one end, rotates it to release CO_2, and rotates it again to recondition and cool the filter. This is important because it eliminates the need for a vacuum to regenerate the CO_2 filter.

CarbonCapture uses zeolites to absorb CO_2 from the air, which reduces the operating costs of its machines and will enable it to scale quickly since zeolites are inexpensive, stable, and abundant. Like Carbon Engineering and Svante, CarbonCapture uses steam to regenerate the zeolites after the carbon capture process.

Heirloom seeks to use what is called "enhanced carbon mineralization" to perform DAC. It takes limestone (mostly $CaCO_3$) and heats it to release the CO_2, just like what is done for cement production.[27] The CO_2 gas that is emitted from the rock is then captured and sequestered. The resulting product (CaO) can then be exposed to air to capture CO_2 and transform back into $CaCO_3$, which can be put back through the process. As long as CO_2 is captured in each cycle, it has the potential to be a negative emissions technology.

However, heating $CaCO_3$ to form CaO must often occur above 900 Celsius. The most conventional way to perform this transformation in traditional cement kilns is to use a hot flame (Figure 1, top). The burning of fossil fuels to heat the rock often emits toxic compounds like NOx and SOx, as well as additional CO_2. To prevent these excess emissions, Heirloom uses an electric furnace (Figure 1, bottom). Since the furnace has no direct emissions, the only CO_2 that must be captured comes from the limestone itself.

Figure 1: Heirloom's Technological Advantage: Electric Furnace



Heirloom's competitive advantage stems from its cheap input (rocks) and the well-understood process of heating limestone developed by the cement industry (which has been researched nearly all of human history). It claims it will be able to perform carbon removal for \$50/tCO_2 once it reaches commercial scale.[27] For comparison, Carbon Engineering aims to price captured carbon between \$94 - \$232/tCO_2 once the technology reaches commercial scale.[22] Customers are currently paying \$600 -

\$1200/tCO_2 removed by Orca, although Climeworks hopes to reduce this price to \$200 - \$300/tCO_2.[9] Industry experts estimate that carbon capture will become economically viable at around \$100 since US customers today typically pay between \$65 and \$110 for commercial CO_2.[28]

However, there is another aspect of Heirloom's technology that is surprisingly not mentioned. Heating limestone to release CO_2 is exactly the process for the creation of cement for the building industry. Large concrete producers, like Holcim, have been working to apply carbon capture tech to their cement kilns, which are heated with fossil-fuel flames. If Heirloom has electric kiln technology, it could try applying that to the cement industry first, as the cement industry is looking for exactly that. Especially if Heirloom has brought together expertise on electric kilns and post-kiln CO_2 capture, it could gain powerful clients, like established cement companies.

In the future, these startups may be able to collaborate with more established names, who can help scale them up. These startups can provide solutions for inefficiencies in established players' technology, like with Svante's rotary device replacing Climeworks' vacuum.

Carbon Utilizers

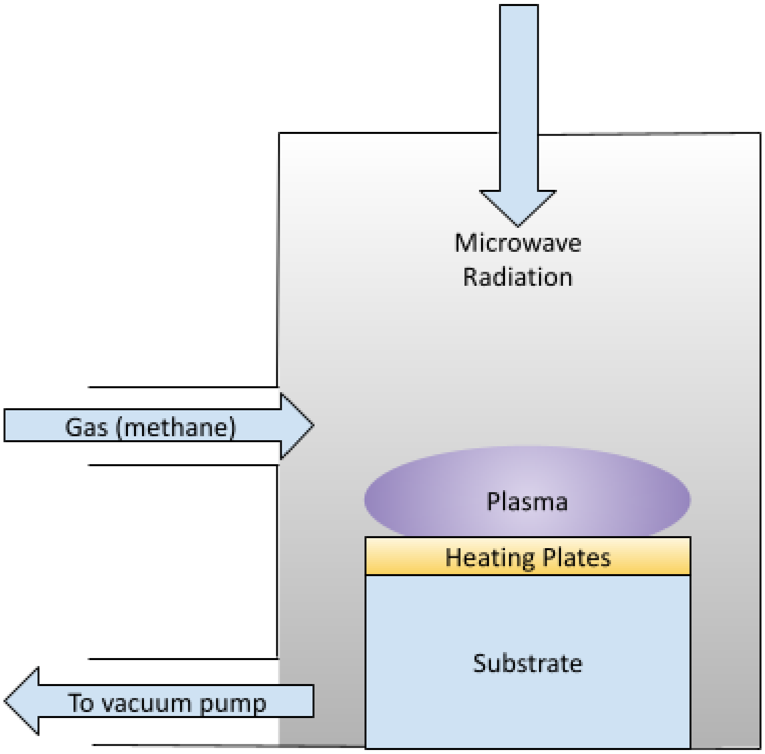
Sequestering carbon underground is an effective way to remove it from the atmosphere, but transforming it into sellable products can add value to carbon's cycle. Underground sequestration will remain the primary destination for captured CO_2, as far more CO_2 must be captured than there is demand to use CO_2 to create customer products. However, utilizing carbon can create more demand for captured carbon with an end product that can benefit consumers, as opposed to simply storing CO_2 underground. If consumers are willing to pay for products containing captured carbon, then carbon utilizing startups are incentivized to create these products. This increases demand for carbon capturers and can help them become more economical. A variety of industries demand carbon — carbon fibre is used in the construction of buildings and structures, concrete injected with CO_2 is stronger, beverage companies carbonate beverages, higher CO_2 levels in greenhouses can increase plant growth, etc. Currently, these industries get their carbon by drilling it out from underground, which is counterproductive to sequestration efforts. Indeed, several food-grade CO_2 producers are "CO_2 Domes" in Colorado, New Mexico, and Mississippi.[29] If these industries were to source captured carbon, both capturers and utilizers could benefit. Part of the reason that this collaboration is not happening now is that the cost of captured carbon is higher than prices from drilling underground. CO_2 sourced from the Jackson Dome carbon field in Mississippi costs \$10 - \$15/tCO2.[30] This is significantly less than CO_2 captured from power plants, which costs less than direct-air-capture carbon. CO_2 captured from coal plants costs \$37 - \$55/tCO_2, while CO2 captured from natural gas plants costs \$49 - \$114/tCO_2.[31] To offset the higher costs, startups that use captured carbon must highlight their clean solution to customers to increase their willingness to pay for a low carbon product. If carbon capturers are able to achieve their planned cost reductions, there will likely be a boom of carbon utilizers as the business becomes more economically viable.

Whereas market share among carbon capturers is likely to remain concentrated among a few key players, the market for carbon utilizers may include many smaller companies. The main reason for this is the capital intensity of capturing vs. utilizing carbon. Capturing carbon requires significant capital expenditures to build large plants, as well as immense R&D costs and resources spent on regulatory approval. While utilizing carbon is still research- and technology-intensive, the end product is meant for consumers and therefore on a much smaller scale. Therefore, there are lower barriers to entry to becoming a carbon utilizer, which is why many more startups will exist in this space. Another reason for this is that the amount of captured carbon far exceeds the demand for captured carbon. With a high supply of captured carbon, there will not be competition among carbon utilizers to purchase the carbon, and there will be plenty of supply for more utilizers to enter the market.

There is also more room for product differentiation and expansion into different industries through carbon utilization. Carbon capturers are essentially performing the same operation, capturing carbon from the air or from flue gas and sending it into pipes underground. However, carbon utilization can be categorized into various markets, as carbon can be turned into cement, plastics, fuels, and chemicals that can be used in various industries such as construction, fashion, and feedstock. There are more possibilities for creative applications in this market. (Carbon Removers is a great source to view the business environment). For example, Mirreco creates hemp-based products that store carbon, and plans to use these polymers to 3D print sustainable homes. Air Protein transforms carbon into alternative air meats, and Graviky captures soot and pollutants from exhaust to convert into ink. Since these products are niche and specialized, they do not compete with each other even though they are all carbon utilizers. Once carbon capture becomes more mainstream, there are likely to be even more futuristic applications that are unimaginable today.

A unique carbon utilizer is Aether, which creates diamonds out of atmospheric carbon. The startup obtains captured CO_2 from Climeworks, and synthesizes it into methane, which can be used as chemical precursors for diamond growth by Chemical Vapor Deposition (CVD) (see below diagram).[32] Though Aether does not disclose their particular setup, most CVD growth of diamonds occurs by plasma-induced deposition from methane in a high-vacuum chamber. A plate is heated to the appropriate temperature, and the chamber is filled with methane. Then microwaves are pumped into the chamber to heat the gaseous methane to the point where a plasma forms. Once the carbon radicals contact the carbon-containing substrate on the heating plate, the carbon atom binds. Thus, the diamond grows one atomic layer at a time.

Figure 2: Schematic Drawing of a CVD Chamber for Diamond Growth[32]



This application is notable because the economics and high price points of diamonds can enable Aether to become profitable and self-sustaining, while other CCUS startups lack a clear path to profitability and must be subsidized by government regulations and carbon trading markets. Diamonds have such a high price point because of the De Beers cartel, which controlled 90% of the production of mined diamonds through the 20th century. De Beers limited supply and advertised the ring as a symbol of love and loyalty through engagement to raise prices.[33] When a customer resells a diamond to a jeweler, they typically only receive around 20% of the retail value due to this large markup.[34] High diamond prices offset input costs from purchasing captured carbon, which can make Aether profitable. One carat of diamond weighs 0.2 grams.[35] Carbon weighs 12.0107 g/mol, while CO_2 weighs 44.01 g/mol. Each gram of carbon requires

$$\frac{44.01\ g\ CO2/mol}{12.0107\ g\ C/mol} = 3.664\frac{g\ CO2}{g\ C}.$$

Therefore, each carat of diamond requires

$$0.2\ g\ C \times 3.664\frac{g\ CO2}{g\ C} = 0.73\ g\ CO2,$$

or $0.73\ g\ CO2 \times \frac{1\ ton}{907185\ g} = 8.069 \cdot 10^{-7}\ tCO2.$

Even if Aether were to pay Climeworks a price in its higher range of $1200/tCO$_2$, the cost of carbon for a carat would only be

$$8.069 \cdot 10^{-7}\, tCO2 \times \frac{\$1200}{tCO2} = \$0.001.$$

Therefore, Aether's actual input cost of CO$_2$ is negligible for each diamond produced, so CO$_2$ prices have little influence over the final price of Aether's diamonds. Even if an oil and gas plant were to capture CO$_2$ more cheaply from flue gas, it would not significantly affect diamond prices and threaten Aether's business.

While maintaining the same physical, chemical, and optical properties of traditional diamonds, Aether sells at a lower price than mined diamonds. For example, a diamond solitaire ring that would cost $13,000 - $15,000 from a traditional jeweler would cost $7,000 made from Aether's lab.[36] This is more expensive than other lab-grown diamonds, likely because Aether can charge a green premium for creating the only truly sustainable diamonds in the market. The green premium represents the cost of choosing a sustainable technology over one that emits more greenhouse gasses. Given the lower price of synthetic diamonds and high-profit margins of mined diamonds, it seems that De Beers can undercut the prices of synthetic diamonds at any time. However, De Beers wants to maintain a distinction between lab-grown diamonds and reinforce the glamor of natural mined diamonds. It would want to keep a significant gap between the two, even if it must lower prices as diamond supply overall increases. Additionally, De Beers is entering the synthetic diamond business, as it is investing $94M to produce 500,000 carats of lab-grown diamonds a year.[37] Therefore, lowering the prices of synthetic diamonds would hurt itself as well, so prices for both synthetic and mined diamonds are likely to remain elevated. The diamond industry can present opportunities for startups to utilize captured carbon and still be profitable, which makes it stand out from other carbon capture and utilization applications.

Conclusion

Direct air capture is a relatively new and promising technology that can lower atmospheric greenhouse gas concentrations as global temperatures accelerate to unprecedented levels. By extracting CO$_2$ directly from the atmosphere, DAC requires much less land than nature-based solutions. Although it requires more land than capturing CO$_2$ directly from flue gases due to a lower concentration of CO$_2$ in the air, DAC has the advantage of siting flexibility, whereas flue gas capture must be located directly at industrial or power plants. As fossil fuel-burning power plants close in the upcoming decades, DAC will play an important role in reducing CO$_2$ that has already entered the atmosphere and will remain for hundreds of years.[38,39] There are currently just 19 DAC facilities in the world capturing over 10,000 tCO$_2$/year, but with more startups entering the space and more companies announcing net-zero commitments to fund them, DAC will become a useful technology to capture and sequester CO_2.[40]

Due to high capital expenditures, R&D and construction periods, and large production volumes required to achieve economies of scale, the carbon capture industry is likely to develop into a few key players. The industry is currently in the phase of new technology ideation, development, and testing with emerging startups like Heirloom and CarbonCapture. As startups complete more tests and prove their technology to be effective and scalable, the industry can move past the experimentation stage. Startups with comparative advantages in different parts of the process, such as air absorption and filtration, can collaborate to build more effective plants, leading to overall industry consolidation. On the other hand, carbon utilization requires relatively smaller industrial facilities to convert carbon into everyday materials and consumer products. Since they create a diverse range of products, from fuel to carbon fibre to diamonds, they operate in different markets and do not compete with each other. With a relatively unlimited supply of captured carbon, there will be many more carbon utilizers than carbon capturers, and they will operate on a smaller scale in many different industries.

Although most captured carbon will be sequestered and stored underground, carbon capturers and utilizers will have increasing opportunities to collaborate. This interaction would provide both parties with benefits. Utilizers will receive pure, negative emissions carbon to form products, and capturers will gain an additional customer as well as marketing and recognition surrounding their contribution to the end consumer product. This paper provides an overview and a potential future outlook for the DAC market. In addition, it hopes to inspire individuals to find unique low-carbon products and innovate new creative ways to use carbon to create products. For entrepreneurs interested in the DAC space, this paper provides an overview of upcoming carbon capturers and more mature companies, which can present an avenue for discussion and collaboration.

Additional Examples and Supplementary Calculations

DAC Plant Size vs. Coal Plant Size

Although it is hard to compare the sizes of DAC plants to coal power plants because carbon captured cannot be directly compared with MW production, it can be helpful to estimate the average size of a coal power plant. A standard 500 MW coal plant that mines 19 acres/MW has a footprint of

$$19 \frac{acres}{MW} \times 500\ MW = 9500\ acres,$$

which is much larger than 1PointFive or Orca.[41,42] This huge acreage is partially due to the footprint of coal mining operations, which may include open pits and underground mine shafts and tunnels.[42] When estimating the power density of fossil fuels, it is important to consider the land used for mining. Not including such land use gives a falsely high land-use efficiency of fossil power compared to renewables like wind and solar.

For example, the WA Parish Generating Station is the largest coal-fired power plant in Texas and the ninth-largest CO_2-emitting coal plant in the United States.[43] It has four coal-powered units and four natural gas-powered units, and generates 3.65 GW (3650 MW) of power on 4,664 acres of land.[44] The Petranova capture plant (capable of capturing 1.6M tCO2/year) was sited on 4.6 acres of land.[45,46] Therefore, Petranova captures

$$\frac{1{,}600{,}000\ tCO2/year}{4.6\ acres} = 348,000 \frac{tCO2/year}{acre}.$$

The capture rate thus follows: 348,000 (Petranova) > 24,000 (Orca) > 10 (Trees). By putting carbon capture directly at the source, it can be much more efficient.

CO_2 Captured: Human and Vehicle Emissions

Another way to think about the impact of DAC plants is quantifying in terms of actual human emissions. Climeworks' ability to capture 4,000 tCO_2 annually offsets the emissions of just 600 European people, a small fraction of Iceland's small population of 345,000.[47,48] This rate is based on the 2018 European average of 6.6 tCO_2 emissions per capita. However, emissions vary largely throughout the world. The average American emits 16 tCO_2/year, while the average carbon footprint globally is around 4 tCO_2/year.[49] Therefore, a 4,000 tCO_2 DAC plant would offset the footprint of around

$$4,000\ tCO2/year \times \frac{1\ American}{16\ tCO2/year} = 250\ Americans,$$

or $4,000\ tCO2/year \times \frac{1\ person}{4\ tCO2/year} = 1,000\ humans\ globally.$

America's higher carbon footprint partially stems from higher car ownership. While 18% of the world owns a car, 91% of U.S. households have access to a vehicle.[50,51] The average passenger vehicle has a fuel economy of 22 mpg. Assuming 11,500 miles driven per year, a vehicle emits 4.6 tCO_2/year.[52] Therefore, 1PointFive would offset

$$1,000,000\frac{tCO2}{year} \div 4.6\frac{tCO2/year}{car} = 217,000\ cars,$$

while Orca would offset the emissions of

$$4,000\frac{tCO2}{year} \div 4.6\frac{tCO2/year}{car} = 870\ cars.$$

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