Technologies series

Direct Air Carbon Capture (DAC)

Awaiting demonstration at scale, DAC technologies are nonetheless required for negative emissions

As simple as squeezing a rock out of thin air

What it is

Direct Air Capture (DAC) involves chemical absorption of CO_2 directly from the air, as opposed to other carbon capture and storage or utilisation (CCUS) technologies, which sequester CO_2 at the source or point of release – such as industrial processes or fuel combustion at power plants.[1]

How it works

The two most developed methods of DAC are liquid absorbing systems and solid adsorption filters. These involve forcing air through a system at pressure, where it is exposed to a chemical reaction that pulls CO_2 out, while the rest of the air passes through and back into the atmosphere.

- Liquid systems use alkaline chemical solutions that continuously form carbonates upon exposure to CO_2.[2] To extract the CO_2 the carbonates are heated to ~900°C.
- Solid sorbent filters of various chemistries can bind the CO_2 from the air. Treatment at lower temperatures (using steam for example) then releases concentrated CO_2 in sequential adsorption-desorption steps, for storage or use.[3]

A third, early stage technology involves gas separation membranes, which selectively retain CO_2 when air is passed through.[4]

Applications

Although most CCUS projects planned for the coming decades employ biological methods,[5] predominantly bioenergy with CCS (BECCS),[6] most scenarios to achieve net-zero emissions, or <1.5°C of warming, also require significant deployment of DAC.[7]

Whether or not these routes are carbon negative depends on how the captured CO_2 is used. If stored or used in long-term products it may be considered carbon negative. If the captured CO_2 is used to create synthetic fuels (i.e. methane or methanol) or short-term products (i.e. carbonating drinks or fertilisers) this would not result in negative emissions. But they could assist carbon removal, and constitute carbon neutral emissions if they displace fossil fuel usage.[8]

Approximately 40 million tonnes of CO_2 are captured each year from power and industrial processes, out of a current total global CO_2 emissions of ~40 gigatonnes.[9] There are currently 15 DAC plants operating worldwide, capturing just over 9,000 tonnes of CO_2 per year.[10]

Implications and issues

Most of the DAC plants in use are prototypes. Given the ambitious projections for their global use, this has implications for their deployment and scaling.[11] These projections also frequently rely on unproven technology.[12] Other issues and considerations for DAC include:

- **Energy.** A principle factor governing both cost and carbon neutrality of DAC is access to large amounts of renewable energy: ensuring its availability is imperative.
- **Materials.** Rapidly scaling DACs will require production of large quantities of energy-intensive materials:[13] comprehensive cost assessment is necessary.[14]
- **Land usage.** DAC has a dramatically smaller footprint than natural CCUS solutions.[15]
- **Market.** There are companies providing DAC,[16] but the market for captured CO_2 currently is small,[17] and valuing these companies is difficult, given their early stage of development.
- **Carbon cycle.** As CO_2 is removed from the atmosphere, CO_2 sinks can become sources.[18]
- **Postponing mitigation.** Rollout of DAC may defer CO_2 emission mitigation efforts,[19] stall investment in renewable energy systems, and fails to consider tipping points.[20]
- **Policy.** Carbon credits and trading schemes are already in place and are being expanded,[21] but are insufficient to support DAC.[22] Support for further innovation is also necessary.[23]

In summary: as one means by which atmospheric CO_2 is reduced rather than avoiding its release, demonstration of, and investment in, innovative DAC technologies at scale is rapidly required.■

[1] See: Budinis, S., 2020. *Direct Air Capture*. IEA [online] Available at: <https://www.iea.org/reports/direct-air-capture> [Accessed 22 July 2021].

[2] In a liquid absorbing system, air is bubbled through a solution containing an aqueous sorbent such as potassium hydroxide (KOH). These hydroxides react with the CO_2, forming water (H_2O) and potassium carbonate (K_2CO_3). Following this, calcium hydroxide is added to the solution to precipitate out the CO_2, forming calcium carbonate ($CaCO_3$), and regenerating the potassium hydroxide (KOH) so that it can cycle back to react with more CO_2.

The precipitated solid calcium carbonate (CaO_3) is then calcined, heated to ~900ºC in a pure oxygen environment, to release concentrated CO_2 and calcium oxide (CaO). Other chemistries can be employed, such as sodium hydroxide (NaOH). These liquid absorbtion systems can be run continuously, in contrast to solid adsorption systems. However, their cost and complexity increase dramatically in dry environments, where water loss becomes a concern. See: Keith, D. W., et al., 2018. A Process for Capturing CO_2 from the Atmosphere. *Joule* [e-journal] https://doi.org/10.1016/j.joule.2018.05.006.

[3] Solid adsorption systems can utilise a wide variety of different chemistries, including alkali carbonates, amine-silica composites, amines supported on oxides, metal-carbon frameworks, and solid carbon-based materials. In the amine-CO_2 adsorption process, air is passed over amines that are supported on a solid scaffold, and CO_2 binds to form a carbamate. The unit is then prevented from reacting with further CO_2 and it is heated to ~100ºC under a vacuum. The CO_2 is released, and the unit is then able to react with further atmospheric CO_2. Other processes require a high degree of humidity (essentially steam) to release the CO_2. See: Stampi-Bombelli, V., van der Spek, M., & Mazzotti, M., 2021. Analysis of direct capture of CO_2 from ambient air via steam-assisted temperature–vacuum swing adsorption. *Adsorption* [e-journal] https://doi.org/10.1007/s10450-020-00249-w & Didas, S. A., et al., 2015. Amine-Oxide Hybrid Materials for CO_2 Capture from Ambient Air. *Accounts of Chemical Research* [e-journal] https://doi.org/10.1021/acs.accounts.5b00284

[4] Membrane based DAC (mDAC) can enrich CO_2 in filtered air up to 1,000 fold, from atmospheric CO_2 concentrations of 0.04% up to 40%, through sequential membrane layers. This multi-stage process is required in order to overcome the limitations of the low atmospheric CO_2 concentration, and the lower ability of enrichment possible with a single membrane compared with liquid absorption or solid adsorption. However, it also has advantages, such as lower energy input and no requirement for chemical sorbents. Although a concentration of 40% CO_2 product is not suitable for geological storage, or many chemical feedstocks, it can be further increased by downstream processes such as electrochemical reduction. Further research into membranes is required, together with a full analysis of costs. See: Fujikawa, S., Selyanchyn, R. & Kunitake, T., 2021. A new strategy for membrane-based direct air capture. *Polymer Journal* [e-journal] https://doi.org/10.1038/s41428-020-00429-z.

[5] A non-exhaustive list includes: afforestation (tree planting); weathering rocks; restoration of peatlands; soil maintenance; and planting crops for bioenergy and carbon capture (BECCS). Evidence is strongly supportive of "nature-based solutions" to pull down CO_2 from the atmosphere and protect biodiversity, although serious consideration warrants being given to land use and mono-culturing. Maintaining biodiversity and adequate food security is of utmost importance, and an inability to maintain them alongside reductions in CO_2 emissions should be regarded as a failure. See: Girardin, C. A. J., et al., 2021. Nature-based solutions can help cool the planet — if we act now. *Nature* [e-journal] https://doi.org/10.1038/d41586-021-01241-2

[6] Bioenergy with Carbon Capture and Storage (BECCS) is regarded as a lynchpin of most strategies to reduce CO_2 emissions to ensure temperature rises below 2ºC. The International Panel on Climate Change (IPCC) suggest that BECCS will be responsible for the sequestration of 0.4-11.3 $GtCO_2$ per year. See: International Panel on Climate Change (IPCC), 2018. *Special Report On Climate Change And Land, Land–Climate interactions*. IPCC [online] Available at: <https://www.ipcc.ch/srccl/chapter/chapter-2> [Accessed 22 July 2021] & Hickman, L., 2016. *Timeline: How BECCS became climate change's 'saviour' technology*. CarbonBrief [online] Available at: <https://www.carbonbrief.org/beccs-the-story-of-climate-changes-saviour-technology> [Accessed 22 July 2021].

[7] The International Panel on Climate Change (IPCC) recognises that very large amounts of carbon capture and sequestration will be required to avoid catastrophic global temperature increases. They suggest that it will be essential to sequester permanently ~10 billion tons of CO_2 per year by 2050, and double that each year by 2100. See: International Panel on Climate Change (IPCC), 2018. *IPCC Special Report Global Warming of 1.5 °C*. IPCC [online] Available at: <https://www.ipcc.ch/sr15> [Accessed 22 July 2021] & IEA, 2021. *Net Zero by 2050*. IEA [online] Available at: <https://www.iea.org/reports/net-zero-by-2050> [Accessed 22 July 2021].

[8] This is also closely linked to the electricity source. If fully renewable energy is used, then neutral emissions are approached (there is still waste). If a different energy mix is used, then this is no longer carbon neutral.

[9] 1 gigatonne = $1x10^9$ tonnes. Annual emissions are currently around 1,000 times greater than the current CO_2 capture capacity.

[10] This number will increase rapidly in the coming years, but it is not yet clear how fast the scaling will be. For example, Climworks has commissioned a 4,000 tonne CO_2/year removal plant, named "Orca", and Carbon Engineering is developing a 1 million tonne/year plant in conjunction with Occidental Petroleum Corp to capture CO_2 for use in enhanced oil recovery (EOR) for their US Permian Basin operation. See: Climeworks, 2021. *Orca*. Climeworks [online] Available at: <https://www.climeworks.com/orca> [Accessed 22 July 2021], Reuters Staff, 2020. *Occidental-backed company will build new U.S. CO2 removal plant*. Reuters [online] Available at: <https://www.reuters.com/article/us-usa-carboncapture-dac/occidental-backed-company-will-build-new-us-co2-removal-plant-idUSKCN25F1VN> [Accessed 22 July 2021], and Bloomberg New Energy Finance, 2021. *Direct Air Capture of CO2 to Increase 150-Fold By 2024*. BNEF [online] Available at: <https://about.bnef.com/blog/direct-air-capture-of-co2-to-increase-150-fold-by-2024> [Accessed 22 July 2021].

[11] Notwithstanding issues of public acceptance, the scale required (gigatonne removal) still confront all the issues that any early-stage technology faces. The uncertainties surrounding the various technologies available, their durability, energy requirements and need of a market are considerable. See: Realmonte, G., Drouet, L., Gambhir, A. et al. 2019. An inter-model assessment of the role of direct air capture in deep mitigation pathways. *Nature Communications* [e-journal] https://doi.org/10.1038/s41467-019-10842-5 And Obersteiner, M., Bednar, J., Wagner, F. et al. 2018. How to spend a dwindling greenhouse gas budget. *Nature Climate Change* [e-journal] https://doi.org/10.1038/s41558-017-0045-1.

[12] Assumptions inherent in current pathways include increases in efficiency and improvements in cost for DAC. See: Nemet, G.F., et al., 2018. Negative emissions—Part 3: Innovation and upscaling. *Environmental Research Letters* [e-journal] https://doi.org/10.1088/1748-9326/aabff4.

[13] The two principal materials required for DACs are hydroxide solutions for liquid absorption systems and amines for solid adsorption systems. Hydroxide solutions are manufactured principally as a by-product of chlorine production. For massive upscaling of DAC this would be flipped, and chlorine gas production would outstrip potential use, presenting risks. In addition, to reach the requirement of 30 gigatonnes of CO_2 capture per year would take of the order of 12-20% of total global energy supply.

It is more difficult to price solid adsorption systems: fewer technical details are available, and the sorbent lifespans are less well characterised. In the literature, assumptions are commonly based on the use of monoethanolamine (MEA), which is synthesised from ammonia and ethylene oxide using fossil fuel feedstocks. To meet the same level of CO_2 capture, the energy requirement for ammonia and ethylene oxide synthesis would potentially outstrip total global energy supply, requiring 78–133% and 18–34% respectively.

Furthermore, these energy costs are only for the creation of the materials required for massively upscaled DAC of 30 gigatonnes of CO_2 capture per year; they do not include the energy required to run the processes themselves. It is feasible that further innovation will reduce these energy requirements. See: Chatterjee, S., Huang, KW. Unrealistic energy and materials requirement for direct air capture in deep mitigation pathways. *Nature Communications* [e-journal] https://doi.org/10.1038/s41467-020-17203-7 & Realmonte, G., Drouet, L., Gambhir, A. et al., 2020. Reply to "High energy and materials requirement for direct air capture calls for further analysis and R&D". *Nature Communications* [e-journal] https://doi.org/10.1038/s41467-020-17204-6.

[14] Both life-cycle assessments, and techno-economic assessments are required to assess the costs, for both solid and liquid systems. The costs of liquid systems are currently better understood due to unknown stability of solid-amine based systems. A rough average across current company-reported costs for capturing 1 tonne of CO_2 using DAC is between $100 and 900 per tonne, significantly less than many estimates made in the literature, although these often do not factor in subsidies. See: Keith, D. W., et al., 2018. A Process for Capturing CO2 from the Atmosphere. *Joule* [e-journal] https://doi.org/10.1016/j.joule.2018.05.006, Deutz, S., Bardow, A. Lif, 2021. Life-cycle assessment of an industrial direct air capture process based on temperature–vacuum swing adsorption. *Nature Energy* [e-journal] https://doi.org/10.1038/s41560-020-00771-9 (paywall), Kiani, A., Jiang, K., & Feron, P., 2020. Techno-Economic Assessment for CO2 Capture From Air Using a Conventional Liquid-Based Absorption Process. *Frontiers in Energy Research* [e-journal] https://doi.org/10.3389/fenrg.2020.00092, and de Jonge, M.M.J., et al., 2019. Life cycle carbon efficiency of Direct Air Capture systems with strong hydroxide sorbents. *International Journal of Greenhouse Gas Control* [e-journal] https://doi.org/10.1016/j.ijggc.2018.11.011 (paywall).

[15] Estimates of land usage differ significantly, but it is clear that even massive rollout of DAC will use an order of magnitude less land than required by natural carbon capture methods. See: Poppa, A., et al., 2017. Land-use futures in the shared socio-economic pathways. *Global Environmental Change* [e-journal] https://doi.org/10.1016/j.gloenvcha.2016.10.002 and Smith, P., Davis, S., Creutzig, F. et al., 2016. Biophysical and economic limits to negative CO2 emissions. *Nature Climate Change* [e-journal] https://doi.org/10.1038/nclimate2870 (paywall).

[16] The most advanced are Climeworks, Carbon Engineering, and Global Thermostat. Climeworks is a Swiss company who have developed a modular solid adsorption system. They are currently the only company to provide a truly carbon negative process, at their Hellisheiði plant in Iceland, utilising excess heat and storing CO_2 geologically. Carbon Engineering is a Canadian company which utilises a liquid absorption system. The company is currently developing a 1 million tonne/year plant in conjunction with Occidental Petroleum Corp to capture CO_2 for enhanced oil recovery (EOR) for their operations in the US Permian Basin. Global Thermostat is an American company, which also uses a solid adsorption system. Climeworks and Carbon Engineering claim costs of around $100 per tonne of CO_2 captured, and Global Thermostat, around $50/tonne. See: Climeworks, 2021. *Our Mission*. Climeworks [online] Available at: <https://www.climeworks.com/climate-positive-mission> [Accessed 22 July 2021], Carbon Engineering, 2021. *Our Technology*. Carbon Engineering [online] Available at: <https://carbonengineering.com/our-technology> [Accessed 22 July 2021], Reuters Staff, 2020. *Occidental-backed company will build new U.S. CO2 removal plant*. Reuters [online] Available at: <https://www.reuters.com/article/us-usa-carboncapture-dac/occidental-backed-company-will-build-new-us-co2-removal-plant-idUSKCN25F1VN> [Accessed 22 July 2021], and Global Thermostat, 2021. *About Global Thermostat*. Global Thermostat [online] Available at: <https://globalthermostat.com/> [Accessed 22 July 2021].

[17] The market for captured CO_2 is niche, and focused primarily around public subsidies such as the 45Q tax credit. However, several technology and e-commerce companies have declared their decisions to offset their emissions and include DAC and carbon capture methods in these plans. Most notably these include Microsoft, Stripe, and Shopify. Furthermore, there are technological approaches, such as Nori, that enable businesses to buy "carbon removal certificates" from verified farmers using

blockchain-issued tokens. In order for it to succeed the validation of carbon sequestration is key. See: Bednar, J., Obersteiner, M. & Wagner, F., 2019. On the financial viability of negative emissions. *Nature Communications* https://doi.org/10.1038/s41467-019-09782-x, Chay, F., et al., 2021. *New lessons from reviewing carbon removal proposals*. (carbon)plan [online] Available at: <https://carbonplan.org/research/stripe-2021-insights> [Accessed 22 July 2021], Bullard, N., 2021. *Stripe, Shopify, and the E-Commerce Approach to Drawing Down Carbon*. Bloomberg [online] Available at: <https://www.bloomberg.com/news/articles/2021-06-03/stripe-shopify-and-the-e-commerce-approach-to-drawing-down-carbon> [Accessed 22 July 2021], and Nori, 2021. *Reach Your Business Climate Goals Faster*. Nori [online] Available at: <https://nori.com/for-business> [Accessed 12 July 2021] & Baylin-Stern, A., & Berghout, N., 2021. *Is Carbon Capture Too Expensive?* IEA [online] Available at: <https://www.iea.org/commentaries/is-carbon-capture-too-expensive> [Accessed 22 July 2021].

[18] Carbon sinks are processes that absorb CO_2 from the atmosphere. One of the primary planetary carbon sinks is the oceans. These exist in a dynamic equilibrium with the atmosphere, and are currently absorbing CO_2. If the CO_2 concentration in the atmosphere significantly decreases due to large-scale carbon capture, then this equilibrium will shift, and CO_2 will be released into the atmosphere from the oceans. The percentage of CO_2 released by the oceans compared with that captured is estimated to be approximately 10-20%, requiring additional removal to meet the same carbon budget. There are many other natural carbon sinks, and modelling their behaviour must be considered in future assessments of carbon capture technologies. See: Keller, D.P., Lenton, A., Littleton, E.W. et al., 2018. The Effects of Carbon Dioxide Removal on the Carbon Cycle. *Current Climate Change Reports* [e-journal] https://doi.org/10.1007/s40641-018-0104-3.

[19] Several routes may lead to failure to mitigate increasing CO_2 emissions and rising global temperatures including; any political or economic shortcomings in the coming decades; technical issues such as leaks or use of captured CO_2 in short-term products such as fuels and fertilisers; various rebounds, multipliers, and side-effects, for example those arising from increased use of land for crops, or use of CO_2 in enhanced oil recovery (EOR). Estimates of these unanticipated effects could be equivalent to an additional temperature rise of 1.4ºC. See: McLaren, D., 2020. Quantifying the potential scale of mitigation deterrence from greenhouse gas removal techniques. *Climatic Change* [e-journal] https://doi.org/10.1007/s10584-020-02732-3 and Obersteiner, M., Bednar, J., Wagner, F. et al. 2018. How to spend a dwindling greenhouse gas budget. *Nature Climate Change* [e-journal] https://doi.org/10.1038/s41558-017-0045-1 (paywall).

[20] Global carbon budgets are a commonly used tool for developing policy. However, they are a linear approximation of the global carbon-climate system's response to anthropogenic CO_2 emissions, and do not consider non-linear climatic tipping points. One example of these climatic tipping points, that of permafrost thaw and subsequent release of large quantities of methane, suggests that carbon budgets may be smaller than previously thought, as well as subject to considerable uncertainty. See: Gasser, T., Kechiar, M., Ciais, P. et al. 2018. Path-dependent reductions in CO2 emission budgets caused by permafrost carbon release. *Nature Geosciences* [e-journal] https://doi.org/10.1038/s41561-018-0227-0 (paywall).

[21] The two most prominent policies are the USA's, recently amended, 45Q tax credit and the EU's carbon emission trading scheme (ETS). The recent expansion of the 45Q tax credit for carbon capture and storage is significant. The credits rise from $35/tonne CO_2 in enhanced oil recovery (EOR) to $50/tonne CO_2 stored, and apply to a wide range of industrial facilities down to those producing 100000 tonnes of CO_2 per year and to applications that use more than 25000 tonnes CO_2. The EU ETS currently prices CO_2 at €50/tonne and covers ~40% of the EU's emissions. Its expansion to cover "cross border carbon emissions" is expected soon. See: Ochu, E., 2021. *Proposed 45Q Tax Credit Reform Could Give a Big Boost to Carbon Capture Projects*. Columbia Climate School [online] Available at: <https://news.climate.columbia.edu/2021/05/06/proposed-45q-tax-credit-reform-boost-carbon-capture-projects> [Accessed 22 July 2021], European Commission, 2021. E*U Emissions Trading System (EU ETS)*. European Commission [online] Available at < https://ec.europa.eu/clima/policies/ets_en> [Accessed 22 July 2021] and Abnett, K., 2021. *EU's carbon border tariff to target steel, cement, power – draft*. Reuters [online] Available at: <https://www.reuters.com/business/sustainable-business/eus-carbon-border-tariff-target-steel-cement-power-draft-2021-06-03> [Accessed 22 July 2021].

[22] Given the lack of a market for captured CO_2, its price is currently determined politically by policies such as the United States 45Q tax credit and the EU's emissions trading scheme (ETS) which currently price captured CO_2 at $50 and €50, respectively. These prices are significantly below the reported costs for DAC ($100-900/tonne CO_2). In addition to carbon pricing, large scale public investment may be required to ensure that DAC technologies are developed further and deployed rapidly. See: Rosenbloom, D., et al., 2020. Opinion: Why carbon pricing is not sufficient to mitigate climate change—and how "sustainability transition policy" can help. *Proceedings of the National Academy of Sciences (PNAS)* [e-journal] https://doi.org/10.1073/pnas.2004093117.

[23] Examples of support for innovation outside of basic research funding include the $20m Carbon X prize, which was recently awarded to two companies producing CO_2-enriched cement. In the US, the federal government *"…did not meaningfully invest in direct air capture until FY2020, when it appropriated $60 million for carbon removal technologies, including at least $25 million for direct air capture."* See: Mulligan et al., 2020. CarbonShot: Federal Policy Options for Carbon Removal in the United States. World Resources Institute [online] Available at: <https://www.wri.org/research/carbonshot-federal-policy-options-carbon-removal-united-states> [Accessed 22 July 2021], and XPRIZE, 2021. *Xprize Announces The Two Winners Of $20m Nrg Cosia Carbon Xprize, With Each Team Creating Valuable Products Out Of Co2 Emissions*. XPRIZE [online] Available at: <https://carbon.xprize.org/prizes/carbon/articles/xprize-announces-the-two-winners-of-20m-nrg-cosia-carbon-xprize-with-each-team-creating-valuable-products-out-of-co2-emissions> [Accessed 22 July 2021].