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Is Direct Air Capture ready for VC investments?

Direct Air Capture (DAC) is a vital technology for removing CO_2 from the atmosphere to mitigate climate change, but its scalability faces two key challenges: clean energy availability and cost. DAC requires substantial energy, making it expensive compared to other decarbonization methods, with current costs ranging from $300-$4000 per ton of CO_2 removed. While DAC can serve carbon offset markets and sustainable aviation fuel production, cheaper alternatives like biogenic CO_2 may delay its widespread adoption until the mid-2030s. Though long-term demand is expected to surge post-2040, near-term market growth is limited. Early VC investments could yield returns through acquisitions, but significant risks include high costs, regulatory uncertainty and potential for superior emerging technologies.

1. Introduction

In order to mitigate further climate change, humanity needs to re-establish pre-industrial levels of CO_2 in the atmosphere as soon as possible. This corresponds to removing roughly 800 billion tons of CO_2 in total. However, the global economy currently adds approximately 50 billion tons of CO_2 to the atmosphere per year. So, closing the tap of emissions, i.e. decarbonizing the economy, is a necessary step to stop things from getting worse. Key innovation and scale up topics for industrial decarbonization are point source capture, electrification of industrial process and low carbon fuels among others. These topics are outside the scope of this discussion. Rather, in addition to stopping emissions, active removal of CO_2 is required to get back to the safe space we were some 100 years ago. This can be done by restoring and amplifying nature-based absorption mechanisms (forests, oceans, mineralization) or engineered approaches, of which Direct Air Capture is the most discussed avenue. This is the focus of this piece.

2. So what is DAC?

The beauty of DAC is its conceptual simplicity: A vacuum cleaner for extracting CO_2 from ambient air that can be built wherever clean energy is available at low cost and where favorable geology allows for sequestration without much transportation. DAC's fundamental challenge is that the energy needed to capture and separate CO_2 from a gas mixture increases rapidly as its concentrations decrease. The key performance indicator of different technologies is therefore their energy need per ton of CO_2 (either as heat or electricity), which ranges between 2-18 GJ/ton (0.6-5 MWh/ton) with current technology approaches. Adding to the energy cost, the capital cost of large-scale equipment that needs to treat massive amounts of air, results in levelized costs for DAC of approximately 300-4000 $/ton at a (hypothetical) one million ton per year (Mtpa) facility size, without sequestration. Such a size has not been built yet. The largest operational facility has a capacity that is 25x smaller than that (Climeworks Iceland, 0.04 Mtpa). The largest plant in construction is 1PointFive's U.S. facility with a nameplate capacity of 0.5 Mtpa (operational due mid 2025). The lowest levelized cost forecast for 2050 is currently with electroswing, hybrid electroswing and amine technology, all coming in at around 130-140 $/ton (in current USD, without inflation adjustment).

There are a number of different technical approaches that are being pursued. The focus here is only on those that have reached a level of technological readiness that allows them to see industrialized application within the next 5-10 years. The technically more mature approaches are thermochemical, using CO_2-selective solvents (calcium looping) and sorbents (amines, zeolites, metal-organic frameworks) that first capture CO_2 and in a second step release it to create a concentrated CO_2 stream. Less technically mature approaches are electrochemical, either partially (solvent/sorbent capture + electrochemical regeneration) or complete electrochemical absorption and regeneration. See the table below for a brief summary of the main technologies, their estimated cost-down potential and some of the associated startups working on them.

Technology	Description	$/ton in 2030	Startup examples
Solvent/Calcium looping	CO_2 reacts with alkali metal hydroxides in an air contactor to form $CaCO_3$. The carbonate is subsequently decomposed back to the oxide and CO_2 at temperatures between 700°C and 1,000°C in a calciner.	400	Carbon Engineering (Oxy), Heirloom, 8Rivers
Amine sorbent	CO_2 adsorbs to surface of amine (-doped) sorbents which are regenerated by heat to release CO_2. Operating temperatures are on the order of 100°C. Most commercially mature technology.	170	Climeworks, Global Thermostat, Skytree
Zeolite sorbent	CO_2 adsorption on zeolites, aluminum- and silicon-based compounds with high porosity and large surface area. Zeolites are regenerated by heat to achieve desorption of CO_2.	410	Carbon Capture, TerraFixing, Removr
MOF sorbent	Metal-Organic-Frameworks, a class of expensive, porous polymers, adsorb CO_2 and release at temperatures below 100°C. They can be combined with pressure- or vacuum-swing desorption.	3600	Svante, Baker Hughes (Mosaic Materials), Promethean Particles
Hybrid electroswing	Use of CO_2-selective materials to capture CO_2 (as above), but then using electrochemical means for desorption and regeneration. No heat required. Mostly based on acid-base bicarbonate chemistry.	200	Parallel Carbon, Carbon Atlantis, Mission Zero, Carbominer, RepAir
Electroswing	Electrochemical cells that use charge and discharge currents to capture and release CO_2 from selective electrodes.	140	Verdox, RedoxNRG

3. What needs to be true for DAC to scale up?

While DAC technologies will continue to be piloted at increasing scale in the coming years, there are two fundamental barriers to the massive scale up that is required to create any meaningful climate impact. One is the availability of enough clean energy and the second is a revenue model that would make direct air capture financially attractive.

The industrial decarbonization that is required to close the tap of today's massive CO_2 emissions requires a substantial scale up of clean energy generation, storage and distribution. Because there is scarcity of clean energy, there is a need for prioritization to maximize the decarbonization impact of every kWh generated. For example, with the same amount of energy needed to remove 1 ton of CO_2 from the atmosphere, one can avoid the emission of roughly 5 tons of CO_2 via point source capture or via the electrification of heat. Therefore, as long as there is not enough clean energy to decarbonize the growing economy, DAC will unlikely be able to scale beyond a few Mtpa's, concentrated in a limited number of favored locations. This will probably be determined more by politics (incentives and taxes) than by economics (cost of energy, value of carbon). The only development on the horizon that could radically change this situation is the scale up of nuclear fusion, potentially providing enough energy for industrial decarbonization AND for massive scale up of DAC.

Even if the first condition of clean energy availability was met, what exactly is the economic value that DAC generates, who is willing to pay for it and why? DAC is valuable for those in the economy who have no other way to decarbonize their activities. This is foremost the aviation industry. Battery powered or hydrogen powered electric planes don't work for long distance flights. They will continue to be powered by liquid fuels that generate CO_2 when combusted. To result in a carbon-neutral flight, the production of sustainable aviation fuel (SAF) must remove that same amount of CO_2 from the air in the first place. For a certain type of SAF CO_2 is actually a feedstock in the production. Industry commitments and government regulations are in place creating a market pull for CO_2 coming from the air to produce SAF. However, the CO_2 can be sourced more easily and cheaper from scrubbing flue gases of biowaste incineration plants than from DAC. The biowaste removed the CO_2 from the air during its growth and releases it when incinerated. Only when biowaste capacity for sourcing CO_2 is not sufficient anymore, will the industry scale up DAC-derived CO_2 to produce SAF.

Another approach to reach net zero emissions is by offsetting via carbon credits. Emissions that cannot be avoided by decarbonization efforts are balanced out by removing the equivalent amount of CO_2 from the atmosphere, transferred between the parties as carbon credits. All major industrial players have net-zero targets in place, but will only offset when they have exhausted other options, not in the least to avoid the criticism of green-washing. However, offsetting can also be done by planting trees and other nature-based solutions that are cheaper than DAC and provide additional benefits in terms of biodiversity, nature preservation and support of indigenous livelihoods. It is not clear how heavy the expected longer permanence (how long the CO_2 will be locked away) of DAC vs nature-based solutions will weigh in the companies' decision process to select the one or the other carbon credit type.

Finally, what will the economic incentive be for DAC to further scale up once the world has reached net zero? Who will pay DAC operators then? The massive drawdown of historic CO_2 to get back to pre-industrial atmospheric levels might need to be executed via public sector buyers and financed by general taxation. This would likely require another Paris Agreement mid-century to reach consensus between countries on their respective contributions in order to be implemented.

4. Our expectation of the resulting DAC technology providers' market growth

After the qualitative discussion in the previous section, let's try to quantify the market size development of DAC for core technology providers over the next 15 years in a simple model.

Volume assmptions:

- **Offsets:** Biggest DAC buyers having placed purchase orders today are: Microsoft (0.8 million tons), Airbus (0.4 million tons). Amazon (0.25 million tons), Google (0.1 million tons), Frontier (0.1 million tons). The three biggest providers (1PointFive, Heirloom and Climeworks) together have so far sold future rights for offsets for a volume of 1.8 million tons. Delivery dates for those volumes are not publicly available, but likely to happen over the next five to eight years. As industries reach the limits of decarbonizing their footprints around 2035, they will have to use more carbon offsets, of which DAC will be a part.

- **SAF:** Today, sustainable aviation fuels (SAF) make up 0.2% of the total global jet fuel consumption (0.5 million tons of 300 million tons, all bio-based). There are binding quotas in the EU for synthetic fuel (requiring CO_2 feedstock for production): 1.2% by 2030, 5% by 2035 and 35% by 2050. This translates to a demand of two million tons of CO_2 feedstock in 2030, eight to 10 million tons in 2035 and 80-100 milliontons in 2050 (Europe only, about 20% of global market). However, this CO_2 demand will not likely use DAC before all other biogenic CO_2 sources have been exploited, notably from bio-energy with carbon capture and storate (BECS). A European study estimated that about 50 Mtpa of biogenic CO_2 is accessible in Europe and that therefore only post 2035 will there be a significant need for DAC-sourced CO_2 to serve the European SAF market. Non-European markets and other transportation sectors (maritime, road) are expected to introduce similar synthetic fuel quotas that create DAC demand post 2035.

Revenue assumptions:

- Technology providers capture 30% of plant capex, no maintenance revenues.

- No recurring revenues on captured volumes. Plant operators recoup those.

- Capex is assumed to be $2 billionn per 1 Mtpa until 2030 (in alignment with the announced 0.5 Mtpa Stratos plant by 1PointFive for $1.3 billion).

  Between 2030 and 2040 average plant sizes grow to 1 Mtpa and cost-down efforts achieve a capex of $1 billion per 1Mtpa capacity.

Time period	Growth driver	Added Volume (Mtpa)	Cumulative global capacity (Mtpa)	DAC providers' annual market size ($bn p.a.)
2025-30	Offsets	1-2	1-2	0.1-0.2
2030-35	Offsets and SAF quota in EU	5-10	6-12	0.3-0.6
2035-40	Offsets and SAF growth globally and other sustainable fuels (maritime, road)	40-80	56-92	2.4-5

5. Conclusion: Why or why not to invest as a VC in DAC now

Why invest in DAC now:

DAC is a long term opportunity. Investing in the right technology early allows massive value creation. First market demand is already there today, first regulations are in place that create a secure initial market size and longer term, this demand will only increase. Looking at post 2040, with current developments in place, the demand is likely to skyrocket even if the technology remains expensive. With breakthroughs leading to cost-down, that growth is going to be pulled forward and amplified.

For a VC, there can be profitable exits even before demand takes off, as energy majors and aviation industry players acquire technology provider to secure their future business, mainly around SAF. Proof point here is the acquisition of Carbon Engineering by Oxy.

Why invest in DAC later:

Significant market demand will only happen in 10+ years and many DAC startups will run out of funding before they can generate sufficient revenue. With costs for the technology remaining high compared to other offsetting options and bio-based CO_2 sources, the market will only need few facilities before 2035. Startups will get stuck between their First of a Kind (FOAK) product and when the market requires many units. The market has to be created in parallel with the technology being developed. Heavy regulation could accelerate this, but banking on the political will is a major risk.

We might expect emerging technologies to further mature and surpass current pre-industrial stage approaches in performance and cost in the next 10 years. This could create a second wave of DAC excitement in the market down the road, risking investments in current approaches and startups.

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