Direct Air Carbon Capture and Sequestration: How It Works and How It Could Contribute to Climate-Change Mitigation

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Owing to the small quantity of carbon dioxide (CO_2) that can be emitted before we exceed the 1.5°C–2°C target of the Paris Agreement on climate change, we are increasingly likely to require ways of removing significant CO_2 from the atmosphere. In addition to the biological options considered to date such as afforestation and bioenergy with CO_2 capture, direct air carbon capture and sequestration (DACCS) is emerging as a potentially important synthetic CO_2 removal technology. Here, we explain how DACCS works, focusing on two major processes that have been developed into large-scale pilot plants. We discuss cost estimates and operational energy requirements, as well as ecological and ethical considerations. We highlight the role of DACCS in the low-carbon transition by discussing its benefits, while also noting potential trade-offs and uncertainties that deserve further investigation.

Why We Might Need DACCS

The United Nations Framework Convention on Climate Change Paris Agreement of December 2015 states that the world should seek to limit global warming to "well below 2°C," and pursue efforts toward a 1.5°C limit, compared with preindustrial temperatures, in order to avoid dangerous levels of climate change.

To achieve this target, it is estimated that cumulative CO_2 emissions (as of January 1, 2018 onward) must not exceed 320 $GtCO_2$ (66% chance of success) or 740 $GtCO_2$ (33% chance of success). This 1.5°C "carbon budget" has a number of associated uncertainties, including those related to historical emissions, the sensitivity of global warming to CO_2 emissions, and the level of emissions and emissions reduction potential of non-CO_2 greenhouse gases. Nevertheless, given that anthropogenic CO_2 emissions are currently exceeding 40 $GtCO_2$ per year, and have increased by ~1% per year this decade, it would seem that without measures to drastically and rapidly reduce emissions, we may breach the 1.5°C carbon budget in just a few years' time. Should this budget be exceeded, the only way to return to the recommended levels is to remove CO_2 from the atmosphere, using what are generally referred to as negative emissions technologies (NETs). The occurrence of NETs in mitigation pathways is not new. Indeed, the majority of 1.5°C emissions pathways that featured in the IPCC (2018) report require the implementation of NETs to some extent, particularly in the second half of the century (Figure 1).

Of the negative emission strategies considered in the IPCC's reported CO_2 emissions reduction pathways, biological options, such as large-scale afforestation (essentially, tree planting) and a technology called bioenergy with carbon capture and storage (BECCS) feature most heavily.

Afforestation removes atmospheric CO_2 through tree growth, as part of the photosynthesis process. In the case of BECCS, atmospheric CO_2 is also removed by purpose-grown plants and trees, which are then harvested as biomass. The biomass can be burned to generate heat and electricity, with the majority of CO_2 released during combustion being captured, liquefied, and sequestered in underground storage sites. Alternatively, the biomass can be converted into liquid fuels (known as biofuels) in chemical processes that release CO_2, which is once again captured. So long as the captured CO_2 exceeds that emitted by the biofuels when they are combusted, this process can also achieve net removal of atmospheric CO_2.

For both BECCS and afforestation, there have been increasing concerns regarding the viability of achieving net removals of CO_2 from the atmosphere at the scales necessary to match those illustrated in many mitigation pathways. Such concerns have arisen principally because of land availability for afforestation, as well as the water and fertilizer requirements involved in the growth of biomass, with potentially adverse consequences for grand challenges such as food security and biodiversity. Alternative mitigation pathways have been explored, including those that depend less on NETs and those that encourage and foster faster social and technological progress in other sectors. However, afforestation and BECCS are not the only forms of NET, and recent assessments consider alternative approaches, potentially with less adverse consequences. One such approach is direct air carbon capture and sequestration (DACCS).

What Is DACCS, and How Does It Work?

The basic concept of DACCS is that, even though CO_2 is not highly concentrated in the atmosphere, occurring at just over 400 parts per million by volume (ppmv), it is nevertheless possible to remove significant quantities every year by placing large volumes of air in contact with chemicals known as sorbents. There are essentially two processes by which the

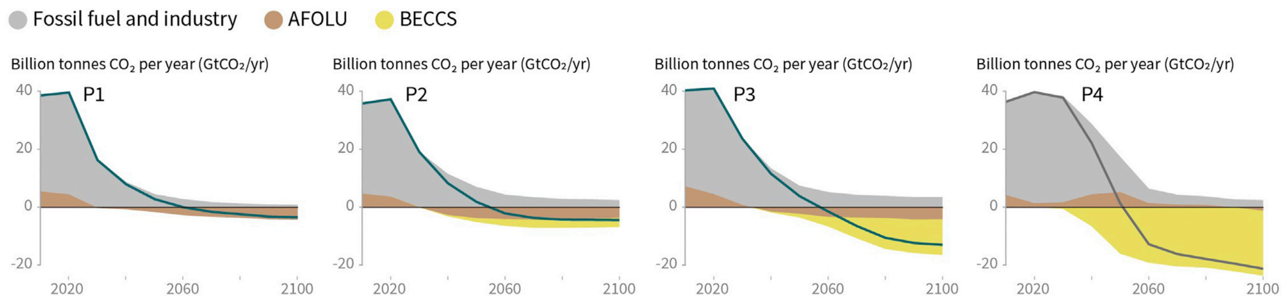

Figure 1. Global CO_2 Emissions from the Present until 2100 in Four Illustrative 1.5°C Emissions Pathways
Different contributions from fossil fuel and industry, agriculture, forestry, and land use (AFOLU) and bioenergy with carbon capture and storage (BECCS)—a negative emissions technology—are detailed. P1 does not rely on BECCS, since it uses an underlying scenario in which energy-efficient technologies and energy-saving societal behaviors occur to such a degree that there is no requirement for BECCS. Reproduced from the IPCC (2018).

sorbents work. The first is known as absorption, whereby the CO_2 dissolves into the sorbent material. The second process is adsorption, whereby CO_2 molecules adhere to the surface of the sorbent material. In both cases, the sorbents are treated so that the CO_2 is released from them, for sequestration in geological storage sites or for utilization in the production of carbon-based fuels and other chemicals.

Within this broad conception of DACCS technologies there are many different basic designs. One design type, being developed by major DACCS companies including Canada-based Carbon Engineering, Swiss firm ClimeWorks, and US-based Global Thermostat, involves banks of fans that can circulate large volumes of air among sorbents in a given time period. Alternative designs include artificial trees, as have been developed at Arizona State University, which place large surface areas of sorbents in contact with the atmosphere, mimicking how leaves on natural trees absorb CO_2 for photosynthesis. In both of these designs, after the CO_2 is removed from the sorbents, they can be reused.

ClimeWorks', Carbon Engineering's, and Global Thermostat's latest plant designs (as of October 2019) are capable of capturing CO_2 on the order of 1 $MtCO_2$/year or more. Each of these plants could be replicated in many locations, but there would need to be about 40,000 1-$MtCO_2$/year plants in operation to capture all current global CO_2 emissions. A full life-cycle analysis of the material, energy, and other implications of constructing and maintaining anything like this vast quantity of plants remains a major analytical gap.

The specifics of the different DACCS processes are worth elaborating, since they involve different chemical sorbents with different sorbent regeneration processes, resulting in different energy requirements and by-products from the sorbent manufacture.

DACCS Using Strong Base Sorbents

The most technically mature method for capturing atmospheric CO_2 is to place ambient air into contact with a strong liquid base, such as potassium hydroxide or sodium hydroxide (NaOH), which dissolves the CO_2. This also leads to a chemical reaction between the CO_2 and base, forming a carbonate solution, from which the CO_2 can then be removed in a separate process that involves combining the carbonate solution with a calcium hydroxide ($Ca(OH)_2$) solution in a precipitator. This regenerates the base and forms solid calcium carbonate ($CaCO_3$), which is precipitated out of the base solution. The precipitate is then sent to a calciner, where it is reacted at very high temperatures (about 800°C) with oxygen (O_2) from an air-separation unit, forming pure CO_2 and calcium oxide (CaO). The CaO is combined with water in a slaker and forms $Ca(OH)_2$ for reuse (Figure 2).

DACCS Using Solid Sorbents

The most common alternative design to the strong base variety of DACCS is to use solids (made of chemical compounds called amines) that adsorb (rather than absorb) atmospheric CO_2 in a two-step process: step 1 consists of the adsorption of ambient CO_2, while step 2 consists of the separation of the CO_2 using relatively low-temperature heat (around 100°C or less), pressure or humidity changes, or some combination of these, to regenerate the sorbent (Figure 3). Less energy is required to separate the CO_2 from the amine sorbent because adsorption results in a weaker bond between the CO_2 and sorbent when compared with absorption into a strong base.

In all cases, to ensure that these technologies provide significant CO_2 removal, all electricity and heat input to operate DACCS will have to come from low-carbon sources (such as renewable electricity and/or natural gas combined with capture of the CO_2 released by the gas's combustion). One analysis, for example, estimates that if a DACCS plant is operated with electricity generated by a gas power plant (without carbon capture and storage [CCS]), the gas combustion would return CO_2 equal to 70%–90% of that captured by the DACCS plant to the atmosphere.

Key Characteristics of DACCS

How Does DACCS Compare with CCS?

Compared with conventional CCS processes, DACCS is more energy and material intensive because of the greater difficulty in capturing the CO_2 from ambient air, where it is between 100 and 300 times as diffuse as when concentrated in the flue gases of power stations burning coal and gas. This means that DACCS plants need to have a much greater surface area of CO_2-absorbing chemicals in contact with ambient air compared with the areas or volumes of sorbents in contact with flue gases. This results in DACCS being on the order of three times as energy intensive as CCS per ton of ambient CO_2 removed.

DACCS does, however, have some distinct advantages compared with conventional CCS, which could prove

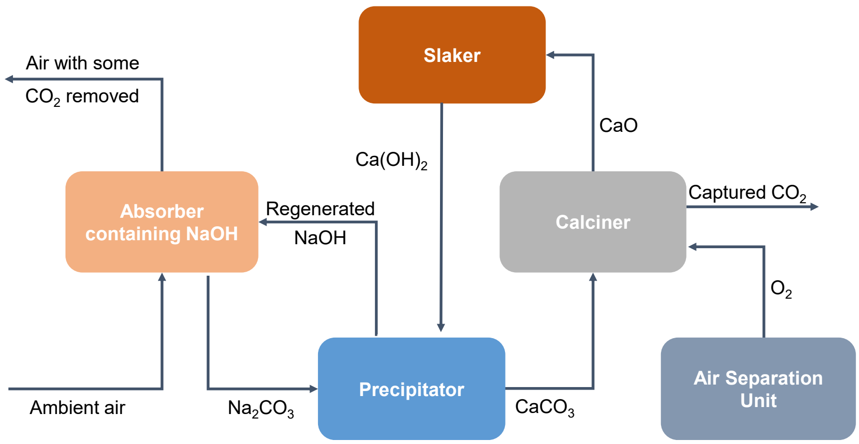

Figure 2. Direct Air Capture Using a Strong Base, such as Sodium Hydroxide
Based on the plant scheme in Socolow et al. (2011)—see Recommended Reading.

beneficial to deploying the technology at significant scales. For example, DACCS plants may be placed anywhere, provided low-carbon energy inputs and appropriate CO_2 storage and/or transport facilities to appropriate storage sites are available. They do not have to be colocated with fossil fuel power generation plants or industrial manufacturing plants, as with conventional CCS, and could even be based offshore. This means DACCS can in principle capture the CO_2 emissions from highly distributed sources such as transport, buildings, and land use for forestry and agriculture, which together make up about 35% of global man-made CO_2 emissions and which cannot be captured by conventional CCS. However, if the deployment of DACCS plants is limited to those designed to utilize waste heat from sources such as industrial manufacturing and thermal power plants, then (even though this would avoid the use of CO_2-intensive natural gas for heat) the geographical flexibility of DACCS as a NET will be suppressed.

How Much Does DACCS Cost?

There have been several estimates of DACCS costs over the past 15 years. The earliest placed CO_2 capture costs in the range US\$140–200/tCO_2. A detailed assessment from the American Physical Society (APS) (2011) report "Direct Air Capture of CO_2 with Chemicals" estimated a cost of US\$610–780/tCO_2 using the sodium hydroxide (strong base) method, about eight to ten times more expensive than the US\$80/tCO_2 for CCS from a coal power station. No explicit reason is provided for the discrepancy between this and the earlier, lower estimates, although the APS report became a benchmark for several years given the relatively conservative assumptions made. More recent detailed estimates based on Carbon Engineering's sodium hydroxide-based operating plant place costs within the range US\$94–232/tCO_2. Long-term sustainable capture costs of DACCS remain uncertain because the technology has yet to be commercialized, and cost reductions through learning-by-doing and scale-up have yet to take effect (this is also the case with other NETs such as BECCS). At this stage, DACCS cost estimates are higher than many other emissions reduction strategies such as renewable energy, energy efficiency, and fossil fuel CCS, although the modular nature of DACCS technology, as well as its relative immaturity, suggests there is considerable scope for innovation and cost reduction.

The total cost of DACCS will also depend on where it is deployed. One analysis of the deployment of large-scale DACCS in the Maghreb region of North Africa, for example, indicates that excellent solar resources and rapidly reducing solar photovoltaic and battery costs could contribute to a reduction in DACCS CO_2 removal costs of around US\$50/tCO_2 by 2050, even with what are deemed to be relatively conservative cost-reduction assumptions for the DACCS plants themselves.

What Are the Ecological Impacts of DACCS?

The overall land use, water removal, and ecosystem health impacts of DACCS plants are small compared with other technologies that remove CO_2 from the atmosphere, but uncertainty remains. One set of estimates suggests that DACCS has a land intensity (measured in hectares per ton of CO_2 removed per year) of less than one-thousandth that of BECCS (although this would increase if also accounting for the land area of dedicated solar photovoltaic plants to provide the DACCS plants' energy inputs). Some DACCS plants designs involve no water removal in their operations, although water removals during the manufacture of sorbents may be significant. There are also potentially adverse consequences if the chemicals used for sorbent manufacture, and the disposal of sorbents at the end of their useful lives, are not handled in an environmentally responsible manner. In particular, the sodium hydroxide used in some DACCS plants is highly corrosive, and the chlorine gas by-product that results from its production from brine is highly poisonous.

Are There Ethical Issues Related to DACCS?

The mass deployment of DACCS, as with other NETs, raises a fundamental intergenerational equity issue. If used as a way of delaying near-term emissions reductions until the future, it places a higher burden on future generations. Although a future global society may be collectively more affluent than today's generations thanks to economic and social progress, it will bear most of the impacts and costs of climate change. The more we value the future, the faster we should reduce emissions in the near term and thus need less or even zero negative-emissions technology, including DACCS. For example, a reduction in the "discount rate" (a measure of how much we value the future), from market based (5%) to social value (2%) would halve the demand for NETs over the course of the 21st century. Similarly, emissions reduction pathways that aim to minimize or forbid the overshoot of the 1.5°C carbon budget and temperature limit would also reduce the value of NETs. Finally, policies to remunerate DACCS and other NETs could require public subsidies, which in the long term might be financially and socially challenging, raising questions about who will own this technology.

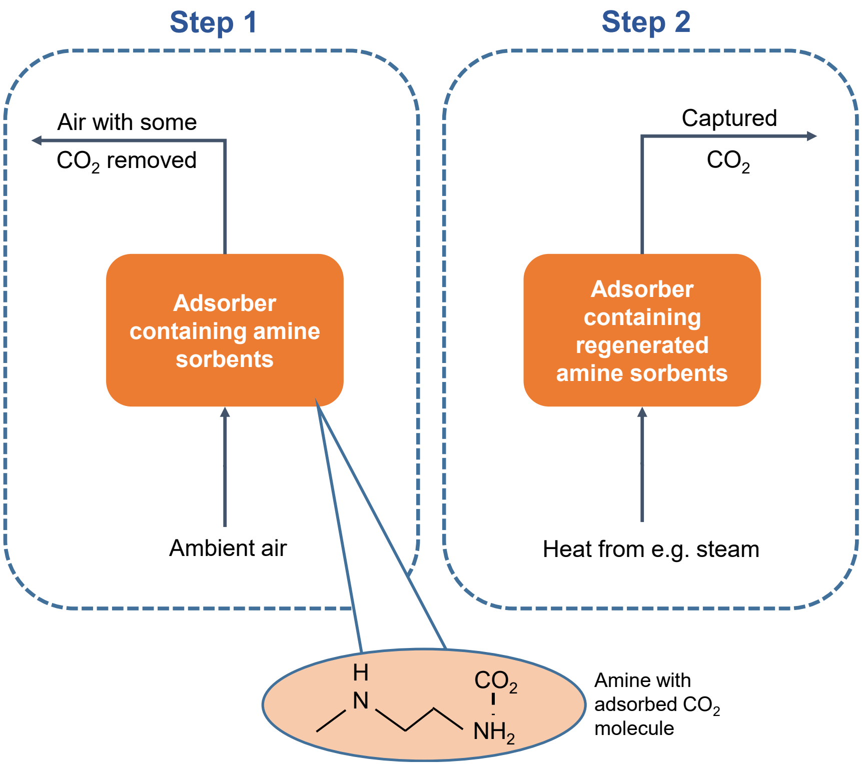

Figure 3. Direct Air Capture Using Amine-Functionalized Solid Sorbents
Based on Global Thermostat and ClimeWorks plant process descriptions.

Can DACCS Help Meet Paris Agreement Targets?

DACCS could play a significant role in achieving stringent climate-change targets when it is made available as a technology option at the scale required. According to a recent study comparing results across two global energy models (TIAM, a technology-rich model representing the global energy system; and WITCH, a model with less technological granularity but with an integrated macroeconomic representation), reaching the Paris climate targets with DACCS would allow a less drastic decarbonization in the near term, with required emissions reductions falling from 75% to less than 50% over the period 2020–2030. This study also showed that DACCS could significantly reduce policy costs and associated carbon taxes needed to deliver emissions reductions. The study highlighted that DACCS is the most significant CO_2 removal option when included in mitigation scenarios, compared with the other NET options (i.e., BECCS and afforestation). Inclusion of DACCS reduces the need for BECCS by 20%–40% compared with scenarios when DACCS is not included (Figure 4), but DACCS may require significant energy inputs: by 2100 it could require about 300 EJ/year in the scenario limiting temperature rise to 1.5°C–2°C.

The critical factor governing the role of DACCS in the TIAM and WITCH energy model simulations (more so than sensitivities around DACCS cost or energy input requirements) is the rate at which DACCS capacity is allowed to scale up. Although capacity expansion rates in the most ambitious mitigation scenarios are massive (at almost 20% per year over the period 2030–2050, equivalent to deploying about 1,500 1-MtCO_2 plants each year), these are not outside the ranges of other technological revolutions, such as solar photovoltaics, wind turbines, and jet engines. However, the study found that if we undertake a mitigation strategy on the assumption that DACCS can be scaled up in this way, but ultimately, we find it is not viable at scale (for example because of technical, regulatory, economic, or other limitations), we might overshoot our global temperature goal by up to 0.8°C. This suggests that DACCS, as well as other NETs, should not be used as an excuse to postpone early emission reductions, particularly by delaying fossil fuel phase-out, which would also affect society in other negative ways such as through persistent air pollution.

Prospects of DACCS and Gaps in Knowledge

A number of pilot DACCS plants are currently being tested, such as the Carbon Engineering, Global Thermostat, and ClimeWorks plants already described, as well as designs from several other organizations. If innovation and testing continue at the current pace, we could realistically expect to see several large-scale DACCS plants deployed within the next decade. However, to realize the ambitious 20% annual capacity growth considered in some mitigation scenarios there will need to be strong policies and financial investment that further encourage research and development, deployment, operation and maintenance, and supporting skills and infrastructures. Regardless of DACCS investment, deployment of this NET must be accompanied by a rapid decarbonization of the energy system: if the two processes are not coordinated, the rationale for DACCS disappears.

However, before DACCS can be deployed at scale, greater efforts must be made to understand its broader implications. This will require an interdisciplinary approach, focusing on a number of key aspects in particular. First, a comprehensive life-cycle analysis including material flow and environmental footprint analysis is required, taking into account the possible geographical deployment patterns of DACCS. Second, analysis of the impact of DACCS on biogeochemical systems is critical, including consideration of the effect that induced atmospheric CO_2 removal would have on marine and terrestrial ecosystems. For example, the pace and quantity of CO_2 absorption from the atmosphere is known to interact with the oceans, leading to some degree of CO_2 re-emissions ("outgassing") from the oceans, which could reduce the effectiveness of large-scale NETs. Much less is known about the impact of CO_2 removal on land. Third, the ethical implications of deploying large-scale CO_2 removal technologies must be further discussed among all affected stakeholders in order that DACCS (and NETs more generally) is used in a responsible way that respects

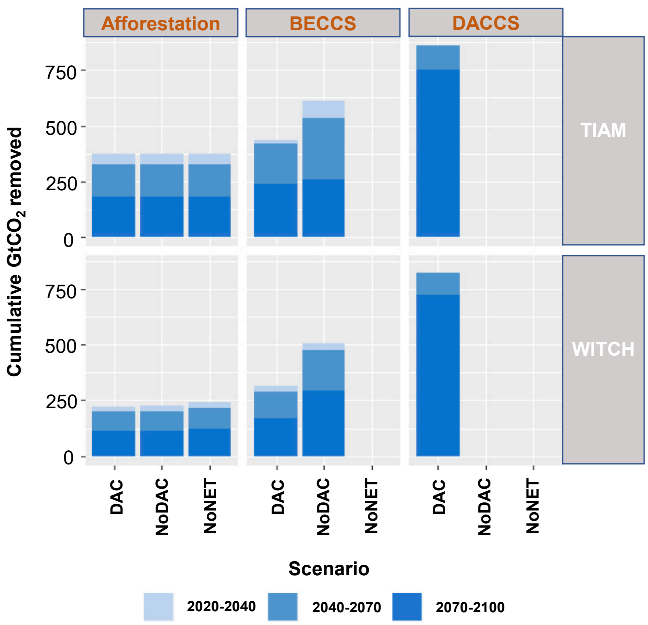

Figure 4. Cumulative CO_2 Sequestration by Three CO_2 Removal Options in 1.5°C Scenarios

Two global energy system models (TIAM and WITCH) are used to calculate cost-optimal CO_2 emissions reduction pathways to achieve a 1.5°C-consistent carbon budget. As can be seen, using central cost and performance assumptions, when DACCS is allowed, it is the dominant CO_2 removal technology, although does not replace BECCS and afforestation and it comes later in the century. Scenario names: DAC, DACCS and afforestation and BECCS allowed; NoDAC, no DACCS allowed but BECCS and afforestation allowed; NoNET, BECCS and DACCS not allowed but afforestation allowed. Reproduced from Realmonte et al. (2019) under the Creative Commons license: http://creativecommons.org/licenses/by/4.0/.

intergenerational equity and reduces moral hazard. Fourth, the role of DACCS in mitigation pathways produced by integrated assessment models should be studied using the latest DACCS cost-projection estimates as new data emerge, as well as using a wider range of scenarios. Mitigation analyses have so far used idealized assumptions about international policy architectures, for example in which carbon pricing or other mitigation policies are widely implemented to meet given temperature goals. More realistic policy cases should be analyzed, including accounting for any policy and governance challenges specific to DACCS, as well its technological progress in relation to other low-carbon options.

In summary, DACCS should be more exhaustively evaluated from a number of angles, together with other mitigation strategies, including not only technologies such as CCS and renewables but also non-technological mitigation options such as cultural and social changes. Doing so would help us to better understand the role of this potentially critical technology in the overarching objective of meeting the Paris Agreement goals and ensuring sustainable development.

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