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Making Direct Air Capture Affordable; Technology, Market and Regulatory Approaches

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Direct Air Capture (DAC) is an important solution to curb global warming and enable a circular economy. As fossil fuels dwindle, carbon for commodities such as plastic, cement, steel and liquid fuel, will need to come from somewhere. With the low cost of industrial CO2 (roughly $80 a ton) as well as the low value of most carbon credits, making DAC-produced CO2 competitive at scale is almost impossible. But what if we could scale DAC processes in markets that make sense now, building on learnings as we go while making industries less carbon intensive? The first such application is air quality and energy efficiency in indoor spaces. DAC technology can stabilize CO2 and water levels inside indoor environments to enhance the recirculation rate of internal air, thereby saving significant energy for the HVAC. Another application is the use of small-scale DAC units—providing CO2 at the scale of kilos a day rather than tons, taking advantage of the high CO2 price at that scale as well as B2C markets that otherwise rely on bottled CO2. The approach is called Decentralised DAC or DDAC (analogous to decentralised solar). DAC processes need to be developed but to scale our learnings and drive down costs, we must fund R&D and introduce a significant carbon tax. Finally, interesting new developments such as electro-swing and humidity-swing carbon capture, have the potential to drastically decrease the energy footprint of DAC (its main cost driver), paving the way to making DAC affordable.

Keywords: Direct Air Capture (DAC), HVAC, industrial CO2 emission, climate mitigation, NETs, Decentralised Direct Air Capture (DDAC), Carbon Direct Removal (CDR), Cleantech

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INTRODUCTION: DIRECT AIR CAPTURE—THE CASE FOR IT

Almost all IPCC scenarios in which global warming is limited to 1.5°C, require NETs (Negative Emissions Technologies). NETs are needed as we will likely exceed our quota of CO2 emissions as a society no matter what we do. The legacy of our fossil fuel infrastructure means that we will not transition to renewables quickly enough. We will likely still require them in certain sectors such as aviation. Therefore, the only way to stop the build-up of CO2 in our atmosphere from exceeding IPCC limits, will be by directly removing it from the air.

There exist many promising techniques to achieve such a feat on a meaningful, global scale. First and foremost is reforestation. With the number of trees in the world reduced by almost half (to 3.04 trillion) since the advent of modern society, particularly *via* agriculture, there's a lot of scope for replanting them and the carbon sink they in turn could represent (Crowther et al., 2015). Best estimates indicate that 1–2 trillion trees could be replanted. A benefit of reforestation, apart from the sequestration of carbon, is the parallel effect it has on the re-wilding of natural landscapes which in turn provides habitable space for wildlife. Reforestation also battles erosion, desertification and can provide local communities with livelihoods in farming or forest management. Pachama (pachama.com) and Mossy Earth (mossy.earth) are two examples of how reforestation can be inspiring and commercially viable at the same time.

Another natural means to achieving negative emissions includes mineral weathering. An example is seeding agricultural soil with rock powders (such a ground olivine) that go on to naturally absorb CO2 over time. Such passive CO2 sequestration techniques are cost effective, require little to no energy and have minimal side-effects on the local ecosystem. Another example is farming fast growing kelp. The plant absorbs carbon from the ocean at a phenomenal rate. Once the organism reaches a certain size, it is either processed into useful material or sunk to the bottom of the ocean where the carbon remains locked up.

These techniques, while their effect in reducing the amount of CO2 in our atmosphere is real, do nothing for the provision of carbon dioxide as a molecule. As we move away from fossil fuel production and our CO2 supply dwindles, we will still require our carbon from somewhere, especially to produce liquid fuels, plastics and even cement. Other industrial processes such as crop fertilization and beverage carbonation also require it. Both these sectors consume millions of tons of industrial CO2 every year.

Controllable, and potentially quick to implement, unlike natural means, Direct Air Capture (DAC) can supply carbon from the air. The process works in similar way to trees. Carbon dioxide is removed from the air *via* a capture medium (rather than leaves, a solid or liquid "sorbent" is exposed to the air) and once the medium is full, the CO2 is released from it usually *via* the application of heat. In doing so, a clean stream of concentrated atmospheric CO2 is created which can then be sequestered or used (or both). There is an associated cost with the process; mainly the energy required for the heating of the sorbent. Its energy footprint makes it currently the most expensive way to remove CO2 from the air. However, the technology is nascent, and much as solar did, could benefit from technological breakthroughs and economics of scale in the near-term.

THE CHALLENGES TODAY

There are two main techniques used in DAC processes to capture atmospheric CO2: the use of solid sorbents functionalised with amines (a molecular compound widely used in liquid form for Carbon Capture & Storage applications) and the use of liquid chemicals which upon contact with CO2, turn to limestone (Carbon Engineering uses this technique).

Both techniques require an enormous amount of infrastructure to set-up on a meaningful scale. Unfortunately, DAC is a volume game. The more carbon we aim to capture, the more solid or liquid sorbent required to do so, and the more surrounding machinery required to manage the process. In addition, the energy consumed in the process is largely linear to the size of the plant desired. We have not even addressed the post-processing requirements, where if CO2 is to be sequestered, it will need to be injected into storage sites (e.g., old oil wells or saline aquifers) at considerable pressure or if used in industry, may need to be concentrated and cleaned to pass as food-grade.

The challenge is compounded by the fact that industrial CO2 today is extremely low-cost at between $20 and 80 per ton (The Business Research Company, 2021). The sources of industrial CO2 are mainly gas refineries, where CO2 is siphoned off in a nearly pure form from a natural gas stream, or in fertilizer plants, where again, it is emitted in a nearly pure form. So while the carbon from a DAC process could potentially be re-used (e.g., in the production of cement), and therefore possess added value beyond that of simply sequestering it, there exists steep competition.

There is also no well-regulated, standardized price for a carbon credit. After failing in the early 2000s cap & trade markets never fully recovered. There are at least local regulations in place now, namely the 45Q Tax Credit implemented in California, or the EU's cap and trade program, but there's no standard price of a carbon credit to be relied upon wherever you might find yourself in the world. Implementing consistent carbon pricing across regions and nations will be critical to promoting the widespread adoption of NETs. Governments need to do more here.

NEW MATERIALS AND SMART BUSINESS CASES

While there is scope for existing DAC methods, if scaled correctly and complemented with consistent and high enough carbon pricing, to be commercially and technically viable at a globally meaningful scale, it would make it far easier if higher-performing CO2-capture materials were to be developed. The main parameter to improve is the ratio of CO2 captured per unit weight of capture medium over time. Such an improvement would not only reduce the volume and weight of material required to capture the same amount of CO2, but also the energy penalty incurred in the process (the less underlying capture medium to heat up to release the carbon dioxide molecules, the less energy required for regeneration). However, if the energy cost for regeneration could also be reduced, for example by engineering the bonding between the CO2 and the capture medium to be weaker or using a means to release CO2 other than heat or vacuum (e.g., humidity-swing, currently being explored at ASU by Prof. Klaus Lackner, or electro-swing currently being developed at Verdox), then all the better.

The development of marketplaces in which individuals and companies can permanently offset their carbon footprint will itself benefit the DAC sector, and they need to be regulated and supported by governments. It should be expected that as the DAC process becomes less costly, more and more entities will be tempted to fund the sequestration of their carbon emissions.

Abbreviations: NETs, Negative Emissions Technologies; DAC, Direct Air Capture; DDAC, Decentralised Direct Air Capture; CCS, Carbon Capture and Storage; DoE, US Department of Energy; HVAC, Heating Ventilation & Air Conditioning.

ADVANCED FILTRATION IN BUILDINGS

Removing CO_2 from a building environment or "advanced filtration" as it has been coined by the Department of Energy (DoE), was recently included in the top ten of over forty technologies assessed to have the highest potential in improving building energy efficiency (Goetzler et al., 2017). By stabilizing CO_2 as well as humidity levels inside a building, a higher indoor air recirculation rate can be enabled, thereby limiting the in-take of fresh air and the load on the HVAC system. The energy gains of doing so can be huge, especially in climates where the outdoor temperature is quite hot or cold. Recent pilots by enVerid show 20–40% reductions in building energy consumption and recent studies corroborate their findings (Baus and Nehr, 2022). The technology is currently being applied to large commercial buildings such as offices and hotels, where operating costs are closely monitored. It is also easier to apply the technology to these buildings, as opposed to private homes, due to advanced HVAC infrastructure already in place.

The benefit of pursuing a business case here for DAC, is that it's an easier sell. The product is not the carbon itself (a rather inexpensive commodity), but instead energy efficiency and air quality. People understand those things, people do not, on the whole, understand carbon capture. With HVAC sales exploding in developing countries, the case for advanced filtration and energy efficiency solutions becomes ever more urgent. According to a recent UN report, improving the energy efficiency of HVACs and reducing the use of HFCs, could lead to a reduction of 0.4°C in global warming by 2100 compared to the status quo (Millen and Logan, 2020).

Linking DAC units in buildings to local demand for CO_2 will close the loop fully. For example, captured CO_2 could be converted into fuel on the roof of a building to be used as a back-up energy source for the renewable grid, or it could be used to promote crop growth at a local vertical farm.

A CARBON PRICE

Setting a price on carbon emissions, not only those created at source, but the carbon footprint generated in corporate supply chains or in running commercial property, will be crucial to stemming the amount of carbon going into the air. Just as we place a tax on cigarettes (which levy a huge cost on national healthcare systems), we need to start doing the same for carbon emissions, which take a huge toll on our environment, and ultimately lead to reduced GDP growth due to the economic damage cause by extreme weather events.

Standardizing such a carbon tax on a national level is hard enough, let alone internationally. However, once the cost of offsetting carbon becomes less than paying the tax, massive markets will be created. To make DAC viable at scale, a carbon tax of over >$200 per ton needs to be levied. Combined with the value of the captured CO_2, the cost of the capture process then becomes less than the revenue earned, and the operation becomes profitable.

SKYTREE'S LESSONS LEARNED

One of the key drivers of the energy required in atmospheric carbon-capture processes (as well as traditional CCS processes), is the heating of the capture medium (McQueen et al., 2021b). In traditional approaches to DAC, a solid sorbent requires exposure to air to capture CO_2, and subsequent heating combined potentially with exposure to vacuum, to release it again. Roughly 80% of the energy used in the process goes to thermal heat applied to the capture medium, while the remaining 20% to electricity to power the fans, vacuum pumps, compressors as well as other equipment (McQueen et al., 2021a). It follows that the more CO_2 required from a DAC system, the more capture medium needs to be deployed and in turn, the more energy is required to heat it and subsequently concentrate the CO_2 released from that process.

The holy grail will be to find a capture medium with the ability to adsorb much more CO_2 relative to its weight, allowing for less material to be used for the same amount of carbon captured. Doing so will reduce the energy required to drive the heating and concentration process, as there will be less material to heat, and less volume around which to create a vacuum. Some materials have the potential to do this (eg. Metal Organic Frameworks otherwise known as MOFs) but are relatively expensive and not yet reliably produced at scale.

Another approach would be the ability to apply thermal energy directly to the capture sites, without having to heat up their structural support. The approach is being investigated by Verdox (www.verdox.com), which is using a electro-swing adsorption process to capture CO_2 from the air. The energy provided in the process is delivered through a redox reaction and has the potential to reduce the energy footprint of the regeneration process by 80% (Voskian and Hatton, 2019).

One of the best ways to reduce the cost of a process is to simplify it. We've already discussed how a significant amount of energy is required to concentrate CO_2. We also see huge energy demand in compressing it so that it can be stored for later use in industrial processes or pumped underground for long-term sequestration. The former almost always requires the creation of a vacuum (energy intensive), the latter the use of a high-power pump and pressure vessels (again, energy intensive and expensive).

At Skytree, we've seen that for certain small-scale applications, there is no need to compress CO_2 or even supply it at high concentration. For example, in fertilizing crops in vertical farms, the concentration of CO_2 in the air only needs to be increased by 2–3 fold. Such a "CO_2 enrichment" process forgoes the need to concentrate and compress the CO_2, allowing the hardware to be less costly and the process less energy intensive.

We've also seen that at smaller volumes, the relative price of industrial CO_2 increases exponentially due to the higher infrastructure costs relative the value of the gas itself. These infrastructure costs include replacement gas cylinders or cryogenic storage systems. At a volume of a few kilos a day, DAC can be competitive to current commercial sources of CO_2 without any need for subsidies or carbon credits. In fact, it will make for a more convenient supply of CO_2 for customers located in areas without nearby sources of CO_2 such as the

Middle-East or most of Africa. We've coined the approach as Decentralised-DAC (DDAC).

Applying DDAC to indoor air purification removes the needs of the second step of the process as well. Removing the need to concentrate or compress the CO2, by venting it instead, simplifies the hardware, reduces costs, and reduces the energy requirement of the system. On top of that, the performance of the system improves when applying DDAC to indoor air purification as the sorbent beds are exposed to much higher concentrations of CO2 (1,500–3,000 ppm) found indoors compared to those found outdoors (400 ppm), allowing the system again, to be smaller and more energy efficient.

To be meaningful on an industrial scale, most DAC plants will have to be huge (think an apartment block or larger). Such a requirement means high initial investments and extended lead times as well as return on investment. Applying DAC technology to small-scale CO2-supply or indoor air purification entails that the DDAC modules can be much smaller (think refrigerator-size), allowing them to be deployed at a fraction of the cost and to start paying for themselves right away. Such an approach will allow for a more rapid and organic rollout of DAC technology, potentially creating a far greater reduction in carbon footprint sooner than a more traditional approach would allow. Technical learnings in the process of doing so could then be applied to larger-scale DAC plants.

DISCUSSION

A number of initiatives have been kicked off to accelerate the development of DAC. Biden's infrastructure bill earmarks ten billion dollars for carbon removal technology, the European Green Deal supports it as does Elon Musk's $100M X-prize and finally VCs are pouring $100M's into DAC start-ups. All are important to accelerating R&D efforts around the technology. But just as we taxed cigarettes and alcohol due the immense burden they placed on our healthcare systems, carbon emissions should also be taxed. The emission of CO2 causes immense negative externalities in the form environmental destruction (much like CFCs did or air pollution and plastic production are doing today) which are not costed into the price of the carbon-emitting goods and services we consume.

Minimum government intervention is a useful free-market philosophy, but in the case of DAC and other tools we need to fight the climate emergency, we need to be more pro-active. The biggest and most effective driver of change will be a carbon tax. The massive effect it could have on reducing our emissions is reflected in the En-ROADS model developed at MIT (en/roads.climateinteractive.org/) and strongly supported by Bill Gates in his book "How to Avoid a Climate Disaster" published in 2021. Just as certain economic structures (i.e., the free market) can propel massive growth, a carbon tax will level-up our efforts to fight climate change. Large-scale DAC can be viable once a carbon tax of at least $200/ton is established.

Developing commercially viable routes to market is an approach that can be taken until then. For example, there may be quicker, more effective ways of deploying DAC technology in small-scale CO2-supply or indoor air purification applications otherwise known as DDAC. And a key breakthrough for the DAC sector will be the discovery of a capture medium with a much higher CO2-capture capacity with respect to weight ratio, and one with a minimal energy footprint. Promising methods such as humidity and electro-swing adsorption could completely decouple the volume of CO2 captured from the amount of energy and space required by a DAC plant. With significantly increased government funding, and the eventual introduction of a high carbon tax, DAC will become affordable and common place.

DAC is just one of many tools at our disposal to fight climate change—others include CCS, reforestation, sustainable agriculture, meat substitutes, wind & solar, electrification, circular materials, synthetic fuels and nuclear energy, to name a few. Many of these represent more bang for our buck compared to DAC and should be pursued in parallel. But DAC is unique in its ability to draw down CO2 and reuse it—both processes that will become ever more important as the climate emergency heightens and we move towards a circular economy.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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