Getting real about capturing carbon from the air

Howard Herzog[1,*], Jennifer Morris[1], Angelo Gurgel[1] and Sergey Paltsev[1]

[1]Massachusetts Institute of Technology, Cambridge, MA, USA

[*]Corresponding Author: hjherzog@mit.edu

Many modeling studies depend on direct air capture (DAC) in their 1.5°C stabilization scenarios. These studies rely on assumptions that are overly optimistic regarding the cost and scaling-up of DAC systems. This can lead to highly misleading results that can ultimately impact the ability to reach climate stabilization goals.

Despite the commitments to the Paris Agreement's goal of pursuing efforts to limit the global temperature increase to 1.5°C, the world exceeded this target for most if not all of 2023, raising questions about its longer-term feasibility. Most modeling studies rely on carbon dioxide removal (CDR) or negative emission technologies, such as direct air capture (DAC), bioenergy with carbon capture and storage (BECCS) and afforestation/reforestation, to keep long-term temperature targets in reach.[1] DAC, in particular, has drawn substantial interest in recent years[1,2,3] because it can generate high-quality carbon removal credits. Specifically, (1) the removal is immediate as opposed to over time as in, for example, afforestation/reforestation projects, (2) it is straightforward to measure and verify the "net" amount of carbon removed, and (3) when coupled with geologic storage, the CO_2 will remain out of the atmosphere for millennia or more.[4] While these advantages are compelling, there are also many practical challenges associated with real-world deployment of DAC that affect its cost and potential deployment, including challenges related to scaling-up, energy usage and siting. However, many modeling studies diminish or neglect these challenges, assuming costs of DAC deployment that do not align with the engineering realities of the technology. Overly simplified or optimistic consideration of these challenges can lead to highly misleading results related to mitigation and adaptation strategies and their associated costs, and ultimately impact the ability to reach climate stabilization goals.

A brief overview of DAC

Carbon capture and storage (CCS) technologies have long been evaluated as potential options to scrub CO_2 from the exhaust gases of fossil-based electricity generation or industrial processes, thereby preventing the release into the atmosphere of most of the CO_2 created by burning fossil fuels. In contrast, DAC removes CO_2 directly from the atmosphere and, if the CO_2 is stored indefinitely, creates negative emissions. Like CCS, DAC captures CO_2 by using a chemical sorbent, which can be categorized as either a weak base like amines or a strong base like hydroxides. In addition to electricity, a weak base sorbent generally uses low-grade heat (100°C), which has the possibility to be generated from electricity with a heat pump, while a strong base sorbent generally uses high-grade heat (900°C) generated by fossil fuel (e.g., natural gas), which requires additional capture of the CO_2 from the fossil fuel. Currently, the largest DAC plant removes 4,000 metric tons (tonnes) of CO_2 per year and the price for a carbon removal credit is $1,500/tCO_2$.[14] However, recent modeling studies use DAC costs in the range of $100-200/tCO_2$ and project DAC deployment on the scale of 5-40 gigatonnes of CO_2 ($GtCO_2$) per year.[1] Unavoidable engineering challenges make such estimates rather unrealistic.

Challenge 1: Scaling Up

Nature presents DAC with a major, non-negotiable challenge—the very low CO_2 concentration in the air, currently about 420 parts per million (ppm), or roughly 0.04%. This is two orders of magnitude lower than the CO_2 concentration of flue gases from power plant and industrial process, which is in the range of 3-20%. As such, capturing CO_2 from air is much more difficult than capturing CO_2 from flue gases. The difference is akin to needing to find 10 red marbles in a jar of 25,000 marbles of which 24,990 are blue (air capture) vs. needing to find about 10 red marbles in a jar of 100 marbles of which 90 are blue (flue gas capture) (see Figure 1a). This means that DAC needs to process large amounts of air, typically about 1.8 million cubic meters to remove a single tonne.[6] This is equivalent to the volume of 720 Olympic-sized swimming pools.

In a DAC process, moving this large amount of air and contacting it with a sorbent to capture the CO_2 requires large equipment sizes which translates into high capital costs. For example, a design proposed by Carbon Engineering to capture just one million tonnes of CO_2 per year ($MtCO_2$/year) would require the air contactor cross-sectional area to be 46,000 square meters,[6] equivalent to a structure about 3 stories high and 3 miles long. These structures must also be hardened to the elements, requiring significant amounts of steel, concrete, and other building materials, resulting in high costs. Properly accounting for the massive amount of capital, land and costs involved means the feasibility of deploying DAC at the gigatonne scale is highly uncertain.

Challenge 2: Energy Requirement

Another challenge attributable to the low concentration of CO_2 in air is the significant energy requirements for DAC processes. We can calculate the theoretical minimum electric energy required (known as "minimum work" in thermodynamics) to separate CO_2 from the air, which is 133 kilowatt-hours (kWh) per tonne of CO_2 removed (about three times greater than the minimum work to capture CO_2 from a power plant flue gas). But this is only part of the story because one cannot operate real processes at minimum work. For example, the real-world capture of CO_2 from a coal-fired power plant flue operates at about four times its minimum work. There is empirical evidence that the more dilute the feed stream, the larger the ratio of actual work to the theoretical minimum work.[5] The best DAC processes today operate at about 8 times minimum work.[6] Adding in the work to compress the captured CO_2 for transportation and storage, the best DAC processes today require the equivalent to about 1.2 MWh of electricity per each tonne of CO_2 removed,[7] which translates to large energy costs.

The energy requirement must be satisfied using either low-carbon electricity or fossil fuels with CCS applied to the flue gas. All-electric DAC deployed at large scale—say 10 Gt CO_2 removal annually—would require 12,000 TWh of electricity, which is more than 40% of total global electricity generation today (see Figure 1b). That electricity would need to be carbon-free— an all-electric DAC process using coal-based electricity would generate 1.2 tonnes of CO_2 for every tonne of CO_2 captured,[6] which would result in net emissions increasing, defeating the whole purpose of DAC. Given electricity consumption is expected to grow due to increasing overall electrification of the world economy,[2] low-carbon electricity will be in high demand for many competing uses in power generation, transportation, industry and buildings. Using clean electricity for DAC instead of emission reductions raises concerns about the best uses of clean electricity.

Most DAC processes require a combination of electric and heat energy. Some studies assume that energy requirements can be greatly reduced by using “waste heat” generated by some industrial process or facility nearby. However, this may be more wishful thinking than reality. First, the DAC plant needs to be sited in close proximity to the heat source, as it is uneconomical to transport heat more than a few miles. Second, since the high capital intensity of DAC justifies running the unit as much as possible, ideally the heat would be available 24/7 for the lifetime of the DAC plant. Third, there is not much waste heat available at the minimum of 100^oC needed for DAC. Fourth, even excess heat at relatively low temperatures has value (for example, forced hot water systems used to heat buildings operate at about 55^oC) and therefore does not deserve the label of “waste” as there is market competition for such heat (i.e. it would not simply be readily available for DAC). Finally, when large-scale DAC deployment (on a gigatonne per year scale) is envisioned, waste heat opportunities will likely be a very small fraction of the needed energy.

Challenge 3: Siting

It has been stated that since air is everywhere, DAC units can be located anywhere. However, this kind of statement trivializes the very complex issue of siting. Critical considerations include access to low-carbon energy, availability of CO_2 storage options, acceptable meteorological conditions and access to land and water. As described above, the energy requirement is large and getting adequate low-carbon energy to the DAC site is a major challenge. If a DAC unit is far from existing CO_2 storage sites or pipelines, it will require major new infrastructure to be built to permanently store the capture CO_2. All DAC processes are exposed to ambient air, and meteorological conditions like temperature and humidity will affect process performance and process availability. In addition, the process must be hardened against all nature may throw at it, be it high winds, freezing temperatures, sand storms, and other conditions. In the literature, there is a wide range for DAC land requirements, such as 1-7 square kilometers for a 1 $MtCO_2$/year DAC facility.[4] Part of the reason for such a large range is that there are unresolved questions about the optimal spacing of DAC units. Like wind turbines, DAC units also need to be properly spaced to ensure maximum performance such that one unit is not sucking in depleted air from another unit. Finally, while not specific to DAC, building large infrastructure is a more complicated and expensive challenge, driven by issues related to permitting, environmental justice, and public acceptability, which are commonly underestimated in the real word and neglected in models.

Challenge 4: Cost

The first three challenges feed directly into the largest challenge facing DAC deployment, which is cost. While the typical costs for industrial projects that involve CCS to reduce emissions from power generation, iron and steel or cement production are estimated to be in the range of \$50-150/tCO$_2$,[8,9] the costs for DAC will be substantially higher due to the low concentration of CO$_2$ in the air. Yet, in many cases, DAC is assumed to have costs in the range of \$100-250/tCO$_2$[2,10] or even lower than \$100/tCO$_2$.[11-12] Some prominent scenarios, such as the World Energy Outlook from the International Energy Agency (IEA)[2] do not state the cost assumptions explicitly, but they can be inferred from the projections. For example, IEA's global net zero by 2050 scenario projects 1.7 Gt CO$_2$ removed in 2050 with carbon prices of \$200-250/tCO$_2$, suggesting DAC costs are also in the range of \$200-250/tCO$_2$. Based on the challenges discussed above as well as additional issues such as the cost of storage (which is ignored in many DAC cost estimates), we find these cost ranges unrealistic[6,7] (see Figure 1c).

As discussed above, removing one tonne of CO$_2$ requires the equivalent of approximately 1.2 MWh of electricity. If that electricity costs \$0.10/kWh, the electricity input cost to remove one tonne of CO$_2$ is \$120, without considering any other costs related to capital, labor, materials, storage, permitting, etc. Many studies assume the availability of very cheap renewable electricity, on the order of \$0.02/kWh. However, the realism of such low prices is questionable considering expected increases in electricity demand across the economy, future competition for clean electricity, and higher system costs (e.g., for batteries/storage, backup generation, transmission capacity, etc.) required for renewable-dominated generation.[2,13] While there is room for energy efficiency improvements, DAC units will always be subject to higher work requirements than CCS applied to power plant or industrial flue gas, and there is not a clear pathway to reducing work requirements much below the levels of current DAC technologies.

Considering the sheer size of DAC units needed to process the required amount of air (Challenge 1), capital costs will necessarily be high. In the literature, there is a wide range of DAC capital costs, with the high end reaching over \$5,000 per tonne captured per year.[7] Assessing potential capital costs for DAC requires appropriate engineering expertise, some of which will only come with experience in building actual DAC units. However, the realities of the size required for air processing lend themselves to unavoidably high capital costs, making overall cost estimates of $100-200 per tonne removed unrealistic. As mentioned, the largest DAC plant removes 4,000 tCO_2/year and carbon removal credits cost $1,500/tCO2.[14] Scaling up from these early prototypes to scalable technologies with involve difficulties that will increase costs before learning and improvements can bring costs back down.[8]

Decarbonization must come first

The challenges discussed above highlight some common misperceptions about DAC and real-world practicalities that are often neglected in studies. Ignoring these realities results in overly optimistic and even unrealistic cost assumptions for DAC, which distorts assessments of strategies and costs associated with mitigation and adaptation. This in turn creates the risk of pursuing strategies that avoid deep near-term mitigation in favor of depending on future cheap carbon removal from DAC that may never come to fruition, which in turn would result in unanticipated and expensive climate adaptation needs.

To assess the risks of over-reliance on negative emission technologies, wider DAC costs ranges should be considered in designing climate mitigation strategies. For example, some recent studies provide the ranges for DAC costs of $225-835/$tCO_2$[15] or even $200-1,000/$tCO_2$.[7] Decision-makers need to realize that in the near-term, and even in the medium-term, costs will likely to be at the upper end of these ranges Hence, policies that rely on the assumptions of a DAC technology available at $100-300/$tCO_2$ may underperform and, as such, they may create public uproar that would put into question the overall credibility of global mitigation efforts. This also implies that the focus needs to be on near-term emission reductions and on designing and implementing climate adaptation strategies to reduce the risk related to an uncertain performance of negative emission technologies. While doing the research that seeks to reduce DAC cost, minimize its energy and land use is important, the world needs to be prepared that DAC may not deliver at the scale assumed by some mitigation scenarios.

In summary, DAC is a very seductive concept. We can create machines that suck CO_2 out of the air and generate high quality carbon removals that can offset our hard-to-abate emissions. By doing so, it would minimize disruptions to key parts of the world's economy, such as air travel, certain carbon-intensive industries, and agriculture. However, we would need to generate billions of tonnes of CO_2 credits at an affordable price. Today, we are only generating thousands of tonnes of credits a year with a price of \$1500/tCO_2. Still, even at high carbon removal costs, we should continue to develop DAC because it may be needed for meeting net-zero emissions goals, especially given the current pace of emissions. However, given the high stakes of climate change, it is foolhardy to rely on DAC to be the hero that comes to our rescue.

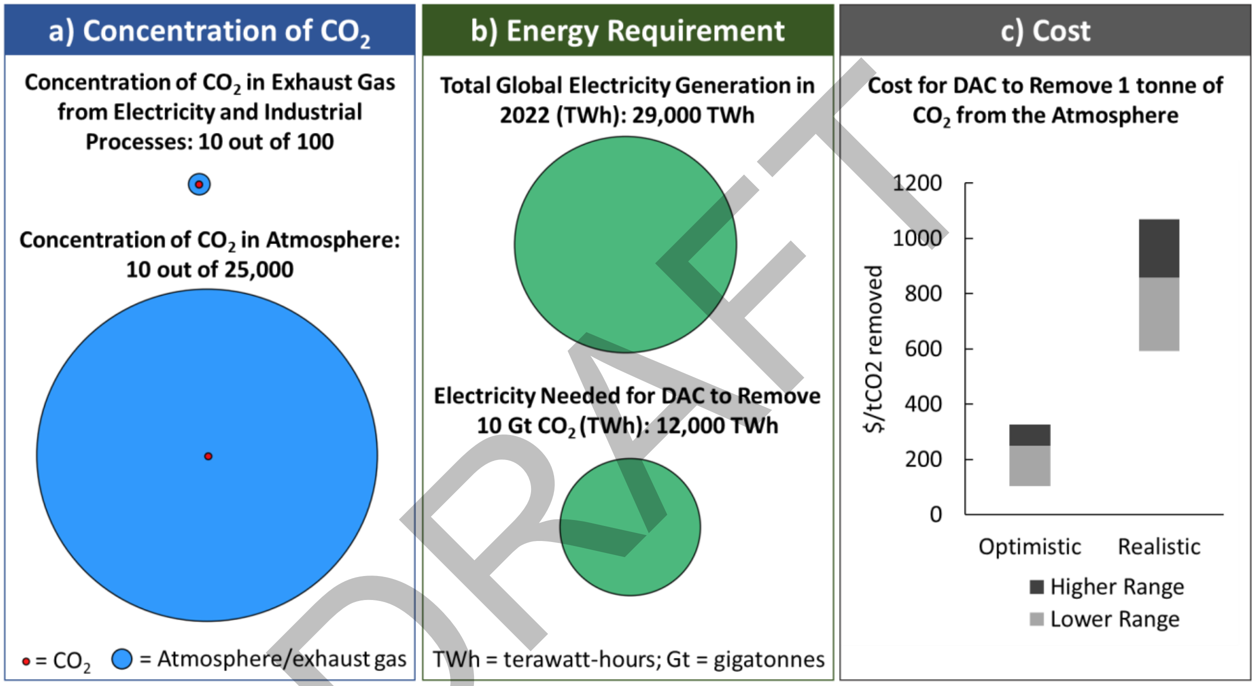

Figure 1. Key challenges for DAC . Challenges include **(a)** the low concentration of CO_2 in the atmosphere, which in turn requires large structures to process massive amounts of air, which requires a lot of capital and land; **(b)** the large amounts of energy required to extract CO_2 from the atmosphere at scale, and **(c)** the resulting high costs to operate DAC accounting for unavoidable engineering challenges. Notes: Global electricity in 2022 in panel b is from the International Energy Agency[2]. The ranges of DAC costs in panel c are based on Desport et al. (2024)[7].

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