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The Commercial Case for Direct Air Capture

FEBRUARY 2021

A White Paper by the Bipartisan Policy Center's Direct Air Capture Advisory Council

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DISCLAIMER

The findings and conclusions expressed herein do not necessarily reflect the views or opinions of BPC, its founders, its funders, or its board of directors.

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BPC's Direct Air Capture Advisory Council was launched in 2019 to explore the role of direct air capture in achieving a net-zero carbon economy and to address related policy and technology challenges. The council's 14 members include leaders from academia, the private sector, labor, and the NGO community.

Introduction

Recent analyses of the mitigation measures needed to avoid dangerous levels of global warming this century conclude that negative emission technologies—that is, strategies for directly removing carbon dioxide from the atmosphere—will be needed, in addition to measures for avoiding and reducing new emissions of greenhouse gases.[1] Options for removing CO_2 are essential, both to address the buildup of greenhouse gases in the atmosphere that has already occurred as a result of historic emissions and because climate-friendly alternatives for some existing emissions sources or sectors will remain either unavailable or prohibitively expensive to implement for at least several decades longer.

Direct air capture of CO_2 from the atmosphere, or DAC, has attracted interest in this context, but, until recently, was often perceived to be too expensive to be relevant. This white paper revisits the commercial potential for DAC, arguing that a significant market opportunity exists for DAC in light of the need for billions of tons of CO_2 removal in coming decades to meet international climate targets. As a readily scalable and locationally flexible complement to other negative emissions strategies—such as growing trees or increasing carbon storage in soils—a strong business case can be made for DAC.

We begin by providing a short update on the current status of DAC technology, including the status of recent projects, and by discussing prospects for continued cost reductions based on experience with other pollution control technologies that have a significant chemical process component. Later sections discuss longer-term market opportunities and economic benefits, and near-term commercial pathways for advancing DAC technology. This paper is a companion to a previous Bipartisan Policy Center paper, which focuses on the environmental case for investment and policy support to advance DAC technology development and commercialization.[2]

Technology Status and Current Pilot Plants

The first technologies for capturing CO_2 from ambient air were developed in the 1930s and later applied in closed life-support systems such as submarines and space stations. However, these technologies were characterized by high costs and low scalability, making them unsuitable for climate-change mitigation purposes. Companies and research institutions have since worked to re-engineer DAC systems to improve their economics and scalability: modern versions employ a combination of mechanical systems and chemical processes, including fans to move large volumes of air and liquid or solid sorbents to capture the CO_2.[3]

The issue of climate change has brought renewed attention, and increased investor interest, to DAC technology. Over the last decade, billions of dollars of private capital have been invested in a variety of carbon management solutions, including DAC. Today there are over a dozen DAC plants operating worldwide (including both demonstration plants and commercial plants).[4] Collectively these plants are capturing a minimal amount of atmospheric CO_2—slightly more than 9,000 tons of CO_2 annually (a few additional plants are currently being planned and/or actively developed). Nonetheless, the existence of these plants and the investor interest they have attracted point toward the possibility of something much larger.

The remainder of this section summarizes recent developments at three companies that are currently active in the DAC space: European-based Climeworks, Canadian-based Carbon Engineering, and U.S.-based Global Thermostat.[5] Information about individual facilities is provided in Table 1.

Climeworks currently has 14 pilot and commercial DAC plants in operation in Europe with a cumulative CO_2 capture capacity of 2,000 metric tons per year. An additional plant in Iceland with a CO_2 removal (CDR) capacity of 4,000 metric tons per year will go online in the second quarter of 2021. The modular design of these systems has allowed for relatively rapid deployment, with plant construction taking as little as six months from when the project breaks ground to when the plant is commissioned.

Climeworks' current business model focuses on selling CDR services to individual customers and corporate customers, such as Microsoft, Stripe, Audi, and Shopify. In collaboration with Carbfix, an Icelandic company that develops CO_2 mineralization technology, the captured carbon is permanently stored underground in solid form.[6] Additionally, Climeworks supplies onsite CO_2 for renewable fuels and materials and carbon product processes—for example, as part of a newly formed consortium together with the Rotterdam The Hague Airport and the sustainable aviation fuel company SkyNRG, to build a demonstration plant for fully renewable jet fuel.[7] The company also sells CO_2 to customers, such as Coca-Cola HBC Switzerland, for use in making carbonated beverages. In 2020, Climeworks closed a $110-million funding round that included a number of private investors.[8] Climeworks has also received support from the European Union's Horizon 2020 program, European incubators, and German and Swiss ministries.

Carbon Engineering has been developing DAC technology since 2009 and began operating its first end-to-end pilot plant in British Columbia in 2015. The company is now constructing a larger and more advanced "Innovation Centre" at the same site. In 2020, Carbon Engineering announced an agreement to license its technology to 1PointFive, a development company formed by two of Carbon Engineering's investors: Oxy Low Carbon Ventures and Rusheen Capital Management. 1PointFive will build and operate DAC facilities that permanently sequester the CO_2 they capture in underground geological formations. Its first planned project is a 1-million-ton-per-year DAC plant in the Permian Basin (once completed, this would be by far the largest DAC plant constructed to date). The final front-end engineering design (FEED) study for this plant will be completed in 2021, with construction planned to commence in 2022 and operations to begin in 2024.[9]

Carbon Engineering recently announced that the e-commerce company Shopify will invest in a demonstration of carbon removal from Carbon Engineering's Innovation Centre in British Columbia. This project, which aims to improve sequestration technologies, will explore multiple options for permanently storing captured CO_2.[10] In 2020, Carbon Engineering also announced partnerships with the Virgin Group, which will offer participants in Virgin's Red loyalty rewards program the opportunity to use points for CDR, and with Pale Blue Dot Energy to deploy DAC in the U.K. (one of the locations being considered for a first U.K. plant is in northeast Scotland).[11,12] In 2019, Carbon Engineering closed a funding round that raised $91 million from private investors including Starlight Ventures, Oxy Low Carbon Ventures, Chevron Technology Ventures, BHP, Lowercase Capital, First Round Capital, and Bill Gates.[13]

In the United States, Global Thermostat has developed several pilot plants in California and Alabama over the last nine years to test and refine its DAC and combined DAC-plus-flue-gas-capture systems. Its most recent DAC pilot, in Alabama, consists of two containerized units. Each unit is capable of removing 2,000 tons of CO_2 per year. Global Thermostat has also begun constructing two additional 2,000-ton-per-year commercial demonstration plants in Oklahoma and is launching a technology center in Colorado. The technology center will support Global Thermostat's existing and emerging projects and involves a number of partners, including industrial companies (engineering, fabrication, and supply chain), the Department of Energy, other customers interested in CO_2 use and sequestration, and academic laboratories.

In 2019, Global Thermostat signed a joint development agreement with ExxonMobil to evaluate the scalability of its DAC technology for large industrial use and climate change mitigation, which will require CO_2 removal on the scale of billions of metric tons. In 2020, Global Thermostat and ExxonMobil announced an expansion of their agreement, with the goal of accelerating the scaling of Global Thermostat's DAC systems for global deployment.[14] Global Thermostat has received funding from private family and individual investors, as well as from strategic investors; it has also received non-dilutive capital, totaling approximately $70 million, from government entities and corporate partners.

Figure 1. DAC facilities around the world. From left, A Climework's facility in Switzerland, a Carbon Engineering facility in British Columbia, and a Global Thermostat facility in Alabama.

Table 1: Summary of Existing and Planned DAC Plants

Company Name	Partners	Plant Type	Status	Plant Location	CO_2 Removal Capacity (metric tons/yr)	CO_2 Market Application, if Commercial	Date of Operation
Climeworks	Several	14 Pilot and Commercial plants	Operational	Across Europe (ex., Switzer-land, Italy, Iceland)	Total of 2,000	CDR services; renewable fuels & materials; food, beverage & agriculture	2015-2020
Climeworks	Carbfix, ON Power	Commercial plant	Under construction	Hellisheidi, Iceland	4,000	CDR services to corporations (e.g., Microsoft, Shopify, Audi) and individuals (permanent storage via mineralization)	Q2 2021
Carbon Engineering	None	Pilot plant	Operational	Squamish, British Columbia	350	Not commercial	2015
Carbon Engineering	None	Innovation Centre	Under construction	Squamish, British Columbia	1,500	Shopify and Virgin will pay CE for CO_2 capture and storage	2021
Carbon Engineering	1PointFive, Oxy Low Carbon Ventures	Commercial plant	Pre-construction	Permian Basin, Texas	1,000,000	EOR and geologic storage (planned)	Mid-2020s (goal is 2024)
Global Thermostat	None	Pilot plant (DAC+ Flue)	Not currently operating	Menlo Park, California	10,000	Not commercial	2013
Global Thermostat	None	Pilot plant	Not currently operating	Huntsville, Alabama	4,000	Not commercial	2019
Global Thermostat	Large Corporates	Two commercial plants	Under construction	Sapulpa, Oklahoma	2,000 each	CO_2 to fuels; CO_2 as industrial gas	Late 2021

Note: The carbon dioxide capture capacity of Global Thermostat's second listed Menlo Park plant (carbon capture capacity of 10,000 metric tons per year) includes both direct air capture and flue gas capture.

Technology Costs and Potential for Cost Reductions

As DAC is a nascent and quickly evolving industry, information on technology costs has been scarce until fairly recently. As successive studies have incorporated greater engineering detail, however, more robust cost analyses have become available. Recent findings suggest that the economics are within the range of $100–$250 per ton CO_2 captured based on the systems that are currently under development, with potential for future costs to fall further through learning-by-doing, particularly as technology deployment scales (we return to this point later in this section). A peer-reviewed study published in the journal Joule in 2018, for example, cites levelized costs for an industrial, megaton-scale DAC plant at $94–$232 per ton CO_2 based on an analysis that accounts for energy and materials balances, a commercial engineering cost breakdown, and pilot plant data.[15]

By way of providing context for these cost ranges, carbon prices in the EU's Emission Trading System over the last two years (i.e., since late 2018) have generally fluctuated between 20 and 30 euros per metric ton CO_2—in other words, well below $50 per ton in dollar terms.[16] A critical point, however, is that achieving net-zero will almost certainly require carbon prices to rise as lower-cost mitigation options are exhausted. (For example, a recent study published in Nature Climate Change finds that illustrative CO_2 prices for the United States to achieve net-zero carbon emissions by 2050 range from $34–$64 per metric ton in 2025 and $77–$124/ton in 2030.[17])

Moreover, DAC costs are already within striking distance of—or in some cases already lower than—the implicit abatement costs associated with a variety of other policy measures that have wide public and political support, based on their climate change and other environmental benefits, such as subsidies for renewable energy and electric vehicles.[18]

Two broader points about abatement cost are also relevant. The first is that effectively combatting climate change will almost certainly require a diverse portfolio of strategies—both for reducing and avoiding future greenhouse gas emissions and for removing carbon from the atmosphere. Investments in abatement options that are still relatively expensive now may be justified in this context as a way to accelerate performance improvements and cost reductions for technologies that may provide considerable benefit in the future.

A second important point is that current estimates of DAC costs reflect a technology that is still at a relatively early stage of commercialization. As project developers optimize pilot plants, go on to build larger facilities, and continue to gain operating experience, costs can be expected to decline further.

As with all energy technologies, capital costs for equipment and commercial financing costs are important considerations for DAC plants. Chemical inputs and energy requirements are the other key cost drivers—for this reason, the trajectory for future DAC cost reductions is likely to differ from that of other prominent climate-friendly technologies such as wind turbines and solar cells, where dramatic cost declines were achieved largely through design and manufacturing improvements. Box 1 summarizes the experience with flue-gas desulfurization systems, which capture sulfur dioxide from the exhaust gases of large industrial facilities and power plants. Because such systems rely on chemical processes to remove a pollutant that is present at very low concentrations, they offer a closer analogy to current DAC systems. Experience with flue gas desulfurization and with a wide range of other pollution control technologies provides confidence that DAC costs are similarly likely to fall, provided the regulatory and policy environment provides sufficient incentives to sustain investments in advancing the technology.

Box 1

The development of flue gas desulfurization (FGD) systems, colloquially known as "scrubbers," dates back to the 1930s, when flue gas from a power plant in London was passed through a spray of Thames river water mixed with chalk in an early effort to limit sulfur dioxide (SO_2) emissions. As with CO_2 capture, the first FGD developers had to contend with significant engineering challenges: SO_2 typically constitutes only about 0.2-0.3% of power plant exhaust streams and removing it involves processing large quantities of hot gases; in addition, the chemical reactions involved are difficult to control on a large scale and the process generates highly corrosive byproducts. Early FGD systems (the first was installed in the United States in 1968) were able to achieve SO_2 removal rates as high as 95%, but they were plagued by reliability problems and widely considered inadequate in terms of offering a cost-effective solution to the growing problem of SO_2 pollution. Over subsequent decades, however, growing regulatory pressure to limit SO_2 emissions, not only in the United States, but also in other industrialized countries (Japan, for example, was at the forefront of FGD development in the 1970s), resulted in steady technology improvements and a sharp rise in commercial FGD installations. In the United States, the introduction of the Acid Rain program in the 1990s created a clear market signal for SO_2 reductions and capital costs for FGD systems declined—from more than $250 per kilowatt (kW) of installed electricity generating capacity in 1976 to approximately $130/kW in 1995. Operating and maintenance costs for FGD installations, meanwhile, fell by approximately 40% between 1983 and 1995.[19] Modern FGD technology is considered reliable, has been widely implemented around the world, and produces salable byproducts, such as gypsum.

Market Opportunities and Economic Benefits

The long-term market opportunity for large-scale applications of DAC technology will be driven by climate change mitigation benefits: absent a robust market for CO_2 reductions in the form of products, services, or credits, in other words, it is hard to discern a viable business model for developing and deploying this technology at the scale needed to materially influence global warming trends. The strength of a future carbon market, as reflected in overall demand for CO_2 reductions and the market price per ton of CO_2 avoided or captured, will be a function (in turn) of policy commitments and of the availability and cost of other mitigation options throughout the economy.

Current understanding of the scale and scope of interventions needed to avert large-scale climate damages points to a substantial market opportunity for DAC and other negative emissions technologies. As one commenter recently observed, to meet international climate goals, “we need on the order of 10 billion metric tons of negative emissions—20% of today’s annual emissions—by approximately mid-century, and 20 billion tons by century’s end.”[20] A recent meta-analysis of the literature on this topic estimates the quantity of negative emissions needed at anywhere from 5 to 15 billion metric tons per year by 2050, and the potential contribution of DAC with carbon sequestration as falling in a range from 500 million to 5 billion metric tons per year of CO_2 removal in the same timeframe.[21] At a CO_2 price of $100 per ton, *The Economist* has estimated that the DAC market could exceed $500 billion per year (assuming deployment at the level of 5 billion metric tons CO_2 removed per year) and require between $40 and $750 billion in related infrastructure investments (by comparison, global clean energy investments totaled approximately $363 billion in 2019).[22]

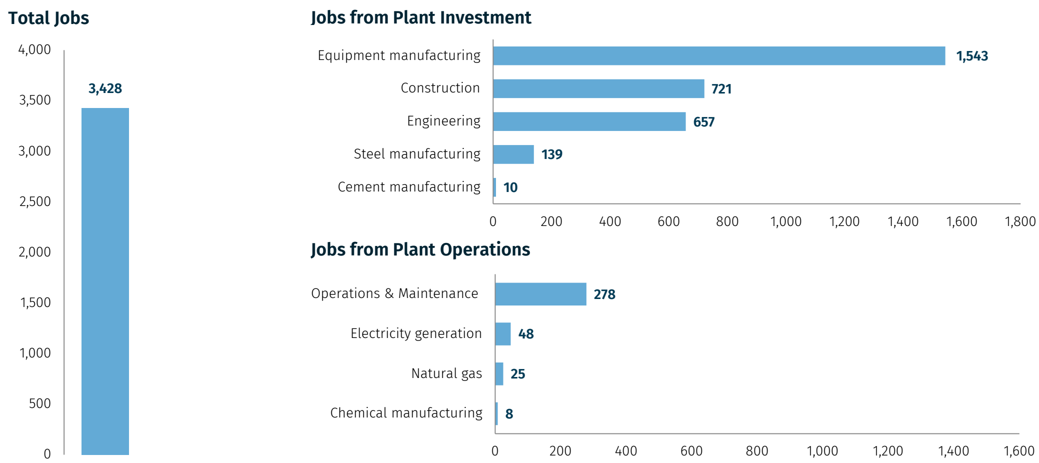
As with all modeling analyses of climate mitigation pathways, these ranges reflect numerous assumptions about the timing and ambition of the mitigation target, underlying techno-economic trends, and the size and cost of other decarbonization opportunities, but the overall conclusion—that the future market for carbon reductions is likely to be enormous and that dramatic scale-up across a portfolio of negative emissions technologies, including DAC, will be needed over the next 30 years—is consistent and compelling.

Assessments of DAC potential for climate mitigation assume that most of the CO_2 captured using this technology will be permanently kept out of the atmosphere, likely by being stored in geological reservoirs (such as saline formations, which exist throughout the United States). In addition, industrial applications for CO_2 and the use of carbon from captured CO_2 in products, such as cement or polymers, can help strengthen the value proposition for DAC projects. At present, nearly 230 million tons of CO_2 are used annually in the global production of chemical and materials feedstocks, with roughly one-third of this demand coming from North America (another 21% comes from China and 16% comes from Europe).[23] Prominent applications include cement/concrete, chemicals, plastics, and fuels.[24] The largest global consumer of CO_2 is the fertilizer industry, which uses approximately 130 million tons per year in urea manufacturing; the next largest user is the oil and gas industry, which uses 70–80 million tons per year for enhanced oil recovery (EOR).[25] The IEA estimates that global annual demand for CO_2 in industrial applications could reach 272 million tons by 2025.[26]

CO_2 is also widely used in food and beverage production, metals fabrication, cooling, fire suppression, and in greenhouses to stimulate plant growth. All of these markets, however, are relatively small compared to the volumes of CO_2 capture needed to meaningfully advance climate mitigation objectives—that said, they could provide early market footholds for the technology to advance and scale.

Successful commercialization of DAC technology could also provide substantial economic benefits, both directly and indirectly, to the extent DAC provides option value and reduces the overall costs of climate mitigation. For example, one recent study estimated that the availability of DAC with carbon storage could reduce marginal abatement costs for achieving either the 1.5°C or 2°C target by 60% to 90%.[27] As another tool for stabilizing and eventually reducing CO_2 levels in the atmosphere, DAC could be particularly valuable over the next several decades, when zero-carbon alternatives for some key applications and energy end uses are still in the early phases of commercialization and scale-up.

In terms of the direct economic benefits of DAC commercialization and deployment, a recent analysis of potential job gains from DAC scale-up in the United States by the Rhodium Group focused on three areas of employment opportunity: construction/capital (equipment, cement, steel, construction, and engineering), energy requirements (electricity and heat), and operations (chemicals, and operations and maintenance). Rhodium estimated that each one-megaton DAC plant will create, on average, approximately 3,500 jobs—mostly associated with design, engineering, construction, and the manufacture of plant equipment. Once construction is completed, plant operations will require approximately 275 workers to maintain and operate a one megaton DAC plant.[28]



Source: IMPLAN Group, Keith et al. 2018. NAS, AISC, Rhodium Group analysis. Note: All values reflect DAC plant median cost and performance estimates. Values will vary depending on technology type and configuration.

Figure 2. Jobs created by a single DAC plant with the ability to capture 1 million tons of CO_2 per year. Image Source: "Capturing New Jobs." Rhodium, 2020. Available at: https://rhg.com/wp-content/uploads/2020/06/Capturing-New-Jobs-Employment-Opportunities-from-DAC-Scale-Up.pdf

Additional employment benefits would be associated with the large-scale (gigaton-level) storage or use of captured CO_2. Operations for capture and sequestration would require job skills that are already widely developed in the oil and gas industry, which currently accounts for 2% of U.S. employment.[29] A carbon-to-value pathway that uses captured carbon in products could have positive job impacts for the manufacturing sector.

Near-term Commercialization Pathways

Although a robust, broad-based, climate-focused regulation or policy would provide the clearest price signal for carbon capture and the strongest market driver for DAC, early opportunities related to CO_2 utilization could be developed before such a regulation or policy is in place. For example, another relatively mature, near-term commercialization pathway in the United States could involve the use of captured CO_2 in EOR applications, where the CO_2 is injected into mature wells to flush remaining hydrocarbons to the surface. After the process is complete, the well is sealed, leaving the injected CO_2 stored underground. CO_2 is already widely utilized for this purpose, but typical industry practice has been to pump CO_2 from natural underground reservoirs, which provides no climate benefit. Using CO_2 sourced from DAC plants, by contrast, effectively reduces the carbon footprint of recovered oil.[30] To test this commercialization pathway, as mentioned above, Oxy Low Carbon Ventures, a subsidiary of Occidental Petroleum, has announced plans to use Carbon Engineering's DAC technology to produce CO_2 for EOR operations in Texas.[31]

Other near-term commercialization pathways leverage the environmental benefits of DAC, for example, by providing another option for corporations and other entities to voluntarily reduce their carbon footprint. For example, as part of its pledge to be carbon negative by 2030, Microsoft recently announced its first round of CDR purchases from carbon removal projects, including from Climeworks.[32] Absent a national-level regulatory framework that implicitly or explicitly attaches a price to carbon emissions, the two policy mechanisms currently in place in the United States that could be relevant for early-stage DAC commercialization are federal Section 45Q tax credits and California's Low Carbon Fuel Standard (LCFS).

The 45Q tax credit was introduced in 2008 and updated in the Bipartisan Budget Act of 2018. It provides a performance-based tax credit to owners of power plants and industrial facilities that capture CO_2, either for use in durable products, for EOR, or for storage in geologic formations.[33] Both technologies that capture CO_2 from the exhaust gas streams of large industrial facilities or from the ambient air (i.e., DAC) are eligible. As updated in 2018, the value of the tax credit increases incrementally over ten years from $10 to $35 per metric ton of captured CO_2 used (and permanently stored underground) in EOR applications and from $20 to $50 per ton for captured CO_2 that is directly stored in saline and other types of geologic formations. Additionally, the tax credit provides $35 per ton for captured

CO_2 used to reduce the lifecycle emissions of other products or outputs. The credit is available to carbon capture projects that commence construction within seven years from enactment; eligible projects can claim the credit for 12 years after being placed into service.[34]

Following a substantial delay, the Internal Revenue Service issued a final rule that provides guidance on the Section 45Q tax credit in January 2021.[35] Shortly before, the requirement for construction commencement for eligible projects was extended by two years as part of the omnibus federal budget and stimulus legislation passed at the end of 2020. The issuance of IRS guidance combined with the extension will help provide regulatory and financial certainty for private DAC investors in the years ahead.

At the state level, California's LCFS is the most prominent incentive program currently in place to encourage both point-source carbon capture and DAC. First implemented in 2011, the LCFS sets a lifecycle CO_2 intensity target for transportation fuels sold in California and requires fuel providers to meet the target. The initial target required a 10% reduction in CO_2 intensity by 2020; recent changes to extend the LCFS call for a 30% intensity reduction by 2030. Recent changes to the program also expanded the number of technologies eligible to meet the standard, including two pathways that specifically allow for the use of DAC. Regulated entities can use offsets from DAC projects anywhere in the world to help meet their compliance obligation under the LCFS; however, the captured CO_2 must be permanently stored according to specific requirements (for example, California requires that companies claiming LCFS credits be responsible for monitoring the stored CO_2 for 100 years).[36]

In the initial years of program implementation, the value of the LCFS credit was under $100. In early- to mid-2016, the value of the credit started to climb above $100. Even then, it was not consistently above $100 on a monthly basis (for instance, the average price of the credit was $89 in December 2016). This trend carried through 2017. In 2018, however, the value of the credit started to rise steadily, reaching an average price of $198 in October 2020.[37] Forecasting future LCFS credit prices is complex, given the many variables in play on both the supply and demand sides. While the California Air Resources Board has projected that credit prices will decline over the coming decade, the adoption of similar programs by other states and/or by the federal government, together with other factors, such as the pace of vehicle fleet electrification, could significantly affect future price trends by increasing or reducing demand for low-carbon fuel. To date, compliance with the LCFS has been achieved primarily through the use of biofuels and, more recently, through expanded sales of electric vehicles.[38]

Conclusion

Multiple analyses have concluded, and BPC's DAC Advisory Council concurs, that a substantial contribution from negative emissions technologies will be needed, as a complement to aggressive emission reductions measures, to limit global average warming this century to levels that would avoid the most damaging consequences of climate change. Until fairly recently, DAC tended to be dismissed as an interesting but immature and likely too expensive technology, relative to other options (including land- and forest-based carbon sequestration strategies), to play a major role. This view has begun to change as the scale of the climate challenge has come more clearly into focus, and as the window of time for dramatically altering the world's carbon trajectory has narrowed. The emergence of several DAC developers, and their ability to raise financing and find large industrial partners to help them scale, is perhaps the clearest sign yet of commercial interest in DAC as more than a fringe technology. Experience gained through these pilot projects has already lowered credible estimates of the CO_2 capture costs that could be achieved when DAC technology is implemented at scale; historic experience with a wide range of similar technologies, meanwhile, offers grounds for confidence that further cost reductions can be realized as the technology matures.

At present, however, policy support and market incentives remain inadequate to support the level of investment needed to develop DAC plants at sufficient scale. We believe the long-term market opportunity for DAC, in a global economy that is likely to demand billions of tons of additional CO_2 reductions even with vastly accelerated adoption of low-carbon technologies, creates a compelling business case—in addition to the environmental case outlined in BPC's companion paper—for additional efforts to nurture DAC technology through the next crucial phases of the innovation and commercialization cycle. Such efforts, particularly if they leverage existing demand for CO_2 as a feedstock and in other industrial applications could deliver large future returns—in economic as well as environmental terms.

Endnotes

1 See, for example: International Panel on Climate Change, *Special Report: Global Warming of 1.5°C*, (2018). Available at: https://www.ipcc.ch/sr15/; Rogelj et. al, Energy system transformations for limiting end-of-century warming to below 1.5°C, Nat. Clim. Change (2015). Available at: https://doi.org/10.1038/nclimate2572; and Luderer et al., *Economic mitigation challenges*: *how further delay closes the door for achieving climate targets*, Environ. Res. Lett. (2013). Available at: https://doi.org/10.1088/1748-9326/8/3/034033.

2 "Investing in Climate Innovation: The Environmental Case for Direct Air Capture of Carbon Dioxide," Bipartisan Policy Center, May 2020. Available at: https://bipartisanpolicy.org/wp-content/uploads/2020/05/BPC_2020_Direct-Air-Capture-of-Carbon-Dioxide_FinalPDF.pdf

3 In some DAC systems, air is passed through a liquid sorbent, such as an alkaline or basic solution, which removes the CO_2. Other systems use solid sorbent filters that chemically bind with CO_2. When the filters are heated, they release a concentrated stream of CO_2, which can be captured for storage or use.

4 International Energy Agency, *Putting CO_2 to Use*: *Creating Value from Emissions*, Sept. 2019. Available at: https://www.iea.org/reports/putting-co2-to-use

5 The information provided in this section and summarized in Table 1 was supplied to BPC by the companies themselves, in response to a query from BPC. BPC did not make independent efforts to verify all of this information.

6 Climeworks is currently selling CO_2 offsets at the relatively high price of 1 euro per kilogram, or approximately $1,000 per ton.

7 Climeworks, along with multiple other companies, aims to demonstrate the potential for onsite renewable jet fuel production. For more information, please see https://www.climeworks.com/news/christoph-gebald-co-ceo-and-co-founder-of-climeworks.

8 Heather Clancy, "2020 was a breakthrough year for climate tech, and there's more to come in 2021," GreenBiz, Dec. 30, 2020. Available at: https://www.greenbiz.com/article/2020-was-breakthrough-year-climate-tech-and-theres-more-come-2021

9 "Oxy Low Carbon Ventures, Rusheen Capital Management Create Development Company 1PointFive to Deploy Carbon Engineering's Direct Air Capture Technology," Press Release, 1PointFive, August 19, 2020. Available at: https://www.1pointfive.com/launch-release

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11 Jennifer Thuncher, "Carbon Engineering: There it grows again," The Squamish Chief, Sept. 18, 2020. Available at: https://www.squamishchief.com/news/local-news/carbon-engineering-there-it-grows-again-1.24205529

12 For more information on Pale Blue Dot, please see https://pale-blu.com/

13 Kenneth Chan, "BC's Carbon Engineering gets $25 million from federal government," Venture Vancouver, June 25, 2019. Available at: https://dailyhive.com/vancouver/squamish-carbon-engineering-federal-government-funding-june-2019

14 "ExxonMobil expands agreement with Global Thermostat, sees promise in direct air capture technology," Press Release, ExxonMobil, Sept. 21, 2020. Available at: https://corporate.exxonmobil.com/News/Newsroom/News-releases/2020/0921_ExxonMobil-expands-agreement-with-Global-Thermostat-re-direct-air-capture-technology; "ExxonMobil and Global Thermostat to advance breakthrough atmospheric carbon capture technology," Press Release, ExxonMobil, June 27, 2019. Available at: https://corporate.exxonmobil.com/News/Newsroom/News-releases/2019/0627_ExxonMobil-and-Global-Thermostat-to-advance-breakthrough-atmospheric--carbon-capture-technology

15 Keith et al., Joule, 2, 1573-1594. August 15, 2018. Available at https://doi.org/10.1016/j.joule.2018.05.006. The Keith et al. analysis is passed on a 1-Mt per year DAC plant using an aqueous sorbent coupled to a calcium caustic recovery loop. The design requires either 8.81 GJ of natural gas or 5.25 GJ natural gas plus 366 kWh of electricity per ton of CO_2 captured. The reported cost range depends on financial assumptions, energy costs, and other specific assumptions regarding inputs and outputs

16 For historic carbon prices in the E.U. ETS, see: https://ember-climate.org/data/carbon-price-viewer/. Note that an exact conversion to dollars would depend on the currency exchange rate at the time of the comparison.

17 Kaufman, N. et al. *A near-term to net zero alternative to the social cost of carbon for setting carbon prices*. Nat. Clim. Chang. 10, 1010–1014 (2020). Available at: https://doi.org/10.1038/s41558-020-0880-3.

18 See, for example, Columbia SIPA Center for Global Energy Policy and Global CCS Institute, *Net-Zero and Geospheric Return: Actions Today for 2030 and Beyond*, Sept. 2020, Available at: https://www.globalccsinstitute.com/resources/publications-reports-research/net-zero-and-geospheric-return-actions-today-for-2030-and-beyond/.

19 Edward S. Rubin, et al., "Experience curves for power plant emission control technologies," Int. J. Energy Technology and Policy, Vol. 2, Nos. 1/2, 2004. Available at: https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.500.9962&rep=rep1&type=pdf.

20 Elizabeth Kolbert, "Climate Solutions: Is It Feasible to Remove Enough CO_2 from the Air?" Interview, Yale Environment 360, Published at the Yale School of the Environment, Nov. 15, 2018. Available at: https://e360.yale.edu/features/negative-emissions-is-it-feasible-to-remove-co2-from-the-air

21 These estimates are for modeling scenarios consistent with limiting warming to 1.5°C. See, for example, Fuss, S. et al., *Negative emissions - Part 2: Costs, potentials, and side effects*. Environ. Res. Lett. 13, 063002 (2018). Available at: https://doi.org/10.1088/1748-9326/aabf9f

22 "Direct Air Capture: leveraging technological innovation to safely remove carbon dioxide from ambient air," Economist, 2020. Available at: https://carbonremoval.economist.com/direct-air-capture/

23 International Energy Agency, *Putting CO_2 to Use: Creating Value from Emissions*, Sept. 2019.

24 Ultimately, for example, synthetic fuels produced from captured carbon could offer a carbon-neutral alternative for otherwise hard-to-decarbonize sectors such as aviation and marine shipping. Although CO_2 itself, as an input, accounts for a relatively small portion of the overall value chain, products that could utilize captured CO_2 collectively represent a large global market—valued at more than $6 trillion according to one recent estimate. Fuels and building materials account for nearly 66% and approximately 23% of this total, respectively. See: Rory Jacobson and Matt Lucas. "A Review of Global and U.S. Total Available Markets for CarbonTech: Executive Summary." Carbon180. Oct 2019. Available at: https://carbon180.org/reports

25 International Energy Agency, *Putting CO_2 to Use: Creating Value from Emissions*, Sept. 2019. https://www.iea.org/reports/putting-co2-to-use

26 *Ibid.*

27 Realmonte, G., Drouet, L., Gambhir, A. et al. *An inter-model assessment of the role of direct air capture in deep mitigation pathways*. Nat Commun 10, 3277 (2019). https://doi.org/10.1038/s41467-019-10842-5.

28 "Presentation: Capturing New Jobs," The Rhodium Group, June 23, 2020. Available at: https://rhg.com/wp-content/uploads/2020/06/Capturing-New-Jobs-Employment-Opportunities-from-DAC-Scale-Up.pdf

29 Jen Wilcox, "A Case for Carbon Dioxide Removal From Air," Presentation, Kleinman Fellowship Program, University of Pennsylvania, Feb. 12, 2020. Available at: https://kleinmanenergy.upenn.edu/wp-content/uploads/2020/11/A-Case-for-Carbon-Dioxide-Removal-from-Air.pdf

30 The specific benefit achieved by using captured CO_2 in this application depends on a variety of factors, including the source of energy used for DAC and assumptions about how much of the oil extracted using EOR would have been produced anyway. For further discussion see: James Mulligan and Dan Lashof. "A CO_2 Direct Air Capture Plant Will Help Extract Oil in Texas. Could This Actually Be Good for the Climate?" World Resources Institute. July 31, 2019. Available at: https://www.wri.org/blog/2019/07/co2-direct-air-capture-plant-will-help-extract-oil-texas-could-actually-be-good-climate

31 *Ibid.*

32 Climeworks has stated that it will not pursue enhanced oil recovery as a business model. For more information on Microsofts CDR commitments, see: Lucas Joppa, "Sustainability: A year of progress and a decade of action," The Official Microsoft Blog, 2021. Available at: https://blogs.microsoft.com/on-the-issues/2021/01/28/sustainability-year-progress-decade-action/

33 Kurt Waltzer, "The Role of 45Q Carbon Capture Incentives in Reducing Carbon Dioxide Emissions," Clean Air Task Force, 2017. Available at: https://www.catf.us/wp-content/uploads/2017/12/CATF_FactSheet_45QCarbonCaptureIncentives.pdf

34 The Bipartisan Budget Act of 2018 reduces the minimum eligibility threshold for qualified facilities from 500,000 metric tons of captured CO_2 per year to 100,000 metric tons per year for industrial facilities and 25,000 metric tons per year used for purposes other than EOR. The 500,000-ton threshold is retained for electric generating units. The owner of the carbon capture equipment can transfer the credits to other entities responsible for managing the CO_2, which provides greater flexibility for actors with different business models. See: Rory Jacobson and Matt Lucas. "A Review of Global and U.S. Total Available Markets for CarbonTech: Executive Summary." Carbon180. Oct 2019. https://carbon180.org/reports

35 Final IRS rule for 45Q available at: https://www.federalregister.gov/public-inspection/2021-00302/credit-for-carbon-oxide-sequestration.

36 Global CCS Institute, 2019 Policy Report: The LCFS and CCS Protocol: An Overview for Policymakers and Project Developers, 2019. Available at: https://www.globalccsinstitute.com/wp-content/uploads/2019/05/LCFS-and-CCS-Protocol_digital_version.pdf

37 For additional information, please see the archived history of pricing of the LCFS, determined through credit trading activity, here: https://ww3.arb.ca.gov/fuels/lcfs/credit/lrtmonthlycreditreports.htm

38 Our discussion of California's LCFS program draws heavily on the Rhodium analysis. See: https://rhg.com/wp-content/uploads/2019/05/Rhodium_CapturingLeadership_May2019-1.pdf.

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