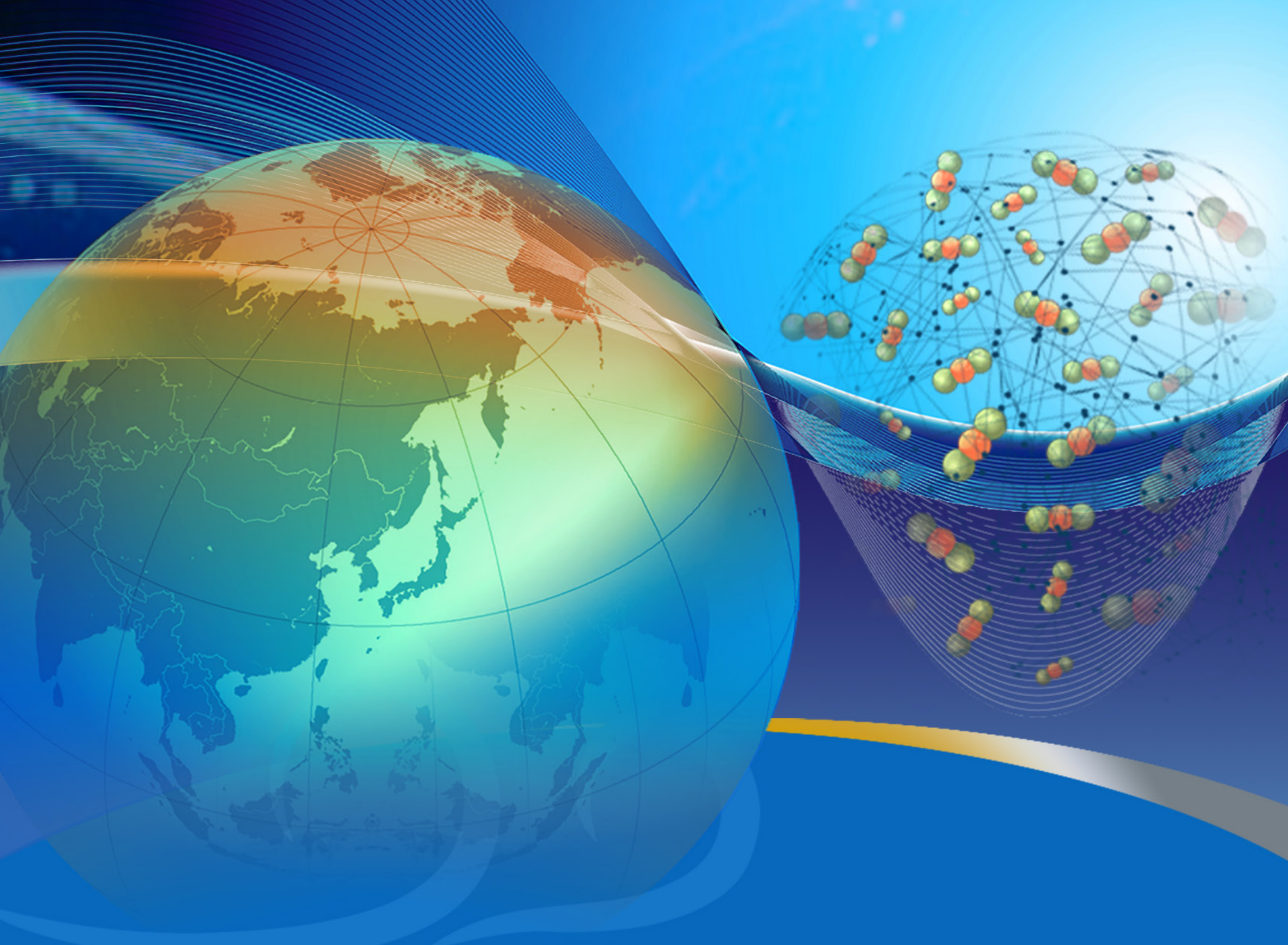
Direct Air Capture of Carbon Dioxide



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Contents

Introduction

Concentrations of carbon dioxide in the atmosphere have reached their highest levels in roughly three million years.

Those concentrations continue to climb, year after year. The Intergovernmental Panel on Climate Change (IPCC) warns of extraordinary risks (including from storms, floods, droughts, heat waves and sea level rise) unless the buildup of carbon dioxide in the atmosphere slows and then reverses in the decades ahead.[1]

More than 175 nations have now ratified the Paris Agreement, which calls for countries to achieve net zero emissions of greenhouse gases in the second half of this century. However, progress towards that goal is slow. Few major economies are now meeting their initial reduction targets under the Paris Agreement. Strategies for deep decarbonization of some sectors of the global economy remain unclear.

Against this backdrop, carbon dioxide removal (CDR) has grown in prominence as a component of global climate strategies. CDR refers to a range of approaches for drawing carbon dioxide (CO_2) from the atmosphere using biological, engineered or hybrid means. Examples of CDR include afforestation, bioenergy with carbon capture and storage (BECCS), and direct air capture of carbon dioxide (DAC). Removal of carbon dioxide from the atmosphere has the potential to play a significant role in climate mitigation, supplementing the many vitally important strategies for reducing and preventing emissions of carbon dioxide in the first place. Indeed the IPCC's Global Warming of 1.5°C report (2018) states that 100-1000 gigatons (GT) of carbon dioxide removal will be required this century to prevent global average temperatures from climbing 1.5°C (2.7°F) above pre-industrial levels.[2]

Carbon dioxide can be captured directly from air using chemicals, refrigeration or membranes. Some of these techniques date to at least the 1930s, when air separation units designed to produce oxygen produced CO_2 as a byproduct. (This CO_2 was often sold to the food and beverage industry.) Atmospheric CO_2 scrubbers have been used in submarines since the 1940s and spaceships since the 1950s. The movie Apollo 13 recounts a dramatic effort to design a CO_2 scrubber aboard a damaged spacecraft en route to the Moon.

This roadmap explores the potential for direct air capture of carbon dioxide to contribute to climate mitigation (and provide feedstock for commercial processes). Chapter 1 of the roadmap examines the need for carbon dioxide removal broadly and surveys the range of CDR approaches available. Chapter 2 describes direct air capture technologies. Chapter 3 discusses the advantages of direct air capture. Chapter 4 explores challenges facing direct air capture, and Chapter 5 considers research pathways for addressing them. Chapter 6 discusses policy options. Chapter 7 offers findings and recommendations.

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1 See IPCC, Global Warming of 1.5°C: Summary for Policy Makers (2018) at p.13, http://report.ipcc.ch/sr15/pdf/sr15_spm_final.pdf, IPCC, Fifth Assessment Report Working Group 1 – Information from Paleoclimate Records (2013) at p. 394, https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter05_FINAL.pdf; NASA, Carbon Dioxide Hits New High, https://climate.nasa.gov/climate_resources/7/graphic-carbon-dioxide-hits-new-high.

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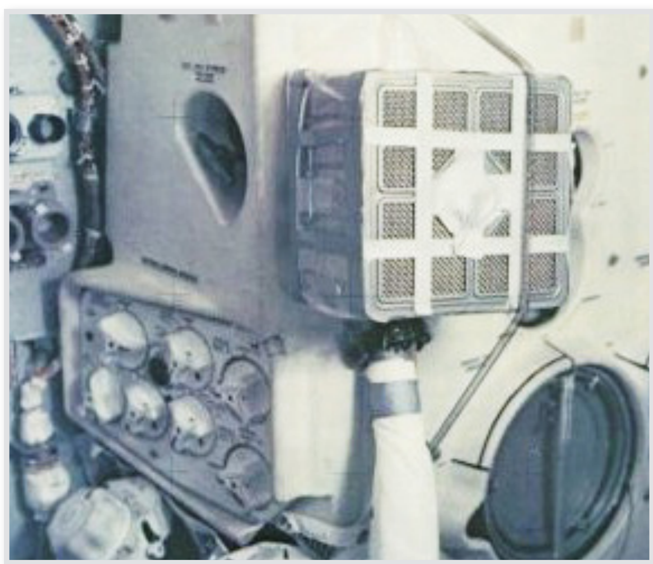


source: nasa.gov

Figure 1-1. *The improvised carbon dioxide scrubber on board the Apollo 13 lunar module.*

Chapter 1

Carbon Dioxide Removal Technologies

A. Need for Carbon Dioxide Removal

Global average temperatures are increasing due to emissions of greenhouse gases, the most important of which is CO_2.[1] In the Paris Agreement, more than 180 countries agreed to:

> *"hold the increase in the global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels."* [2]

The IPCC estimates that, in order to have a 67% chance of preventing global average temperatures from increasing 2°C (3.6°F) above pre-industrial levels (the "below 2°C carbon budget"), emissions of CO_2 after the beginning of 2018 must be kept below 1170 $GtCO_2$ (319 GtC).[3] The IPCC also estimates that, in order to have a 67% chance of preventing global average temperatures from increasing 1.5°C (2.7°F) above pre-industrial levels (the "below 1.5°C carbon budget"), emissions of CO_2 after the beginning of 2018 must be kept below 420 $GtCO_2$ (114 GtC).[4]

To put this in perspective, annual CO_2 emissions from human activities are roughly 42 Gt (11 GtC).[5] Thus, the remaining amount of the below 2°C carbon budget is equivalent to roughly 28 years of global CO_2 emissions at current rates. The remaining amount in the below 1.5°C carbon budget is equivalent to roughly 10 years of global CO_2 emissions at current rates.[6]

Both these estimates are subject to uncertainties due to factors including differences in radiative forcing estimates, pathways for emissions of non-CO_2 gases (e.g., methane, nitrous oxide and aerosols) and other factors. (See **Box 1.**)

Although there are uncertainties with respect to the precise values of the carbon budget for any stabilization target,[11] there is no uncertainty with respect to three important conclusions:

1. to keep global average temperatures from increasing 2°C (3.6°F) or 1.5°C (2.7°F) above pre-industrial levels , the remaining carbon budgets are small in relation to past human emissions of greenhouse gas,
2. with each passing year those budgets grow smaller, and
3. the time remaining before we exhaust those carbon budgets is very small compared to the time required to transition to a zero-emissions society.[12]

The primary motivation for CDR is the expectation that CO_2 emissions will not be reduced rapidly enough or to a level low enough to keep within the carbon budget. This implies that withdrawing CO_2 from the atmosphere will be necessary in the future.[13] Future climate scenarios that seek to limit temperature increases to 2°C (3.6°F)

BOX 1 The impact of non-CO_2 greenhouse gases on the carbon budget

Non-CO_2 GHGs and aerosols have a strong impact on climate but also tend to be short-lived. For example, methane (CH_4) and nitrous oxide (N_2O) have lifetimes in the atmosphere of around 12 years and 121 years, respectively.[7] In contrast, a substantial fraction of CO_2 emitted today will persist for millennia, contributing to warming over that entire time[8]—a factor in determining the carbon budget. If all non-CO_2 GHG and aerosol emissions were halted today, their climate impact would diminish within decades, while CO_2 emissions would continue to warm the planet for centuries.[9] Small differences in the future emissions trajectories of non-CO_2 GHGs and aerosols can have a strong impact on the carbon budget. Both CO_2 and non-CO_2 greenhouse gas emissions must be addressed to tackle climate change.[10]

(e.g., IPCC RCP2.6) reflect this expectation, as most require CDR technologies to deliver "net negative" emissions after 2050.[14] (See **Box 2.**)

Even if emissions were aggressively reduced—far more than implied by current nationally determined contributions (NDCs)—CDR would be required to achieve warming limited to 1.5°C (2.7°F).[15] Indeed, in its Global Warming of 1.5°C report (2018), the IPCC found that all pathways to a 1.5°C (2.7°F) stabilization target require significant CDR—between 100 and 1000 $GtCO_2$ through 2100.[16]

While the primary motivation for CDR is the expectation that we will be unable to meet the constraints imposed by the carbon budget, some CDR approaches could also serve to reduce the impacts of CO_2 emissions.[17] For example, ocean alkalinity modification techniques could help offset ocean acidification resulting from the mixing of CO_2 from the atmosphere into the ocean. Similarly, approaches to increase soil carbon could also increase the ability of soil to retain water, improve plant growth and limit runoff during extreme precipitation events, which are expected to increase as a result of climate change.

As this section highlights, much of the carbon budget available for limiting warming to 2°C (3.6°F) has already been exhausted and the remaining space in the budget is shrinking rapidly. Ambitious mitigation efforts are required to stretch this remaining budget for as long as possible. CDR pathways are not a substitute for conventional mitigation approaches but will be needed as a supplement to deep emissions reductions.[18]

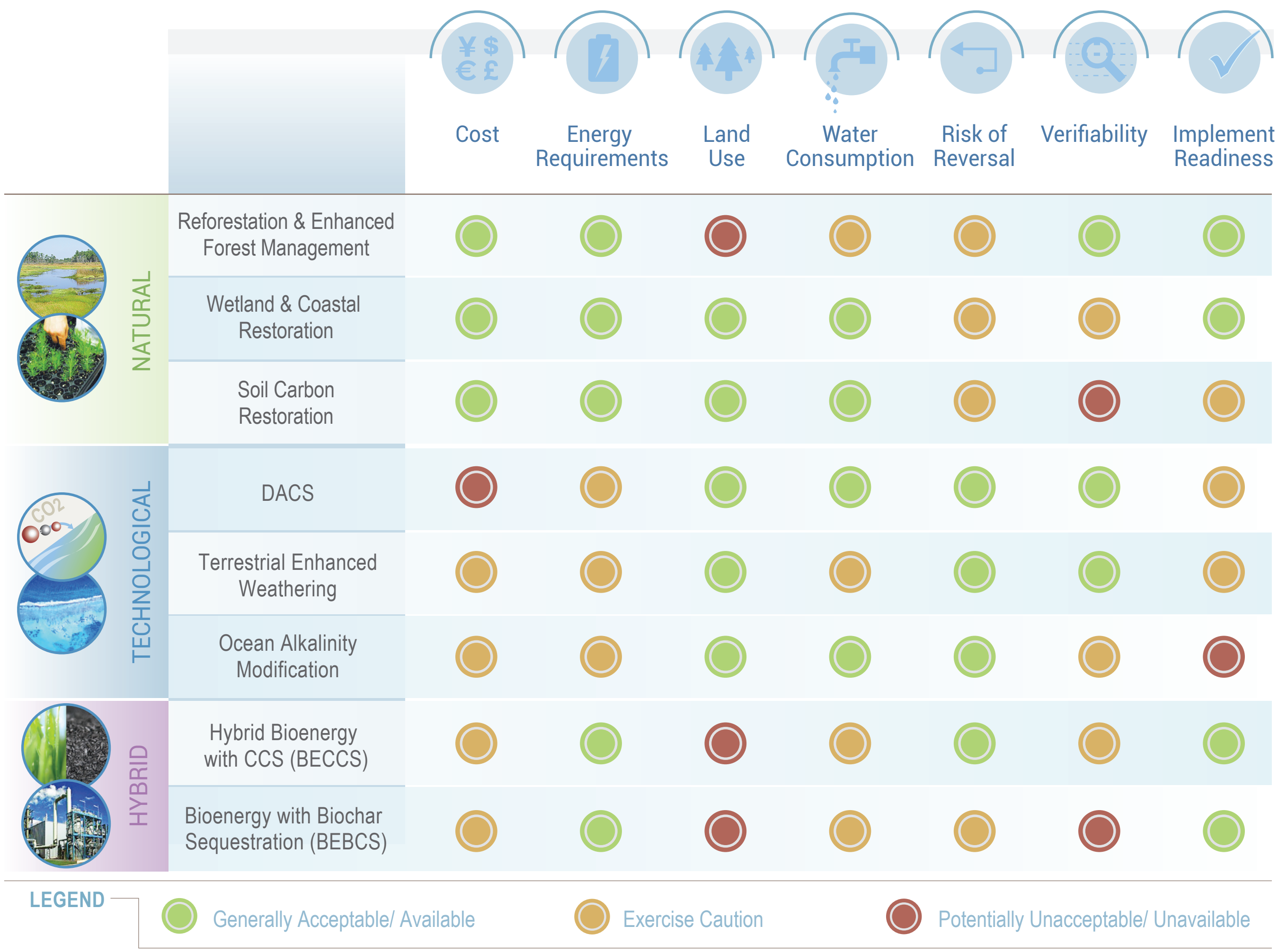


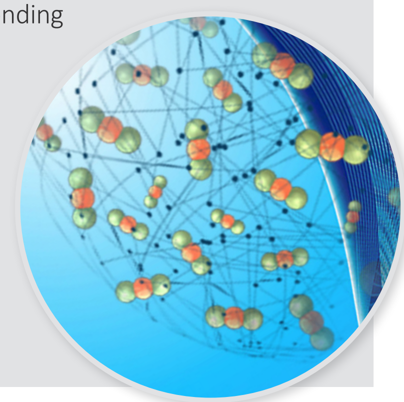
Figure 1-2. *Summary table of pathways in the CDR portfolio, highlighting strengths, weaknesses and indicative technical potential.*

BOX 2 What does “net-negative” mean?

The term “net-negative” appears in both the discussion of carbon dioxide removal (CDR) technologies and long-term emissions trajectories.

CDR technologies are often viewed as simply a mechanism for removing CO_2 from the atmosphere. Unfortunately, they will also be responsible for emitting some amount of CO_2 themselves. For example, direct air capture (DAC) plants will be built from plastics, steel and cement, the production of which emits CO_2 and may consume energy that is not from zero-carbon sources. Therefore, the correct way to consider the climate impact of CDR technologies is in terms of “net” CO_2 removal, which is the amount of CO_2 removed minus any corresponding emissions resulting from removal or as a consequence of removal. This highlights the importance of examining the removal process from a full lifecycle perspective.

If enough CDR is deployed, global emissions could also become “net-negative.” This means that emissions from all human activities—such as power generation, industry, transport and CDR—are smaller than the amount of CO_2 removed from the atmosphere. The result would be a decrease in atmospheric concentrations of CO_2. For the same “net-negative” emissions target, the lower the emissions from human activities, the lower the required CO_2 removal rate.



B. Carbon Dioxide Removal Portfolio

Direct air capture (DAC) is one of several CDR pathways.[19] (See **Figure 1-2.**) No single CDR pathway will likely be able to deliver all the carbon dioxide removal needed to stay within the below 2°C budget.[20]

These pathways were the subject of a major study by the U.S. National Academies to assess the state of current CDR approaches and to develop a research, development and demonstration (RD&D) agenda for many key CDR pathways.[21] The study concluded that all approaches have merits and challenges. Importantly, the study concluded that neither the U.S. nor the world can achieve the required rate and volume of CDR using pathways available today below a \$100/tCO_2 cost. For all 2°C pathways, additional deployment of CDR was needed at costs above \$100/tCO_2 today. The report concluded that innovation, research, development and investment are needed to reduce cost, increase potential volume and rates, and manage the trade-offs between land, cost, energy requirements and other important constraints.

CDR approaches can be grouped into natural, technological and hybrid pathways. Natural pathways are those in which ecosystems are conserved, restored or managed to remove carbon dioxide from the atmosphere and increase carbon sequestration. Examples of natural pathways include reforestation, improved forest management, use of cover crops in farming, changes to animal grazing practices and restoration of wetlands, peatlands and coastlines (often referred to as “blue carbon”).[22]

The cumulative potential of natural pathways to remove CO_2 is large relative to current annual emissions. Moreover, in addition to removing CO_2, many natural pathways enhance other ecosystem services, such as regulating water flow or reducing erosion. The potential of a wide range of natural pathways was recently estimated at 14 GtCO_2/y in 2030 (after accounting for “safeguards”)[23], of which around 5 GtCO_2/y was estimated to cost less than \$100/tCO_2[24]. However, these pathways are limited by the availability of land, water and nutrients.[25] Moreover, this type of approach may have drawbacks such as reductions in crop or grazing land, biodiversity (e.g., replacing virgin forest with managed plantations) or albedo (i.e., increased absorption of solar radiation and, thus, local heating). Many of these pathways are also subject to saturation (CO_2 removal from trees slows over time) and may be reversible (e.g., forest fires releasing previously removed CO_2), meaning that their aggregate removal rates will decline over time and could release CO_2 under a changing climate.

Ocean fertilization, where nutrients are spread over nutrient-limited regions of the ocean—enhancing algal growth and CO_2 uptake[26]—can also be considered a natural pathway. However, the efficiency of ocean fertilization appears low, and the activity may have substantial negative impacts on the ocean ecosystem.[27] Because of the uncertainties about its effectiveness, status in international law and concerns about unintended consequences, we do not consider ocean fertilization in this document.

Technological pathways depend fundamentally on deployment of engineered technological systems to remove CO_2. These pathways include DAC[28], indirect ocean capture[29], terrestrial-enhanced weathering[30] and ocean alkalinity modification.[31] The cumulative potential of some of these pathways has been individually evaluated and is very large, but their practical potential is poorly understood. For example, accelerated weathering using mined, crushed silicate rocks spread on suitable croplands could remove billions of tons of CO_2 annually at costs well below \$100/tCO_2.[32] At very large scales, alkaline runoff from such enhanced weathering would partially mitigate ocean acidification.[33] In contrast, ocean alkalinity modification schemes directly increase the alkalinity of the oceans—mitigating ocean acidification—while sequestering atmospheric CO_2. Some of these pathways (e.g., electrochemical weathering) also have the benefit of generating hydrogen.[34] However, the principal challenge with large-scale (i.e., multiple GtCO_2 per year) use of enhanced weathering or ocean alkalinity modification is the need to mine and process enormous amounts of virgin rock.[35] Additionally, where large-scale enhanced weathering impacts the oceans, it could be limited by marine dumping treaties (e.g., the London Convention and Protocol).

The cumulative removal potential of DAC is constrained by the available capacity for geological (or other) sequestration, while the rate is limited by power requirements of DAC and the rate at which CO_2 can be sequestered. The global geological storage capacity for CO_2 is equivalent to hundreds of years of emissions (though this large theoretical capacity must be resolved on a case-by-case basis through further exploration and characterization).[36] Sustainable rates of CO_2 injection into the subsurface are, likewise, controlled by local factors. However geological storage projects currently in operation have demonstrated sustained injection rates of millions of tons per year,[37] and modeling studies suggest these projects are not outliers.[38] In addition to geological storage, conversion of CO_2 into aggregates and durable products could also be a means of sequestering CO_2, albeit at a much smaller scale.[39] This suggests that DAC with sequestration ("DACS") could play an important role as a "backstop" technology in an overall climate strategy (see Chapter 3 for further discussion).

Hybrid pathways harness both ecosystems and technological systems to remove CO_2. This category encompasses bioenergy with carbon capture and storage (BECCS),[40] in which biomass is converted to electricity or fuels and the resulting CO_2 is captured and geologically stored; and bioenergy with biochar carbon sequestration (BEBCS), where agricultural soils are amended with charcoal derived from bioenergy processes.[41] The capture and subsequent sequestration of CO_2 released from bioenergy and small-scale production of biochar (for use as a soil amendment) are undertaken today. A wide range of studies suggests that both BECCS and BEBCS could be deployed at levels sufficient to remove billions of tons of CO_2 annually.[42] In both of these cases, factors limiting large-scale deployment will likely be competition for land and water and nutrient demand for biomass production.[43] Biomass is used widely as a fuel today, supplying approximately 10% of primary energy demand globally (55 EJ/y) in 2015.[44] Creutzig et al.[45] report that there is a "medium level of agreement" that this could be increased up to 300 EJ/y in a sustainable manner.

Reversibility of carbon removal is a question that is frequently raised in the context of DACS, BECCS and BEBCS, as well as in natural pathways, as discussed above. While carbon contained in biochar tends to be relatively stable in the soil, the factors affecting the permanence of carbon sequestration, the relationship between soil types and productivity benefits of biochar application, and the relationship between feedstocks and production conditions needs to be better understood.[46] Conversely, the permanence of geological storage and the associated risks are relatively well understood.[47] Research and development, demonstration projects, and analogues support the expectation that CO_2 stored in well-characterized geological formations using best practices will be retained for geological time scales with relatively low (and manageable) risks.[48]

In summary, while it is not possible to sum up the current estimates of potential for each of these pathways, it appears that a relatively low-cost portfolio of CDR activities could be created to remove billions of tons of CO_2 per year from the atmosphere. Given the large removal potential associated with DAC coupled to geological CO_2 storage relative to the other CDR pathways, DAC does set an upper limit on the cost of climate mitigation.[49] However, DAC does not offer the co-benefits that are associated with some other pathways, ranging from energy production (e.g., BECCS, electrochemical weathering) to enhancement of ecosystem services (e.g., forest conservation and reforestation). The ultimate composition of the CDR technology portfolio depends on future developments in technology, policy and behavior.

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Chapter 2

Direct Air Capture Technologies

A. What is Direct Air Capture?

Direct air capture (DAC) is the physical or chemical separation and concentration of CO_2 from ambient air. After capture, this CO_2 can be stored underground, used for enhanced oil recovery, or used to make products such as chemicals, fuels and cement. (See **Figure 2-1.**) DAC is distinct from "point-source" carbon capture and sequestration (CCS) because it removes CO_2 from ambient air, not flue gas. Today, the community of investigators and practitioners has focused on three different classes of approaches to separate CO_2 from the air:

- **Chemical:** In this class of separations, CO_2 in the air reacts with liquid solvents or solid sorbents, temporarily binding it. The solvent or sorbent is then heated or subjected to a vacuum, releasing the CO_2 for concentration. This approach is similar to point-source carbon capture systems that remove CO_2 from flue gas.
- **Cryogenic:** Because CO_2 has a relatively high freezing temperature for a gas, it can be frozen out of the air. Currently, CO_2 is recovered from air by freezing, as a byproduct of cryogenic oxygen separation.
- **Membranes:** CO_2 can be separated from air and seawater using membranes, including ionic exchange and reverse osmosis membranes. This mimics the way plants and animals separate CO_2. Today, CO_2 is separated from seawater during conventional desalination.

The companies most actively engaged in DAC mostly favor chemical approaches, using either liquid solvents or solid sorbents. Since heat and power are required to regenerate the key chemical agents, the goal of many companies and researchers is to improve CO_2 loadings, reduce input energy requirements and costs, and improve concentrations of CO_2 in the produced gas mixture.

Currently, mainstream DAC technologies are based on reversible chemical sorbents that can be cycled many times to capture and release CO_2. The choice of sorbent material is an extremely important part of DAC system design since it determines most other aspects of the overall system. Chemical sorbents are of great interest in flue-gas carbon capture, and there are significant research, development and demonstration (RD&D)

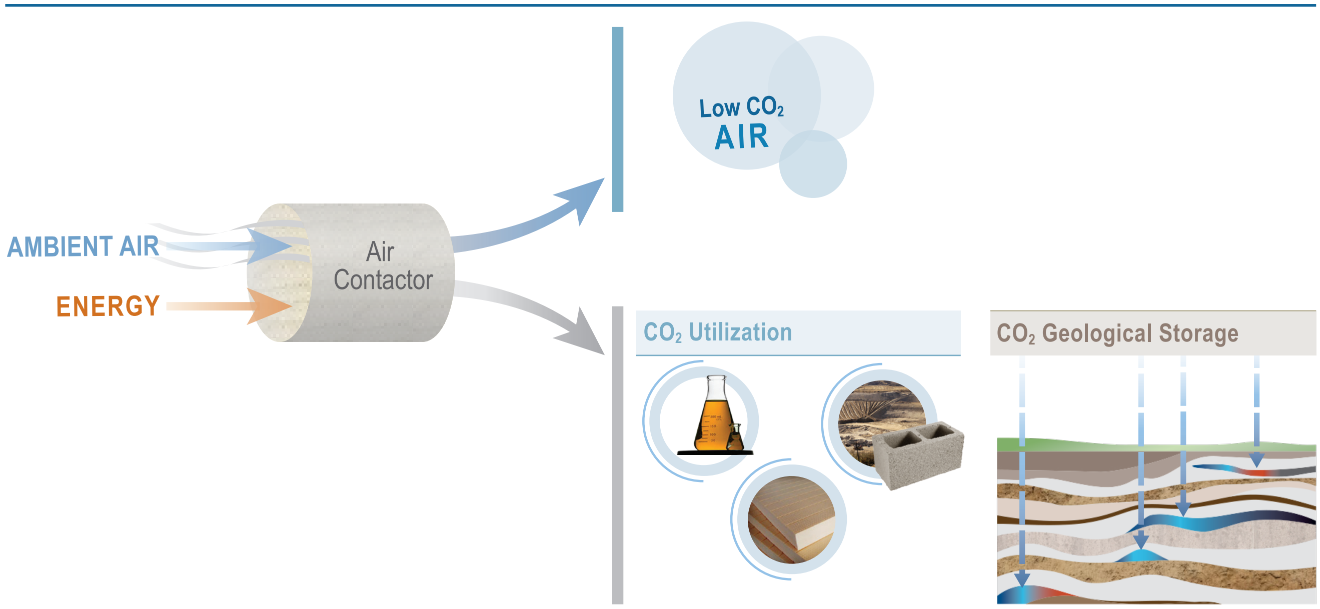

Figure 2-1. *Direct Air Capture of Carbon Dioxide.*

efforts to develop new variants of these materials. While some of this is helpful for DAC design, research on new materials specifically for DAC is extremely limited.[1]

The primary categories of chemical sorbents that are used in DAC designs are aqueous hydroxides, solid-supported amines and solid alkali carbonates (bulk and supported).[2] Research on flue-gas capture technology has also included physiosorbent materials, such as zeolites and metal-organic frameworks (MOFs), which typically bind CO_2 much more weakly than chemical sorbents. However, the limited amount of research on using these for DAC has produced discouraging results since they appear to perform poorly at the very low CO_2 concentrations of ambient air and are also inhibited by the presence of atmospheric moisture.[3] No current DAC designs use primarily physiosorbent materials.

For economic and technical reasons, sorbent materials must be re-used many times, through many cycles of capturing and releasing CO_2. This process tends to degrade the material, reducing its ability to capture CO_2 and making it necessary to replenish it over time. An important design goal in DAC systems is to minimize this exhaustion of material.

The term used to describe the stage of releasing captured CO_2 from the sorbent material is regeneration. The most common way to do this is by heating the sorbent material, whether solid or liquid. Where heat is primarily used to regenerate a solid sorbent the process is known as temperature-swing adsorption (TSA). Some sorbents can be regenerated by changing the amount of ambient moisture/humidity, and systems that primarily use this effect are known as moisture-swing adsorption (MSA). A third way to regenerate sorbents is through changing the ambient pressure of the air, which is referred to as pressure-swing adsorption (PSA).[4] These methods can be used in combination, depending on the properties of the sorbent material.

A crucial component of DAC designs is how the sorbents are brought into contact with ambient air. This is done using an air contactor, designed to handle both large volumes of air throughput and either the flow of a liquid sorbent or the structural support of a solid sorbent. The structural materials, geometric design, pressure drop and other features of the air contactor are important challenges for DAC designs and dominate capital costs. A further important design consideration is to minimize any loss of material to the passing air before it is released, which could pose environmental hazards and increases the amount of sorbent that must be replenished.

B. DAC Technologies Today

This section describes the most prominent DAC designs to date, including what is known about their sorbent materials, regeneration strategy, air contactor and other aspects.

Carbon Engineering. Founded in 2009 with the goal of large-scale DAC deployment, Carbon Engineering is the only solvent-based cycle currently in the market. Although the Carbon Engineering design is suited for large-scale DACS systems, the company is currently focused on combining DAC-derived CO_2 with fuel synthesis (air-to-fuels). Based in Squamish, British Columbia, the company has an operating facility that produces both synthetic gasoline and diesel and partners with GreyRock for fuel synthesis (a modified Fischer-Tropsch process).

Much of the system is described in a recent technical paper.[5] This is the most detailed description of a full DAC system available in the public literature and is supported by data from Carbon Engineering's operating pilot. The paper reports the levelized cost of the design will be between \$94 and \$232/tCO_2 captured for a mature facility, depending on assumptions about financing, utilizing captured CO_2 to make liquid fuel, and component technology costs.

Figure 2-2. *Direct Air Capture system—Carbon Engineering.*

The sorbent is an aqueous solution of potassium hydroxide (KOH), which interacts with solid pellets in a slurry reactor that includes a separate aqueous solution of calcium hydroxide [$Ca(OH)_2$]. A final stage recuperates the CO_2 in a separate high-temperature calcination regeneration process. The air contactor uses a plastic (low-cost) packing material that is designed to allow the sorbent solution to flow downwards under gravity while air is blown across it at right angles (cross-flow configuration), which is uncommon.

What's distinctive about this company: *Carbon Engineering is currently the only company pursuing a liquid-solvent-based approach to DAC. This enables a continuous process which can operate at steady state (in contrast to solid-sorbent-based systems, which are inherently a batch process). Most components of the design are commercially available, meaning that their cost and performance are relatively well understood. The proprietary air contactor is made from low-cost, earth-abundant materials, helping reduce capital costs.*

The design currently uses a combination of renewable electricity and natural gas (burnt in an oxyfired calciner) to provide heat. In this configuration, the requirement for heat energy is four times greater than for electrical energy, on a raw energy content basis. The system can operate in an alternative configuration in which natural gas also provides power, and the CO_2 in the flue gas from the turbine is captured by the system and included in the levelized cost of capture (between 30% and 48% of the CO_2 delivered by the overall system comes from combusting natural gas, depending on the configuration). The company is working to develop a purely electrical process in which high-temperature electrical heating provides thermal energy for the calcination step.

Climeworks. This company has three pilot plants currently in operation (one in Switzerland, one in Iceland and one in Italy). The first plant captures approximately 900 tCO_2/y and sells the CO_2 to a nearby greenhouse.[6,7] The second plant is associated with the CarbFix project,[8] capturing approximately 50 tCO_2/y and sequestering it.[9] The third plant supplies approximately 150 tCO_2/y for production of renewable methane in the framework of the EU-funded STORE&GO project.[10] No cost estimates are publicly available.

Figure 2-3. *Direct Air Capture system—Climeworks.*

The sorbent is amine supported on solid porous granules arranged in a proprietary filter. The regeneration is based on a combined temperature- and pressure-swing process. The air contactor consists of a set of fans that move air horizontally across the sorbent filters. The system requires 1,800-2,500 kWh of thermal energy (at 100°C) and 350-450 kWh of electrical energy per ton of CO_2 (a ratio of four to seven times more thermal energy than electrical energy).[11] The thermal energy is currently provided by free waste heat from a local incinerator and geothermal energy in the Swiss and Icelandic projects, respectively.

What's distinctive about this company: *Climeworks was the first company to deliver CO_2 from DAC as a commercial product and the first to offer CO_2 removal services as a commercial product. While the initial design included sub-optimal components, there are straightforward paths to improving these (e.g., replacing shell-and-tube heat exchangers with higher performing units). They have an intrinsically modular design and an active factory floor and production facility.*

The Climeworks Switzerland plant is currently the only DAC facility in the world operating at near-$ktCO_2$/y scale. The free waste heat and the revenue from CO_2 sales to the nearby greenhouse suggest that it has favorable economics. However, it is difficult to extrapolate this to a larger installed base of DAC facilities because niche opportunities for free waste heat and nearby CO_2 offtake such as this are limited.

Climeworks is focused on food-and-beverage and carbon-removal services at present and is partnering with the Gebrüder Meier greenhouse in Switzerland and the CarbFix project in Iceland. In addition, they have several partnerships developing synthetic fuels, notably with Audi and Sunfire (an electrocatalytic fuel synthesis company based in Germany).

Global Thermostat. This company has a demonstration plant operating in California and is completing a pilot plant in Huntsville, Alabama that will capture approximately 4,000 tCO_2/y.[12] The plant will produce CO_2 for a global food and beverage company. The company claims that the cost of capture at scale (1 million tCO_2/y) would be \$50/tCO_2, although it has not made details of its cost estimates public.[13]

The sorbent is amine supported on a porous ceramic "monolith" structure that is normally used for automobile catalytic converters. The regeneration is based on temperature-vacuum swing, using steam at 85-100°C to strip CO_2 from the amine.[14] The energy requirement is 4.4 GJ of thermal energy and 160 kWh of electrical energy per ton of CO_2 (a ratio of approximately eight times more thermal energy than electrical energy).[15]

> What's distinctive about this company: *Global Thermostat's use of mass-produced honeycomb monoliths for the air contactor enables cheap manufacturing and provides a high surface area per pressure drop. This reduces the energy requirement for moving air through the contactor. The company has a large set of U.S. and international patents and a technology with an intrinsically modular design.*

Figure 2-4. *Direct Air Capture system—Global Thermostat.*

Once commissioned, the facility in Huntsville will be the largest DAC plant in the world. The energy source used will take advantage of the availability of low-temperature heat at the specific site where it will be installed.

Center for Negative Emissions (Arizona State University). This research group is developing a DAC process based on an anionic exchange resin, which is regenerated using moisture swing.[16] The group is not currently affiliated with a for-profit company developing the technology for commercial distribution. The estimated costs of the current design are unclear, but Center leader Klaus Lackner has previously stated they are \$200/tCO_2 for initial prototypes, and would fall to \$30/tCO_2 for Nth-plant through learning-by-doing.[17] The Center has not made engineering details public.

The energy requirement is low, at 50 kJ/mol CO_2, or 1.1 GJ/tCO_2.[18] No estimate is available for the amount of electrical energy required. However, this system produces CO_2 at low concentration (5%) and does not compress it. It also consumes water—approximately 5-15 tons/tCO_2.[19] If a water supply can be secured (at low cost and energy consumption), then this type of system is particularly suited to arid environments where the necessary evaporation to drive the moisture-swing process is favored.

Additional systems under development. Several additional systems are being developed that are less mature than the ones discussed previously. These include the following:

- The VTT Technical Research Centre of Finland has demonstrated a direct air capture system based on an amine-functionalized polymer resin sorbent. The regeneration is based on both temperature and pressure swing, with a day/night capture cycle. This is not a commercial project but is continuously operating at 1-2 kg/day. The mean specific energy requirement for CO_2 capture is 89 GJ/tCO_2.[20,21]
- Oak Ridge National Laboratory has demonstrated a proof-of-concept direct air capture system based on an aqueous amino acid solution. The CO_2-loaded amino acids are reacted with a guanidine compound, which leads to the precipitation of a CO_2-containing salt. CO_2 is released from the salt with low-grade heat (80-160°C), making this a liquid-sorbent system with much lower temperature requirements than hydroxide-based systems.[22]

- The U.S. Naval Research Lab has developed an electrolysis/ion-exchange system for extracting both CO_2 and hydrogen from seawater. Based on an electrolytic cation exchange module, a prototype device has been tested on seawater in Key West, Florida. The current demonstration device is capable of making one gallon of jet fuel from the CO_2 per day, with a CO_2 removal rate of 5 tons per year.[23]
- X (formerly known as Google X) and PARC have developed an electrolytic process for extracting CO_2 from seawater.[24] Known as Project Foghorn, the system was focused on utilizing extracted CO_2 to make liquid fuels. The project was ended in 2016 after concluding that the process was not economically viable.[25]
- Skytree is a spin-out of the European Space Agency (ESA). Their air capture technology was originally developed to make longer space missions possible by extracting the CO_2 exhaled by astronauts on board spacecraft. They are focused on indoor air cleanup but produce a high-CO_2 concentration product.[26,27]
- Infinitree offers a DAC product based on MSA technology (derived from technology developed at the Center for Negative Emissions at Arizona State University) and is focused on the greenhouse market. They do not appear to have any currently operational installations.

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Chapter 3

Advantages of Direct Air Capture

Because direct air capture (DAC) starts with CO_2 capture from the air in any location, it can play two fundamental roles that other carbon dioxide removal technologies cannot. It serves as a backstop technology for managing climate change and provides CO_2 as a feedstock for CO_2 utilization (CO2U) applications. Relative to other CDR approaches, DAC has notable strengths and weaknesses. The strengths include:

- The cumulative removal potential of DAC is very large in relation to other CDR pathways.[1] These removals can be largely permanent (where CO_2 is geologically stored or mineralized).
- The land area requirements for DAC are very small relative to those for other pathways (unless the energy for DAC comes from land-intensive energy sources, such as solar). For example, 12 $GtCO_2$ per year of CDR through BECCS would require between 380 and 700 million hectares of land for cultivation of dedicated energy crops[2]—an area equivalent to at least half the land area of Australia. Moreover, unlike the production of bioenergy crops for BECCS (or biochar), DAC can be sited on unproductive lands.
- Water requirements for DAC are far lower than pathways that harness bioenergy crops for carbon removal. For example, BECCS requires around 600 m^3 of water for each metric ton of CO_2 removed—largely due to biomass cultivation—while evaporative losses from DAC are likely less than 25 m^3/tCO_2. Some DAC approaches produce fresh water as a by-product of operation, as will be discussed later.
- DAC has no direct impacts on nutrient cycling and requires no application of additional nutrients (such as nitrogen or phosphorous fertilizers) in contrast to biomass crop-based pathways,[3] ocean fertilization and enhanced weathering.
- Large annual rates of CO_2 removal by DAC could be sustained for centuries at the global level, as the geological reservoirs that serve as the sinks for captured CO_2 are very large.[4] This contrasts with many natural pathways, whose removal rates decline over time (even if the carbon that has been removed remains permanently sequestered).
- DAC can be sited in a very large number of locations. The facilities could be sited near high energy resources and geologic storage potential (e.g., the Middle East, U.S. Midwest or offshore) and need not be close to population centers or sources of emissions. Moreover, the small footprint of DAC facilities themselves and similarities to existing industrial processes mean that they could often be constructed and operated at industrial facilities under existing local land-use regulations.
- DAC has several technological advantages over flue-gas capture. First, DAC does not require the ability to operate in the presence of high levels of contaminants (particularly SO_2, NOx and mercury), which are present in some flue gas and can degrade sorbent materials. Second, while flue gas capture systems are usually designed for nearly complete capture of CO_2 (because the gas only passes once through the system before being released to the atmosphere), DAC systems need not necessarily achieve near-complete CO_2 removal in a single pass of gas through the system. In fact, some DAC systems are intentionally designed to capture only a small fraction of CO_2 with each pass of ambient

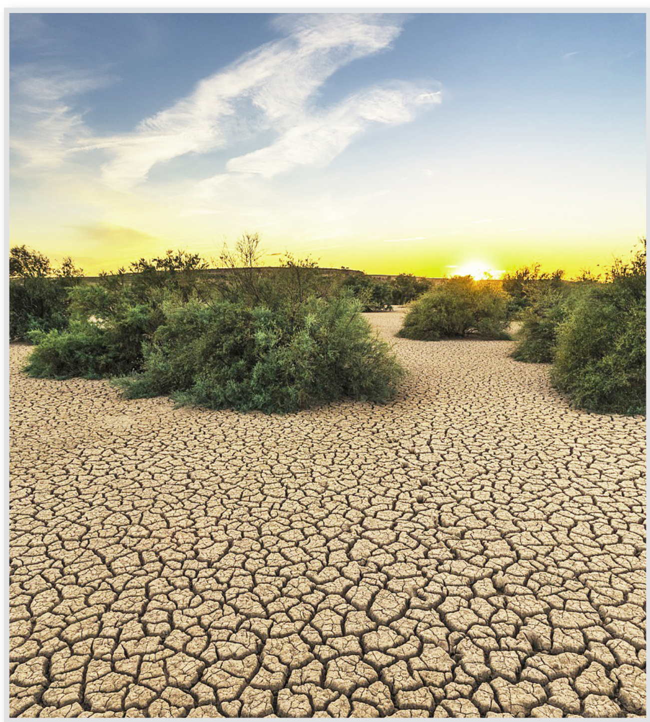

Figure 3-1. *DAC facilities can be sited on unproductive lands, avoiding competiton with food and energy crop production.*

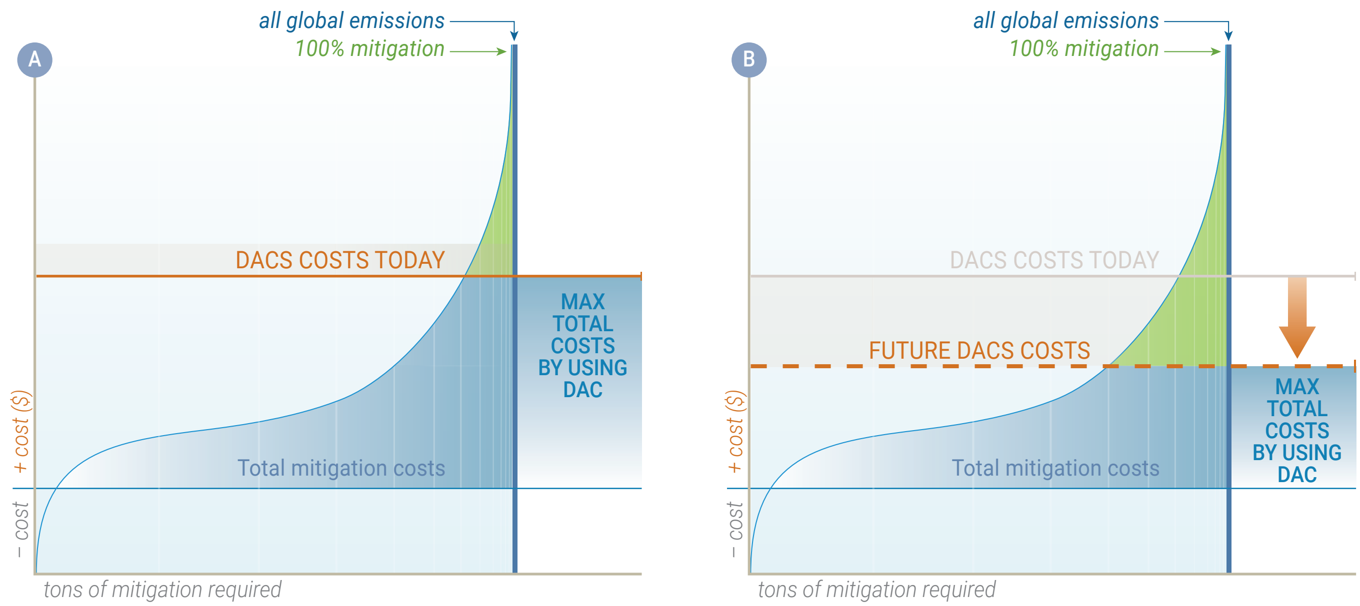

Figure 3-2. *Conceptual cost curves for total climate mitigation with DAC as a backstop technology option.*

air through the system (known as "skimming"). This reduces the energy requirement and may be particularly appropriate for some CO_2 utilization applications that require low-purity CO_2.

- Measuring the CO_2 benefits from DAC is relatively simple, especially compared to many of the natural pathways for CO_2 removal. The mass of CO_2 removed from the atmosphere by DAC can be directly measured, as can any emissions or energy consumption, at the facility level. Where the removed CO_2 is geologically stored, accounting for net removals is also relatively simple, provided adequate monitoring is in place to assess any leakage.[5] This stands in contrast to natural pathways where avoiding reversals may require permanent changes to patterns of land use and sustained effort to manage carbon stocks (e.g., forest management).
- No international agreements are needed to scale up DAC. (Such agreements could be essential for large-scale implementation of ocean-based CDR strategies.)

These facts create an important setting for DAC—solving climate change should never be more expensive than DAC plus sequestration costs (DACS).[6] **Figure 3-2a** shows that the total cost for 100% decarbonization of the economy is the area under the climate mitigation cost curve. The mitigation curve begins with negative costs (revenues) because many efficiency measures save money or avoid costs. The costs grow as more of the system is decarbonized. When that curve intersects the present costs of DAC, it is then possible to fully decarbonize at that price.

The green "wedge" represents costs avoided by choosing DAC above a different, more expensive option (e.g., decarbonizing aviation). The current estimate of the size of that wedge, based on the integrated assessment models of the IPCC, is in the tens of trillions of dollars to achieve 2°C (3.6°F) stabilization by 2100.[7] The DACS price point also sets the maximum cost for CO_2 climate stabilization, with the rate at which stabilization can be achieved set by the amount invested in DACS beyond mitigation of total global emissions. Similarly, every increment of cost reduction associated with innovation and deployment of DACS drops the total costs for climate mitigation and the total costs for climate restoration (**Figure 3-2b**). This is a strong case for investment in DAC innovation and deployment today, creating optionality for climate management.

DAC can also provide CO_2 as a feedstock for carbon-to-products enterprises.[8] Since the cost of capture from many industrial CO_2 sources (e.g., ethanol, ammonia and hydrogen production) is lower than for DAC,[9] there is an obvious tradeoff: the high price of DAC-sourced CO_2 competes with the benefit it provides of a reliable, continuous source that can be delivered anywhere (i.e., independent of pipelines and trucks). While CO_2 supplied from a stationary (point) source is almost certain to have a lower initial cost, the transportation infrastructure to deliver it may be absent or expensive (for example, using trucking). DAC could supply any location anywhere, albeit at higher initial cost per ton of CO_2.

Use of CO_2 drawn from the air also offers the potential for truly carbon-neutral or carbon-negative products, while CO_2 captured from fossil fuel sources can—at best—reduce emissions. It is also possible that CO_2 drawn from the air will be favored by customers who wish to avoid direct use of fossil CO_2. As carbon dioxide utilization (CO2U) technology improves and demand grows for CO_2-based products, the market may place additional value on products with a negative CO_2 emission footprint. In that context, DAC might provide an additional benefit by meeting customer demand for CO_2 sourced from the air.

Some DAC pathways remove substantial amounts of water from the air, which is produced as fresh-water vacuum distillate when CO_2 is recovered. This is particularly true for current sorbent systems, which capture between one and two tons of water for every ton of CO_2 removed. While this has an impact on system-wide cost and performance (see Chapter 5), in water-scarce regions this may prove to be a very attractive co-benefit of DAC.

Currently there are few if any viable approaches for deep decarbonization of some parts of the transportation and agricultural sectors (e.g., airplanes and N_2O emissions from fertilizer). Low-cost viable pathways may emerge, but that is uncertain.[10] DAC provides a certain and secure pathway for deep decarbonization of these parts of the economy. This underscores the potential role of DAC as a “backstop” technology option—it is not a license to continue emissions but rather a strategy to deal with difficult or expensive emissions proactively and overtly.

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Chapter 4

Challenges Facing Direct Air Capture

DAC is currently expensive. Today, DAC costs range from \$300-600/tCO_2, with estimates for future Nth-of-a-kind costs in the range of \$60-250/tCO_2.[1] DAC is generally considered to be among the more expensive CDR pathways.[2] Since these costs are well above today's carbon market prices, DAC will likely need policies for market entry and deployment (see below, Chapter 6).

DAC's high costs reflect the fact that CO_2 is much more dilute in the atmosphere than flue gas. The concentration of CO_2 in the atmosphere is roughly 0.04%, compared to 5% in natural gas-fired flue gas and 12% in coal-fired flue gas. As a result, the theoretical minimum energy needed to separate CO_2 from other gases is approximately three times larger for ambient air than coal-fired flue gas.[3] This minimum energy calculation and others based on real-world performance[4] have suggested to some that DAC could never be a practical mitigation technology, particularly in comparison to flue-gas capture.

These challenges and possible strategies for addressing them were recognized in the early literature on DAC.[5,6] An important study conducted by the American Physical Society[7] attempted to parameterize DAC systems using extant technology and energy costs. More recent studies have explored strategies for cost reduction in greater detail.[8]

Other notable drawbacks for DAC (relative to other CDR pathways) include:

- Most CDR pathways offer benefits besides CO_2 removal. Many natural pathways could help achieve additional global sustainability goals, such as improving biodiversity, reducing runoff, improving agricultural practices and offering a means to adapt to climate change. Other technological and hybrid pathways, such as enhanced weathering, BECCS and BEBCS, generate valuable products, such as electricity, hydrogen and fuels. Coupled with geological storage in saline aquifers, DAC provides no co-benefits (other than some degree of water production as discussed above), although it could be incorporated into a system where it provides CO_2 as a feedstock for CO_2 utilization.[9]
- DAC is a relatively large consumer of energy per ton of CO_2 removed. Thus, large-scale deployment of DAC requires an external energy source, such as fossil fuels (only when their use is integrated with DAC and their emissions captured and used or stored), nuclear energy or renewable resources (e.g., solar, wind, renewable heat, etc.). There is an opportunity cost associated with dedicating carbon-free energy to use for DAC rather than to displacing use of fossil-energy (without CCS). Conversely, DAC could be coupled with bioenergy CCS systems to remove CO_2 both directly and indirectly.

The potential of DAC to contribute to limiting CO_2 concentrations in the atmosphere depends on several factors, the most important of which are the carbon intensity of the energy source and the fate of the removed CO_2. An ideal DAC system, optimized for climate impact, would use near zero-carbon energy and sequester removed CO_2 in a saline aquifer. In this case the net removal would be nearly the same as the gross removal (with minor adjustments for emissions associated with constructing the system).

By contrast, a DAC system that maximizes economic value could be substantially different. If it used low-cost natural gas (with capture and storage) as the energy

Figure 3-1. *DAC requires more energy per ton than flue-gas capture, because CO_2 is more dilute in the atmosphere than in flue gas.*

source and produced liquid transportation fuel with the removed CO_2 as feedstock, the net removal could be extremely small or even increase absolute CO_2 emissions.

Given that various policies (e.g., the California Low Carbon Fuel Standard) and consumer preferences may create value for CO_2 as a feedstock, the latter case may be important in the near-term as a driver for innovation and technology scale-up. However, the climate need for DAC is ultimately predicated on the permanent removal of CO_2 from the atmosphere, implying that it must be geologically sequestered or mineralized.

A related question concerns the energy requirements for DAC. To serve a useful climate function, DAC must operate with sources of heat and power that are effectively zero-carbon. While this may be most easily accomplished using renewable energy, there could be alternative approaches using fossil energy under certain circumstances (see discussion in Chapter 5). The costs, footprint and operating requirements vary substantially based on different assumptions about the energy source. Since DAC is not well represented in today's general equilibrium models, there is little scholarly economic analysis to inform such questions.

Separately, some scholars and environmentalists are concerned that the availability of DAC and other CDR approaches may disincentivize or displace mitigation—sometimes referred to as "moral hazard."[10] Some have argued that the availability of CDR might lead to rebound phenomena, reducing incentives to cut CO_2 emissions.[11]

Potential technological pathways for reducing DAC costs and addressing other challenges in scaling up DAC are discussed in Chapter 5.

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11 Morrow DR. 2014 Ethical aspects of the mitigation obstruction argument against climate engineering research. Phil. Trans. R. Soc. A 372: 20140062. http://dx.doi.org/10.1098/rsta.2014.0062.

Chapter 5

Direct Air Capture Technology Pathways

In order to be successful, DAC technology will need to simultaneously achieve low total costs (including both capital and operating costs) and high amounts of net (lifecycle) CO_2 removal. These two goals interact in complex ways and involve tradeoffs that must be carefully examined. This chapter will explore the possible technology pathways to achieve these goals and the constraints they place on DAC design options.

A. Reducing Energy Consumption

As noted in the previous chapter, removing CO_2 from the atmosphere takes more energy than removing it from a flue gas stream because it is more dilute. Most of the DAC designs that have been proposed to date therefore consume a significant amount of energy per ton of CO_2 removed. This energy is the primary contribution to the operating costs of DAC facilities. Unless this energy comes from low-carbon sources, DAC cannot result in net-negative emissions.

Technology pathways to reduce the energy consumption of DAC are therefore a high priority. It is important to note that this energy is mostly in the form of heat; as outlined in **Table 1,** most DAC designs require four to eight times more heat energy than electrical energy. This heat is used to regenerate sorbents or solvents after they are saturated with CO_2. This means the most important goal for reducing energy consumption is identifying or developing sorbent and/or solvent materials that require less energy for regeneration.

This regeneration energy is directly related to how tightly the sorbent/solvent binds CO_2 (which is determined by the enthalpy of the sorbent-CO_2 reaction). This suggests that sorbents that bind CO_2 only weakly are preferable since they require less energy to reverse that reaction and drive off the CO_2 during regeneration.[1] However, no sorbent is perfectly selective for the CO_2 molecule. Other molecules, particularly water, can also bind to the sorbent material, reducing the total amount of CO_2 that can be removed per mass of sorbent. In the case of ambient air, the very low concentration of CO_2 makes this problem particularly severe. Unfortunately, overcoming it generally requires using a sorbent that binds very tightly to CO_2 and weakly to other molecules. Therefore, there is an innate tradeoff between reducing the energy required for regenerating the sorbent and preferentially absorbing CO_2 over other molecules.

Improved sorbent materials are needed that can appropriately balance this tension based on a larger system design. If energy is available at low cost (and with low CO_2 emissions), then sorbent materials with high selectivity for CO_2 would likely be optimal, increasing the amount of CO_2 removal per mass of sorbent. If this is not the case, then sorbent materials with weaker binding to CO_2 would likely be necessary, at the cost of requiring more sorbent per unit of CO_2 removed.

A further consideration is the speed of reaction (kinetics) of the sorbent. This impacts the rate at which CO_2 can be removed from air passing through the system, and thus the size of the air contactor required for a given removal capacity. Sorbents with fast kinetics are therefore desirable.

For liquid-solvent-based systems, another consideration is the heat capacity of the liquid. It may be possible to further reduce heat energy requirements by using a non-aqueous liquid with a lower heat capacity or improving the heat recovery from the liquid during regeneration.

Table 1: *Energy consumption for major DAC systems as reported. Heat:Power ratios are converted on a raw-energy basis.*

Company	Thermal energy/ tCO_2 (GJ)	Power/ tCO_2 (kWh)	Heat: Power ratio	Reference
Climeworks	9.0	450	5.6	Ishimoto 2017
Carbon Engineering	5.3	366	4.0	Keith 2018
Global Thermostat	4.4	160	7.6	Ishimoto 2017
APS 2011 NaOH case	6.1	194	8.7	APS 2011

However, any negative impacts on viscosity, solubility or other factors would have to be considered in order to identify the overall energy benefits of alternative liquids.

B. Providing Low-Carbon Heat Energy

Given the key role that heat plays in DAC systems, it will be important to carefully examine options for providing low-carbon heat energy. These options depend on the quality (temperature) that is required. Some DAC designs (primarily those using amine sorbents) require relatively low-quality heat (90-120°C), while others (primarily those using hydroxide-based solvents) require higher-quality heat (500-1000°C). Although many government research, development and demonstration (RD&D) programs around the world include some attention to aspects of renewable heat, these are limited and do not focus on specific applications to DAC systems.

Nuclear fission: Conventional nuclear reactors generate high fluxes of zero-carbon heat at medium quality (approximately 320°C), which is used to produce steam for a Rankine cycle to generate power. This heat is mostly too low quality to be useful for DAC systems using hydroxide-based solvents and is of significantly higher quality than the minimum needed for amine-based DAC systems. Ignoring any regulatory or economic hurdles, conventional reactors therefore may be suitable for supplying heat to sorbent-based DAC systems but appear to be poorly suited for supplying heat for hydroxide solvent-based DAC systems.

However, new reactor designs, particularly those being developed for use as small modular reactors (SMRs), may be far more suitable. These reactors could be designed to deliver heat at the appropriate quality for hydroxide-based solvent DAC. They could also be built at much smaller scale than conventional reactors, whose average thermal capacity is approximately 3.5 GW, likely much larger than a single DAC facility could utilize. Adding to their appeal, small modular reactor designs could potentially be deployed in many geographies, providing local, scale-appropriate, high-capacity heat (and power) for DAC. While this class of reactor has not yet been deployed widely, it appears to have cleared some important regulatory hurdles in the United States and may begin entering service soon.[2] Research on system design, costs, integration needs and lifecycle would help resolve key questions regarding DAC applicability.

It is also worth noting that radioisotope thermoelectric generators (RTGs) used by spacecraft operate at approximately 1000°C, illustrating the engineering viability of using nuclear fission to deliver zero-carbon high-quality heat.[3] Unfortunately, these systems appear to be too small-scale to be material for DAC.

Hydrogen combustion: Because hydrogen burns with a very high temperature (1900-2600°C), renewably-sourced hydrogen remains a potential source for low-carbon heat that would be of high enough quality for all DAC applications. This hydrogen could be derived from conventional hydrolysis using renewable power (e.g., wind and solar) or from conversion of renewable feedstocks (e.g., biomass gasification). Advances in electrolyzers and biomass gasifiers would help reduce costs and improve performance of renewable hydrogen, and substantial RD&D programs exist today on these topics. Naturally, the challenges that apply to hydrogen systems generally (e.g., pipeline infrastructure, storage systems) would likely apply to DAC configurations that use hydrogen-derived heat. Today, systems to produce renewable hydrogen are expensive (\$5-10/kg H_2), although there are promising approaches to cost reduction.[4]

An alternative to renewable hydrogen is production of fossil hydrogen combined with CCS. Most commonly, fossil-derived hydrogen comes from natural gas reformation, although some countries (notably China) produce industrial hydrogen supplies from coal gasification. These systems commonly produce a highly concentrated stream of byproduct CO_2. Four sites in the world today capture and store CO_2 from industrial hydrogen production – Quest, Port Arthur, Al Reyadah and Uthmaniyah.[5] Current costs for hydrogen production with CCS provide delivered all-in costs of \$1.6/kg H_2 with 60% reduction of CO_2 compared to conventional steam reforming systems. Importantly, current estimates to achieve 90% H_2 decarbonization estimate delivery at ~\$2.5/kg H_2,[6,7] substantially less than the cost of renewable hydrogen. While this appears to be a cost-competitive approach to low-carbon hydrogen production for heat, lifecycle analyses, including the upstream emissions associated with natural gas or coal production, must be incorporated to fully understand the viability and limitations of this approach.

Fossil fuel combustion with CCS: Fossil combustion provides the significant majority of process heat in the world today.[8] When combined with CCS, this can provide low-carbon heat that could potentially be used for DAC. Notably, one DAC company (Carbon Engineering) uses this approach, combining oxygen-fired natural-gas combustion with carbon capture as one of its central design options (delivering CO_2 that is a mixture of the combustion product and gas removed from the atmosphere). The costs and viability of these systems vary substantially from system to system, based on the fuel (e.g., coal, gas, pet-coke), combustion method, combustion system design, geography, labor cost, capture system and other constraints. Full lifecycle analyses and application-specific techno-economic analysis and designs would help clarify the economic and emissions aspects of this method of providing heat energy. It may be that this approach has special value in particular locations, such as countries with stranded fossil energy assets (e.g., Chad or Indonesia).

Solar thermal energy: Geographic regions with excellent solar energy resources may be able to take advantage of concentrating solar energy to create low-carbon heat. Today, commercial systems focus on concentrated solar power (CSP), which uses the solar heat resource to produce steam for a Rankine cycle to generate power. These systems are relatively expensive compared to solar PV systems, but they may have an advantage in direct heat applications like DAC. Designs based on parabolic troughs operate at temperatures of 400°C and above, while those using power tower technology operate in excess of 500°C.[9] Even higher temperatures are possible with dish-engine technology.

Heat of this high quality may be useful for some solvent-based DAC systems. For amine-based DAC systems, lower quality heat is sufficient, and it may be possible to use emerging medium-temperature solar thermal technologies, such as Scheffler reflectors and Fresnel dishes.[10] Conventional rooftop solar thermal systems, such as those used to provide domestic hot water, are generally limited to temperatures that are significantly lower than CSP but still relevant to amine-based DAC systems. They may also be a source of pre-treatment to reduce the overall heat requirements.

Geothermal heat: In locations with favorable geology, geothermal systems can provide a significant amount of low-carbon heat. Most natural geothermal heat resources are geographically restricted and are relatively capital-intensive to exploit. However, where geothermal energy is available, it is likely to prove a very robust, low-cost, high-capacity approach to providing heat. Notably, the only full DACS (DAC with sequestration) system in the world (the Climeworks facility in Iceland) uses both geothermal power and geothermal heat for operation. The ability of DAC to be deployed in many geographies could create a market for stranded geothermal resources (e.g., the Afar triangle in Ethiopia and La Réunion Island). Additionally, there may be synergies between geothermal power production and CO_2 sequestration, such as CO_2 plume geothermal (CPG) power production.[11] These options are largely unexplored and unassessed.

Renewable electricity: Electricity-based heating technologies are used in a variety of industrial process heat applications. When supplied with renewable electricity (such as from wind or solar), this is a form of low-carbon heat and can leverage the rapid growth of renewable power generation, as well as scale rapidly.

The simplest of these (with the lowest capital cost) is using renewable electricity for resistive heating. Efficiencies can reach close to 100% for some materials, and temperatures can exceed 600°C for convection-based approaches, although it may be challenging to design systems that heat complex structures, such as air contactors, evenly.[12]

Heat pumps: Pumps based on the vapor-compression cycle can provide process heat up to approximately 100°C, using heat sources at significantly lower temperatures.[13] These systems are commonly used in commercial industrial processes and can achieve high electrical-to-thermal efficiencies (up to approximately 300%) by using waste heat or ambient air heat. Notably, high-temperature air-source heat pumps that can reach 80°C are now commercially available, potentially providing a source of low-carbon heat for amine-based DAC systems using only air as the heat source. However, it is important to note that the working fluids for heat pumps are often themselves highly potent greenhouse gases (such as hydrofluorocarbons, or HFCs), and any leakage of these fluids could significantly reduce the overall climate benefit of the system. Alternatives such as HFO- or ammonia-based working fluids may mitigate this concern.

Microwave heating systems: Microwave systems can provide industrial process heat for a number of applications, including drying grain and lumber in the agricultural sector and drying powered materials in pharmaceutical manufacturing.[14] They are generally most appropriate for non-electrically conducting materials, which is the case for DAC sorbents. Since microwave energy can penetrate many materials, it can provide more even heating throughout a volume than applying heat only at a surface; this may be relevant for DAC designs that use liquid sorbents. Related techniques include radio-frequency heating and induction heating, both of which are also fully commercialized and used industrially.[15]

Waste heat: Heat that is rejected to the environment as a byproduct of industrial activity is a good candidate for use by DAC facilities. Generally, waste heat is considered low-carbon, since it was not otherwise being utilized. A very large amount of waste heat is theoretically available; for example, there were approximately 25 quads of waste heat in the U.S. electricity generation sector in 2017.[16] A significant fraction of this is rejected at the steam cycle condenser at a temperature of roughly 40°C, which is not directly useful for DAC. However, this may leave a substantial amount available at an appropriate temperature for amine-based DAC. Industrial processes, such as refining, cement production and aluminum smelting, also generate large amounts of waste heat in the United States—as much as 13 quads in 2017.

It is therefore no coincidence that two of the leading DAC companies (Climeworks and Global Thermostat) use waste heat for regenerating their sorbents. Per Table 1 above, these processes consume approximately 7 GJ of heat energy (plus a significantly smaller amount of electricity) per ton of CO_2 removed, suggesting that 1 quad of waste heat (at appropriate quality) could supply the thermal energy required to operate DAC facilities with a capacity of 150 $MtCO_2$/year. While electrical energy would still be required and there would be increased capital costs from heat-exchanger surfaces, the scale of waste heat in terms of its potential for DAC is clearly very large.

Although the recent National Academies report investigates some sources of low-carbon heat in their cost assessment, this work represents early consideration of current system designs, cost and approaches. Substantial additional work is required as part of a DAC development pathway that is both low-cost and low-carbon footprint.[17]

C. Utilizing Intermittent Renewable Electricity

The increasing penetration of renewable electricity on many grids has led to curtailment, which is considered "excess" or "unusable" electricity. Some analysts consider this an opportunity for DAC, because this otherwise-wasted zero-carbon electricity could potentially be used to power DAC plants. This conclusion appears to be strengthened by the fact that DAC facilities have significant flexibility in their location and could thus potentially be sited in areas with large amounts of curtailed renewable electricity (see below).[18,19]

However, curtailed electricity is intermittent and not easy to predict on short timescales (seasonal curtailment is generally more predictable).[20] This implies that DAC facilities using intermittent curtailed renewable electricity would either have to ramp up and down in operation during the day or draw on other power sources—presumably grid-supplied—to operate continuously. From a capital-utilization viewpoint, intermittent operation reduces the overall capacity of a facility to remove CO_2, thus increasing the capital required to build a plant achieving a given average removal rate. Also, ramping up and down the operation of DAC would likely introduce additional wear and tear on components that would increase O&M costs.

It may be possible to develop DAC plants with either operational strategies or hardware additions to better match an intermittent power supply. Operationally, this could include strategies where the regeneration of the sorbent is scheduled for times that best match the availability of curtailed power, if that can be coarsely predicted (such as day-night variation). Alternatively, additional equipment to provide electrical energy storage (such as batteries) or thermal energy storage (such as phase-change materials) could be used to smooth the delivery of energy to the DAC facility and buffer energy-supply variability, although this would increase the capital cost of the facility.

However, curtailment of renewable electricity appears to be a phenomenon that decreases over time, as transmission lines are built to access stranded power and grid operators become more adept at integrating variable supplies.[21] Therefore, this apparent "wasted" resource may not be available to a DAC facility permanently, undermining the engineering and economic logic of siting the facility near locations with high amounts of curtailment. A better understanding of the status and causes of curtailed renewables is needed before pursuing any large-scale strategy of using this energy source for DAC.

D. Reducing Capital Costs Through Air Contactor Design

In addition to the energy considerations for the sorbent/solvent material discussed above, the rate of the CO_2 binding reaction is another important constraint. If this rate is slow, then building a system that achieves a benchmark capacity of a certain number of tons of CO_2 removed per day would require a much larger area for air-sorbent/solvent contact. Conversely, if the binding reaction rate is fast, this area can be reduced. A larger contact area results directly in increased capital costs for a DAC plant, suggesting that a fast reaction is very desirable.[22] The design of an efficient air contactor must therefore be based on the choice of sorbent/solvent, as well as on its form (solid or liquid).

The geometry and blowing/pumping strategy will determine the efficiency with which air contacts the sorbent/solvent material, the time over which this occurs and the energy required, and thus should be a central focus of design attention. Additionally, while liquid sorbents can be pumped away from the air contactor to a separate location for regeneration, solid sorbents must generally be regenerated in situ, which implies certain design constraints for the air contactor and may also reduce the fraction of time during which it can remove CO_2. The structural materials choice for the air contactor is also an important determinant of capital cost, since this is by far the largest physical component of the overall facility; as noted earlier, some designs appear to offer significant cost savings by using plastic structural materials in place of steel.

Some loss of sorbent/solvent material to passing air is inevitable in any real-world design, and this must be taken into consideration for understanding both operations and maintenance (O&M) costs (for replacement) and environmental impacts (for downwind areas). This issue is of particular concern for caustic sorbents that can become entrained in passing air and are dangerous when inhaled.[23] While initial reports from one company (Carbon Engineering) indicate this entrainment is low for their air contactor design, it will require more testing to validate a variety of designs.

E. Identifying Optimal Locations for DAC

Since DAC uses the atmosphere as the source gas for CO_2 removal, it can in principle be located anywhere on the Earth's surface. However, there are many practical considerations that limit this, and identifying the optimal locations for DAC facilities will be important for reducing their costs and increasing their lifecycle CO_2 removal total. These can be expressed as a series of tradeoffs or as coefficients favoring or discounting sites. The primary considerations are:

- The availability of low-carbon heat and power—particularly waste heat as discussed above—is a high-priority consideration for siting. Waste heat must generally be immediately next to a DAC facility to be used, since it is difficult to transport, so this is the most restrictive factor. It also directly impacts the operating costs, since it reduces the energy that must be purchased. The availability of low-carbon power depends on the fuel mix of the local grid, while the availability of curtailed renewable power may depend on the topology of grid transmission lines. These are both looser constraints than waste heat. They also primarily impact the lifecycle CO_2 removal amount rather than the operating costs.
- CO2 offtake, transport or storage opportunities will be important in influencing the costs, or potential revenues, related to the fate of the removed CO_2. If there is an opportunity to sell the CO_2 (such as to greenhouses) or otherwise utilize it, being located near the point at which this happens will reduce transport costs. Similarly, if the CO_2 is to be sequestered, being located at the point of injection will keep these transport costs low. If the CO_2 does need to be transported, access to a pipeline network will be important.
- Favorable air conditions will help minimize operating costs. These include (1) low levels of moisture, which can lead to reduction of CO_2 adsorbed because of competition with water (unless there is a strong business case to produce and sell fresh water); (2) favorable air temperature (to reduce the heat energy required to regenerate sorbents); and (3) favorable winds (to reduce fan power consumption). These factors will have different impacts on the performance and costs of a DAC facility depending on many aspects of the system design, so these generalizations may not hold under all conditions.

There has been very little research on this issue, and it would be valuable to examine the tradeoffs in greater detail for different DAC technologies and related assumptions.

F. Demonstrating Geological Carbon Storage at Scale

To achieve large volumes of atmospheric decarbonization, it is likely that most DAC facilities would be paired with disposal and storage of CO_2 in deep geological formations, usually called geological carbon storage or GCS. There is a substantial scholarship on GCS, and today nearly 20 large-scale facilities capture, store and monitor anthropogenic CO_2.[24]

If DAC is deployed at the gigaton scale for CO_2 removal, it will likely require thousands of large GCS facilities, and limits on the large-scale viability of GCS would limit DAC.[25] This raises a set of technical, social, legal and policy questions. Some questions (e.g., public acceptance) are ameliorated by DAC's geographic flexibility, and other concerns (e.g., environmental impacts of leakage) have been addressed in existing literature, regulation and experience. Several questions remain in the DAC context and, if left unresolved, may limit DAC volumes and deployment.

Seismic risk: Although no operating CO_2 injection facility has generated large earthquakes, some large-scale injection projects have, mostly at geothermal or oil & gas brine-disposal wells. While many scholars see this risk as manageable, focus on avoiding potentially risky sites will be needed.[26]

Long-term site care: To gain climate benefit, captured and stored CO_2 must stay isolated from the atmosphere indefinitely. Technologies exist to manage and avoid operational risk, and liability stays with operators during injection. However, questions remain about how best to manage large GCS sites after operation. Some of these questions focus on technical questions of long-term monitoring. Others focus on maintaining liability for an appropriate length of time. Legal and policy scholarship on the appropriate structure and mechanisms have proposed many potential approaches that could serve as viable solutions.[27] Until conventional CCS scales up commercially and key questions are resolved, DAC will face these concerns.

G. Ensuring Net CO_2 Removal from DAC

Removing CO_2 from ambient air with DAC facilities may not result in a net reduction in CO_2 concentrations if the energy and materials requirements for removal are themselves very carbon-intensive. The most significant instance of this is energy consumption, as discussed previously. However, emissions associated with producing materials, such as sorbents and structural materials, and with supplying water could also play an important role in the net CO_2 balance of DAC systems.[28]

Similarly, if CO_2 that is removed from ambient air through DAC is used rather than sequestered, the utilization process may result in a lower net reduction of CO_2 concentrations or possibly in a net increase. Understanding this may be particularly challenging in situations in which the DAC facility producing CO_2 as a feedstock and the CO2U utilization process consuming that feedstock are operated separately or participate in a larger CO_2 production-consumption market mediated by a pipeline infrastructure.[29]

These concerns indicate that it will be extremely important to use Lifecycle Assessment (LCA) to assess and account for all sources of emissions in the overall DAC system (with associated utilization, if any). This can identify the relative emissions implications among alternative systems designs and help guide the development of targeted RD&D programs to improve net CO_2 reductions. A key consideration in this process is understanding the longevity of CO2U products and CO_2 storage locations since rapid return of CO_2 to the atmosphere may negate most of the benefits of DAC-based removal.

H. Roadmap: Key Focus Areas For RD&D to Advance Direct Air Capture

- Materials: Research is needed on the discovery, design, manufacture and functionalization of materials that capture CO_2 from the air. For sorbents, the key performance metrics are low regeneration energy, high CO_2 selectivity, fast reaction times and low degradation rates. For solvents, an additional key performance need is liquid solutions that have lower heat capacity than water and comparable or lower viscosity. RD&D programs should consider approaches that include high-throughput materials testing, computational materials discovery and a focus on earth-abundant, low-cost materials.

- Low-carbon heat: Research is needed on new and/or improved technologies to generate renewable and low-carbon heat. Both high-quality and low-quality heat can serve DAC systems. In many cases (e.g., existing nuclear fission plants, fossil plants with CCS), the most valuable area of focus is recovery and integration of low-carbon heat (potentially including waste heat). In others (e.g., concentrating solar power and renewable hydrogen), the focus should be on low-cost, low-carbon energy production. In all cases, research should focus on systems that can scale up and should include full lifecycle accounting. Because of the rapid cost reductions and increased deployment of renewable power, electricity-based technologies merit additional attention, including heat pumps with high lift and, potentially, microwave-based heating.
- Air contactors: Research is needed on improved materials and designs for large-scale air contact with sorbent- and solvent-type systems. These approaches should focus on increasing contact area, while minimizing pressure drop or the equivalent, to limit energy requirements for air movement. These systems should also minimize loss of sorbent/solvent material and may need improved heat integration and high thermal conductivity.
- Process designs: Research is needed on new and improved operational concepts for DAC, including optimizing heat integration for maximum heat recovery. A related focus should be on sorbent/solvent regeneration cycling concepts to maximize equipment usage intensity and minimize equipment degradation and material replacement requirements. For batch processes, there may be opportunities to take advantage of diurnal temperature swings. Further analysis is needed to understand the value of using intermittent sources of renewable energy (particularly those that are curtailed), and RD&D on process designs that are matched to this energy source may be needed. Process concepts beyond primarily temperature-swing sorption should be considered.
- Environmental impacts: Research is needed on improving the understanding of downwind impacts (such as entrainment of caustics), water consumption and other potential impacts.
- System analysis: Research is needed on system performance and economics, including better understanding of optimal location/siting, tradeoffs between water production and CO_2 removal, and the value of CO_2 production at different purity levels.

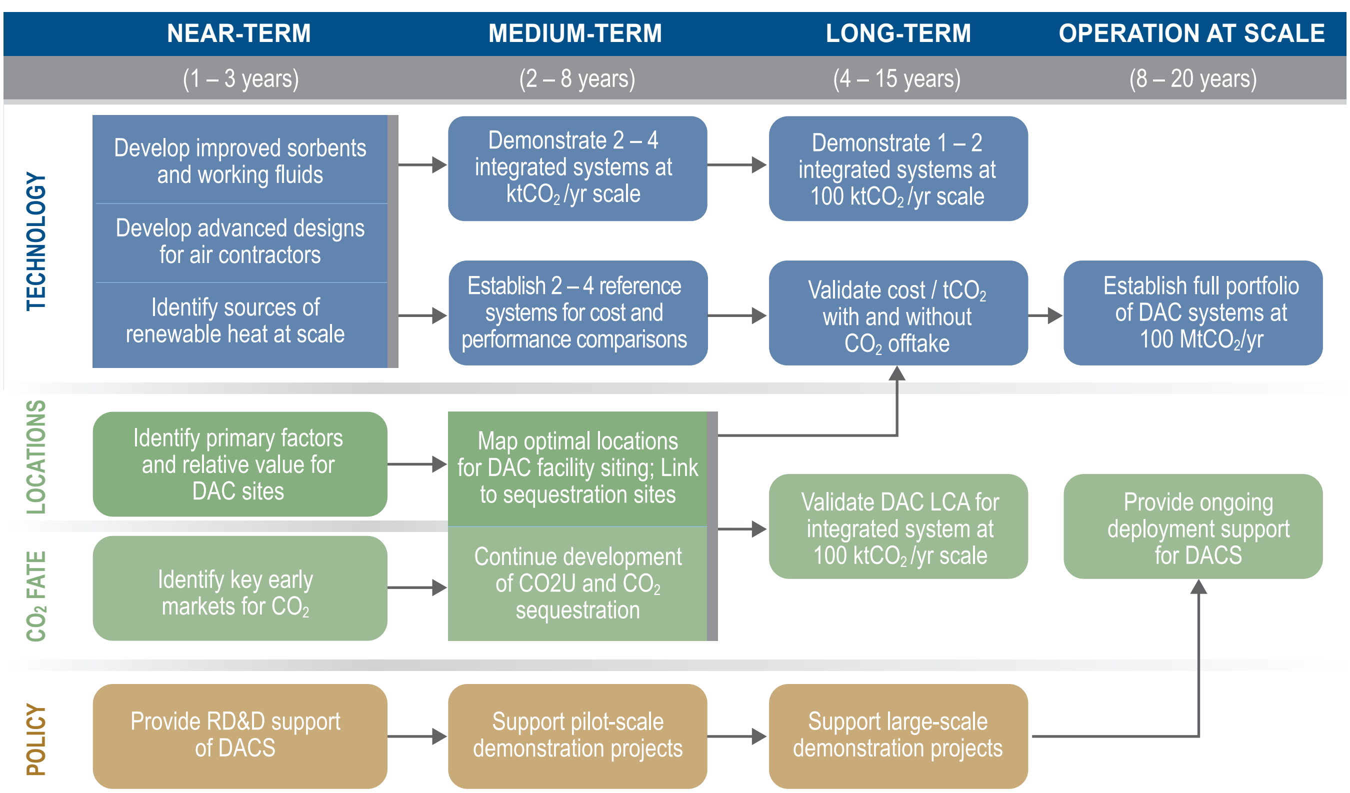

Figure 5-1. *Innovation Roadmap – Direct Air Capture.*

- **Synergistic CO2 utilization technologies:** Research is needed on CO_2 utilization approaches that are synergistic with DAC, particularly those that do not require pipeline transport and/or high purity.

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Chapter 6

Policy Considerations

Policy support will be central to development of DAC, both in the short- and long-term. This chapter discusses the rationale for policy support and range of policy tools available.

A. Rationale

Carbon Dioxide Removal

The concentration of carbon dioxide in the atmosphere is now higher than at any time in human history. Human activities including fossil fuel combustion and deforestation continue to increase that concentration. The impacts include devastating heat waves, more severe and frequent storms, sea level rise, forest loss and ocean acidification.[1]

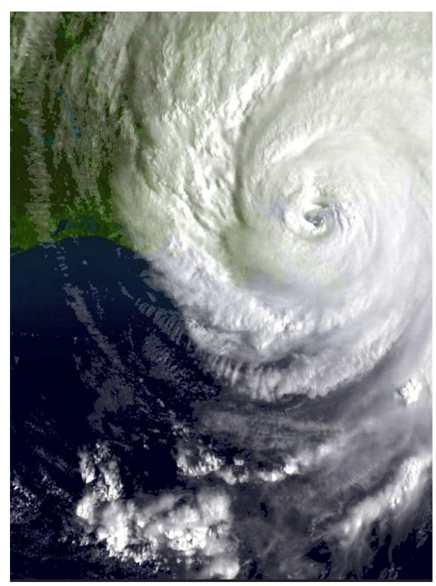
Reflecting this situation, more than 175 countries have ratified the Paris Agreement, which calls for "[h]olding the increase in the global average temperature to well below 2°C (3.6°F) above pre-industrial levels" and achieving net zero emissions in the second half of this century.[2]

The problems that arise from high levels of CO_2 in the atmosphere are classic "externalities," to use the language of economics. Market forces alone will not control carbon dioxide emissions adequately, since CO_2 emitters do not bear the full costs of their emissions. Government policies are essential to provide solutions to these problems.[3]

Meeting the goal of limiting temperature increases requires that cumulative emissions from human activities remain within the "below 2°C budget." Carbon removal technologies are an important part of the toolkit for achieving this. While reducing emissions of carbon dioxide and other greenhouse gases is a priority in the short-term, the Intergovernmental Panel on Climate Change and others have found that emissions reductions alone are unlikely to be sufficient. Removing carbon dioxide from the atmosphere is very likely to be essential to achieving the goals set forth in the Paris Agreement.[4]

Direct Air Capture

The set of policies that may be relevant to CDR technologies is quite broad, and the appropriate policy mix is different for each CDR method. In DAC's case, the early stage of the technology means that government policies should include support for RD&D. Private companies do not usually invest in the socially optimal level of early-stage RD&D (whether or not there are externalities involved), in part because they are unlikely to see returns within time frames important to most corporate managers. This further emphasizes the need for government support of DAC RD&D.[5]



Many climate-relevant technologies enter the market as competitors with well-established conventional technologies. Prominent examples of this include electric vehicles (which compete with ICE vehicles), renewable electricity generation (which competes with fossil and nuclear generation), biofuel (which competes with gasoline and diesel) and LEDs (which compete with incandescent, fluorescent and halogen lighting). In each case, the new technology provides an equivalent energy service to the entrenched conventional technology. This means that customers—individuals, companies, and governments—will generally consider buying and installing the new technology only in the context of the existing market for the conventional one.

This form of market entry implies clear cost targets that these technologies must achieve in order to deploy widely without subsidies. While these technologies are almost always more expensive than their conventional counterparts when they first enter the market, RD&D and learning-by-doing can reduce their costs significantly.[6] If these costs fall to the point that they are equal to or less than their conventional counterparts, market forces will generally ensure that they will be adopted. (There are additional considerations, such as compatibility with technical standards, regulatory barriers, customer awareness and interoperability, that must also be considered, but these are usually less important than cost.)

DAC will follow a fundamentally different pattern, since it does not directly compete with established technologies: there is no conventional market for technologies to remove CO_2 from ambient air at scale. Therefore, it is not clear what cost target would be relevant for DAC to achieve market success. In limited instances, DAC may compete with conventional sources of CO_2, such as geological deposits or co-production with ammonia.[7] However, since the overall CO_2 market is relatively small and the end-point costs are often dominated by delivery costs (as in the case of greenhouses), this does not serve to establish a generally applicable cost target.

This situation implies that policy drivers will be required to scale DAC in a way that is significantly different than many climate-relevant technologies developed to date. These drivers may require a very different structure than policy tools for other climate technologies and may need to be sustained for a relatively long period of time.

Some have questioned whether scarce government resources should be devoted to development of DAC technologies, when those resources could be used for other purposes.[8] The authors of this report believe no potential pathway for reducing the threat of climate change should be ignored. While recognizing that private and governmental capital resources are finite, achieving a 2°C (3.6°F) or 1.5°C (2.7°F) stabilization seems impossible without a wider range of credible, actionable options. Investment and support for innovation is essential to create those options. DAC offers a potentially important set of tools for mitigating and ultimately reversing climate change. Current policy support for DAC is exceedingly modest and could be increased by a factor of 10 or more without meaningfully competing with support for other technologies. Especially given the long lead times required to scale DAC technologies, devoting resources to the development and deployment of those technologies is strongly in the public interest.[9]

B. Policy Tools

Very few policies around the world today specifically target DAC for support. The most significant such policy is probably in the United States, where a law enacted in early 2018 provides a tax credit for direct air capture of carbon dioxide. Some governments invest small amounts in RD&D for DAC. Low carbon fuel standards in California, the European Union and several other jurisdictions provide incentives for DAC.

Supportive policies will be essential for DAC to scale in the decades ahead. Potential policy tools are discussed below.

Government Support for RD&D

National governments spend roughly $15 billion annually on RD&D for clean energy technologies. These programs have played important roles in the development of countless technologies in recent decades.[10]

Government spending on RD&D for DAC is exceedingly modest. In 2015, the U.S. Department of Energy (DOE)'s ARPA-E program offered $3 million for RD&D on DAC. The Government of Alberta has provided grants to support DAC.[11] The U.K.'s Department of Business, Energy and Industrial Strategy supports carbon dioxide removal programs including DAC. Funds for these programs are a tiny percentage of overall government funding for clean energy RD&D.

An increase in funding for RD&D on DAC could speed deployment and yield important benefits. This roadmap identifies a number of priority areas for RD&D investment, including:

- improved sorbent materials,
- improved air contactor designs,
- improved sources of low carbon heat, and
- improved CO_2 utilization technologies

In December 2015, heads of state from more than 20 countries announced Mission Innovation, a coalition dedicated to accelerating clean energy innovation. Member governments (including Japan, China, the United Kingdom, Germany and Saudi Arabia) pledged to double RD&D on clean energy within five years. The increase in RD&D budgets from these countries in the next few years offers an opportunity to scale up government RD&D funding for direct air capture, including in the areas above.

The United States helped launch Mission Innovation and remains a member. Although the United States is unlikely to fulfill its overall doubling pledge under the Trump administration, in 2018 the U.S. Congress increased funding for clean energy programs at DOE by roughly 15% over the prior year.[12] DAC has won bipartisan support in the U.S. Congress and could be an area in which the government's RD&D spending increases in the years ahead.

Tax Incentives

Tax incentives can play an important role in helping spur development of clean energy products. In Norway, for example, generous tax incentives helped plug-in electric vehicles capture 39% of new car sales in 2017. Such incentives could play a similar role in promoting development and deployment of DAC.

Legislation providing a tax incentive for DAC was enacted in the United States in early 2018. Known as the FUTURE Act or "45Q" (for the provision of the U.S. Tax Code it amends), the law provides a tax credit of \$28-50/tCO_2 captured from the air and stored in saline aquifers. (The \$28 credit is available in 2018 and increases \$2-3 per year, reaching \$50 by 2026.) The law also provides a tax credit of \$17-35/tCO_2 captured from the air and used for enhanced oil recovery or converted into useable products. (The \$17 credit is available in 2018 and increases \$2-3 per year, reaching \$35 by 2026.) To qualify for the credit, facilities must capture a minimum of 100,000 tons of carbon dioxide per year.

This type of tax incentive could be a model for similar provisions in many other countries. Alternative or additional tax incentives could include tax-exempt debt financing (e.g., private activity bonds), an investment tax credit or bonus depreciation of capital assets, all of which have been proposed in the U.S. Congress.

Carbon Price

A price on carbon dioxide emissions, whether through an emissions trading program or tax mechanism, provides emitters with an important incentive to cut emissions. Carbon pricing programs are now in place in the European Union, Norway, California, nine States in the northeast United States, the Canadian provinces of British Columbia and Quebec, and seven Chinese provinces. The Chinese government is in the process of launching a nationwide emissions trading program for the power sector.

In the short-term, carbon prices are unlikely to approach the cost of DAC. The lowest cost for DAC envisioned with current technologies that has been publicly presented is \$94/tCO_2.[13] Only three countries—Sweden, Switzerland and Lichtenstein—currently have nominal carbon prices that exceed that amount. Most carbon prices are much lower (below \$25/tCO_2).[14] However, even a low carbon price can create incentives for DAC by contributing to project revenues. In addition, the prospect of a price on carbon may help incentivize private sector investments in research and development on DAC, if market participants expect the price to increase in the medium- to long-term.

A carbon price could provide significant incentives for direct air capture, if emitters receive credit for tons of CO_2 removed with DAC. Indeed, a carbon price is an important part of any long-term strategy for DAC. Although DAC can provide carbon dioxide for commercial purposes, it is unlikely to be the lowest-cost source for doing so, except perhaps in remote locations. A price on carbon emissions is likely to be a central part of the rationale for many, if not most, DAC facilities.

Low-Carbon Fuel Standard

A low-carbon fuel standard (LCFS) sets a limit on the carbon dioxide emissions of transportation fuels throughout their lifecycle. California, Oregon, British Columbia and the European Union (E.U.) have all enacted low-carbon fuel standards and the Canadian federal government is developing a national system.[15] California's LCFS requires producers of petroleum-based fuels to reduce the carbon intensity of their fuels 10% from 2010 levels by 2020 (state regulators are currently considering a 20% by 2030 requirement.) The E.U.'s Fuel Quality Directive requires reductions of 6% in the carbon intensity of fuels from 2010 levels by 2020.

Fuels made with carbon dioxide from DAC, all else being equal, have a lower carbon intensity than fuels made with carbon from fossil fuels. An LCFS therefore incentivizes DAC, providing a potential market for the carbon dioxide DAC produces. The more stringent the LCFS, the greater the incentive.[16] The California LCFS includes a process to gain credit through application of a lifecycle analysis under a regulated protocol. Similarly, existing fuel standards like the U.S. Renewable Fuel Standard or the European Renewable Diesel Standard could be expanded to account for fuels produced using DAC.

Finally, DAC can be interpreted to fall within the purview of fuel standards as a pathway to reduce fuel emissions post-combustion from the air and ocean. The recent revisions to the California LCFS do this explicitly and offer DAC crediting for projects without geographic restriction. Under the revised rulemaking, DAC with geological storage must comport with the other aspects of the CCS protocol to be credited.

Mandates

Governments mandates can be effective in helping build markets for clean energy products. In the United States, many state governments require utilities to purchase a minimum percentage of their power from renewable sources. In India, a similar requirement is imposed by the Ministry of New and Renewable Energy. These requirements have been important to the early growth of wind and solar power in both countries.[17]

Other experiences suggest caution, however. A U.S. federal government mandate has required the use of cellulosic ethanol in fuel supplies for almost a decade. Nevertheless, the cellulosic ethanol industry remains in its infancy and waivers to that requirement have been granted on a regular basis. Technology-forcing requirements—in which governments require private actors to meet standards that are not yet technically achievable—have been successful in some instances but not in others.[18]

There may be instances in which government mandates could help build DAC scale. As one option, governments could require that a certain percentage of the CO_2 used in enhanced oil recovery (EOR) be provided by DAC. This could create a substantial market for CO_2 from DAC. (EOR is one of the largest commercial markets for CO_2 today.) It could also help reduce the carbon footprint of EOR.[19] At present, DAC may be too expensive and unproven for such a requirement to be considered in many jurisdictions. As DAC technologies mature and fall in price, however, such mandates might be more likely to be adopted.

Government Procurement

In many countries, government procurement makes up more than 10% of GDP.[20] Government purchases can play an important role in starting and building new product markets. First, government purchase contracts can provide developers and manufacturers of new products with an assured market, which can be especially important in securing debt capital. Second, government purchases can help establish standard technical specifications for new products, which can help catalyze efficient supply chains.

Governments could spur development of DAC technologies using procurement authorities. For example, governments could target CO_2-based fuels for procurement, with a preference for CO_2 from DAC. (The U.S. Navy has had a similar program for the purchase of drop-in biofuels.[21]) Similar procurement authorities could be applied to CO_2-based plastics, concrete or other synthetic building materials. As DAC technologies mature, governments could play a powerful role in developing the technology with their procurement power.

Lifecycle Assessments.

Lifecycle assessments (LCAs) are essential for evaluating the climate benefits of direct air capture. If the power and heat used in a DAC process come from zero-carbon sources, the climate benefits will be considerable. If the power and heat used in a DAC process come from high-carbon sources, the climate benefits could be negative.

Governments can help develop and standardize LCA methodologies for DAC, in part to facilitate GHG accounting methodologies and protocols. Government agencies, such as the U.S. National Institute of Standards and Technology (NIST) or U.S. Department of Energy (through its national labs), can fund work by experts, convene relevant stakeholders and issue guidelines based on the inputs received. Governments can also incorporate LCAs into their work on DAC, requiring that DAC projects be carbon negative on a lifecycle basis to meet any regulatory requirements or to qualify for government support.

Related to this, CDR should be considered for inclusion in international GHG accounting standards, which would likely require additional work in quantifying and validating CDR volumes for different pathways and approaches.[22]

A wide range of policy tools are available for supporting DAC. Government policies—in particular one that puts a price on carbon—are likely to be central to the growth and long-term role of the technology.

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Chapter 7

Findings and Recommendations

Direct air capture (DAC) lies at one end of the carbon dioxide removal (CDR) spectrum and could play an important role in limiting the increase of atmospheric CO_2 concentrations. The potential scale of deployment is very large. Today, DAC technologies exist, but their costs, energy inputs and thermal requirements are very high. These findings summarize key components of this roadmap and distill a set of recommendations for consideration.

FINDING 1:

Large-scale CDR will likely be essential to achieve the goal of preventing a global average temperature increase of 2°C (3.6°F) above pre-industrial levels. The overwhelming majority of integrated assessment models, including 87% of the IPCC models, find that CDR is required to achieve a 2°C (3.6°F) target. In addition, a substantial number of current published assessments of the global carbon budget suggest that a CDR is required today to avoid both overshoot and the associated consequences of anthropogenic global warming.

FINDING 2:

There are many engineered and natural pathways to achieve large-scale CDR, including DAC. These pathways include reforestation and afforestation, increasing soil carbon uptake, bio-energy with CCS (BECCS), enhanced weathering and DAC. Each approach has challenges, including technical readiness, cost, resource availability and social acceptance. Many have additional economic or environmental benefits. Overall, a full portfolio of options has the greatest chance of success and the lowest risk of failure. Unfortunately, most governments have not yet formally recognized the likely necessity of CDR, and very few have committed to programs supporting CDR.

Recommendation 1:

Governments around the world should begin RD&D on direct air capture today.

FINDING 3:

By its intrinsic nature, DAC can play a major and distinct role in deployment of CDR. DAC is a concentrated process requiring a small physical footprint. It uses earth-abundant materials, and its removal operation is straightforward to quantitatively measure. The capacity of DACS (DAC with sequestration) to remove CO_2 is quite large and is limited primarily by cost, energy requirements and geological storage capacity. RD&D efforts can reduce costs and energy requirements, while geological storage capacity is estimated to be many trillions of tons. For these reasons, DAC plays a role as the "backstop" technology on the cost curve for climate strategies. Although DAC faces specific challenges (see below), including those related to geological CO_2 storage, it has important potential as a CDR technology and as a means to produce CO_2 as a feedstock.

FINDING 4:

The key limits to DAC are costs. Because CO_2 is more dilute in the atmosphere than in emissions sources such as flue gas, more energy is required to separate and concentrate it. On this basis, DAC will almost certainly always cost more than conventional CCS on most power plant and heavy industrial sources. The costs of DAC include both the capital costs and operational costs, including very low-carbon or zero-carbon heat and power. Current costs are difficult to estimate and vary by location and technology; nonetheless, today's DAC technologies appear to operate at \$300-600/tCO_2 removed.

FINDING 5:

Innovation can play an immediate and substantial role in reducing costs and improving performance of DAC approaches. The field of DAC is very young. Today's devices are far from the limits of thermodynamics, and both fundamental research and applied engineering are likely to produce significant cost reductions. It appears likely that costs could be reduced to less than \$200/tCO_2 by 2025 and less than \$100/tCO_2 by 2030. However, accomplishing this would require a sustained investment in focused RD&D.

Recommendation 2:

Direct air capture programs should include fundamental research, applied science and scale-up. These programs should include research on new CO_2 solvents and sorbents, low-carbon heat and other topics. The program goals should focus on reducing the cost of DAC, in part by deploying DAC units to foster learning-by-doing. DAC should be incorporated into conventional CO_2 storage projects as part of an RD&D agenda where possible.

FINDING 6:

Enough companies and technologies exist today for rapid progress in DAC cost-reduction and scale-up. Today, three companies offer DAC devices and services with a clear expectation of performance. Many more companies and innovators have begun work on alternative designs and approaches. In addition, many other new technologies (e.g., additive manufacturing, materials discovery and supercomputing) have the potential to dramatically improve cost and performance for DAC but have not yet been applied to that goal.

FINDING 7:

DAC provides some additional benefits beyond atmospheric separation and concentration of CO2. Some DAC approaches have a co-benefit of freshwater separation. All approaches could help support the manufacturing of goods from CO_2 (e.g., fuels, plastics, cement), and may offer a market differentiation of value in that way.

FINDING 8:

There are many policy options that could support DAC deployment and CDR more broadly. As a first step, governments could recognize DAC as part of a portfolio of CDR options, essential to important climate outcomes. They could invest in innovation and research, as well as procure both DAC services and materials made from atmospherically derived CO_2. They could provide incentives for deployment of DAC technology (e.g., the recent inclusion of DAC into the California Low Carbon Fuel Standard). They could support lifecycle analyses and industrial standards. Furthermore, for DAC to play a major role in a broader CDR portfolio, it will likely be paired with geological CO_2 storage, which faces policy issues around permitting, long-term care, liability and social acceptance.

Private sector policies matter as well. Companies could add DAC to their emissions reduction strategies, both by deploying the technology and buying low-carbon and negative-carbon materials made with DAC-derived CO_2.

Recommendation 3:

Governments, industry and financial institutions should work together to scale up direct air capture. Policies to promote DAC should include investment in RD&D, government procurement, targeted incentives, standard-setting, work on lifecycle analyses and recognition of DAC in carbon markets.

Final Thoughts

The movie Apollo 13 includes several scenes that feature direct air capture. After a malfunction in the space capsule endangers the mission, NASA scientists on the ground in Houston quickly realize that the CO_2 scrubber in the capsule is damaged and requires modification to function. Without the scrubber, CO_2 concentrations in the capsule of the spacecraft will exceed safe limits and the crew will die. A team gathers around a large worktable and dumps out a handful of gadgets and objects, the few expendable and spare parts on board the spacecraft that could be used to fashion a working air-capture device. After 75 minutes, they find a solution and coach the astronauts on how to modify their existing technology to return the CO_2 levels in the air to safe levels.

These scenes serve as a metaphor as we face the threat of climate change. In these scenes, a sudden environmental challenge has become urgent, with too much CO_2 in the space capsule, prompting a reassessment of priorities and a change of mission. Crucial to the success of that mission and to sustaining the lives of the crew, the technology already exists to resolve the issue. Innovation is required, and teams of scientists and decision makers learn rapidly. This allows the team to survive with their limited resources during their trip through space. The government had to assign substantial resources on the ground and learn through action to find a solution.

The growing concentration of CO_2 in the atmosphere is also an urgent threat. With resolve and determination like that showed by those who saved Apollo 13, we can meet the threat. (To quote the movie's most famous line: "Failure is not an option.") Large-scale carbon dioxide removal will likely be essential in the global response to climate change. Direct air capture of CO_2 could be an important part of the solution.

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