

Technological Carbon Removal

Recent Economic and Political Trends in the United States

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ADVISERS

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Executive Summary

In this report, we assess the current state of affairs surrounding technological carbon dioxide removal (CDR)—sometimes referred to as “engineered” CDR or negative emissions technologies (NETs)—in the United States. After defining what technological CDR is and why it matters, we examine the status of technological CDR in the U.S. economy—looking carefully at what companies and investors are doing currently. We then review the policy and political landscape for technological CDR before providing concrete policy recommendations for action at the Federal level.

CDR is the name given to a suite of processes and technologies that remove carbon dioxide from the atmosphere. Removing carbon from the atmosphere lowers the concentration of greenhouse gases (GhG) in the atmosphere, which in turn slows global warming and climate change. Scientists generally agree that substantial use of CDR will be essential to meet global climate goals and prevent catastrophic climate change.

Nature is the oldest and most familiar type of CDR. Trees and other plants absorb CO₂ naturally through photosynthesis, storing carbon in their biomass and in soils. Other natural organisms in the ocean, soil and sedimentary rocks also remove carbon dioxide from the atmosphere. Humanity can harness the power of nature to remove carbon from the air by managing forests, farmlands, oceans and soils for this purpose. Solving the climate crisis will require far greater investments in natural CDR, as we have argued previously in our paper published in June 2018.¹

However, nature is not the only CDR solution. Innovative technologies and chemical processes can also take carbon out of the atmosphere. Today, companies and inventors are working on machines that capture CO₂ from ambient air and either store it underground or turn it into a commercially valuable product, such as an input for concrete. Removing CO₂ directly from the air using artificial technology is known as direct air capture (DAC). Other CDR technologies include bioenergy with carbon capture and storage (BECCS), biochar, ocean iron fertilization, direct air carbon capture and storage (DACCS) or utilization, and enhanced weathering and ocean alkalization. These are considered “hybrid” technologies, as they combine both natural solutions and technology to remove carbon. Based on our examination of the different CDR technologies available today, DAC appears to offer the most promise long term, for both commercial prospects and removal of CO₂.

Most scientists and experts believe that scaling up technological CDR will be essential to stabilize the Earth’s climate at a safe level, as the United Nations’ scientific body on climate change outlined in its report in October 2018. Based on the current trajectory, the world may overshoot global climate goals – i.e. increase GhG concentrations to more than 2° above pre-industrial levels. Should this happen, technological CDR could become essential to bring back GhG concentrations to safe levels quickly in the second half of this century.

During the past two years, entrepreneurs and academics have increased their enthusiasm regarding technological CDR, receiving money from governments, angel investors, and philanthropists. At the same time, a larger number of companies are experimenting with carbon capture and utilization or sequestration (CCUS), with a handful reaching the commercial phase. CCUS is similar but not the same as technological CDR. CCUS technologies capture carbon before it enters the atmosphere—as part of the process that

¹ Langley, Claire. “Creating Negative Emissions: The Role of Natural and Technological Carbon Dioxide Removal Strategies.” *Climate Advisers*. June 22, 2018. <https://www.climateadvisers.com/creating-negative-emissions-the-role-of-natural-and-technological-carbon-dioxide-removal-strategies/>

creates carbon dioxide pollution, including burning fossil fuels—rather than removing carbon from the atmosphere once the pollution has been released into the air. Nonetheless, the carbon capture process overlaps with direct air capture—progress in one area can inform and benefit the other. Both are attractive to businesses, investors, governments, and environmentalists because of their ability to slow climate change. For the purpose of this paper, we will discuss CCUS and companies using this process as it relates to technological CDR.

Despite the private sector’s progress on technological CDR, uncertainty still persists surrounding its long-term viability. Most mainstream financial analysts, private equity firms, asset managers, fossil fuel companies, and venture capitalists see CDR as a high-risk investment, keeping some on the sidelines. Given the high up-front infrastructure costs and the long timeframe to see positive financial returns from technological CDR, many of these investors will likely remain hesitant. The marketplace needs to mature in order for more capital to enter, and critics question whether the industry can scale up quickly enough to become profitable and significantly draw down emissions this century. DAC costs have been estimated as being too high to be economical. Even though company analysis and peer-reviewed studies say the cost is as low as approximately \$100 per ton and may fall further, business prospects remain uncertain and challenging in a purely private-sector driven investment environment.

Because technological CDR is essential and yet far from guaranteed, governments should adopt policies that speed progress while also managing potential economic, financial and environmental risks from these untested technologies. In the United States, the federal government has a large role to play in advancing technological CDR. Startups need resources to determine viable long-term business models and investors see the sector as high risk. Moreover, technological CDR technology needs to advance to a more mature stage before it can significantly impact emissions. Experts argue that public-private partnerships are crucial to developing a mature marketplace. Just as critical is the importance of the U.S. government-led action to export appropriate CDR technologies and strategies for deployment to other countries. Given that combatting climate change is a global effort, other markets will need to scale up alongside the United States.

This report includes recommendations for policymakers to facilitate the widespread use of technological CDR in the United States. A tax credit passed in the 2018 Budget Act to support deployment of carbon capture projects, including direct air capture, in the United States could be the catalyst for government action on fostering the growth of technological CDR. Policymakers should understand that achieving both climate and commercial goals will require long-term commitments and safeguards to mitigate unintended consequences of using technological CDR. Despite polarization in the U.S. Congress, particularly with regards to climate change, lawmakers mostly agree on the potential and benefits of CDR technology. Amid bipartisan support for technological CDR in Washington, D.C., now is an opportune time to enact more policy levers, which could include carbon pricing, research and development programs, direct funding to startups and universities, government procurement of products with CO₂, extension of tax credits, technology transfer to other countries, and other measures.

Introduction

Interest in technological approaches to CDR among people concerned about climate change and those who want to make money from climate solutions is skyrocketing. A number of new companies have moved forward rapidly with CDR technologies to help meet global climate policy goals, including the benchmark set in the 2015 Paris Agreement, which aims to keep global warming below 2°C. Yet, uncertainty continues about how much of a role technological CDR will play in helping to solve climate change in the medium to long term. It is clear that CDR technological advances are crucial to reaching the United States' and the world's climate goals, but research, discussions and investment are still at early stages. Despite progress in CDR technologies and their long-term promise, investor appetite remains cautious due to a variety of risks, and as a result, companies have yet to scale up. Given the nascent state of the industry and the urgency to decarbonize in the next few decades, policymakers should help accelerate momentum on technological CDR to fully bring it into the mainstream. Public investment is needed not only to mobilize private investment, but also to ensure the data generated from pilot deployments are publicly available to researchers, fostering further innovation.

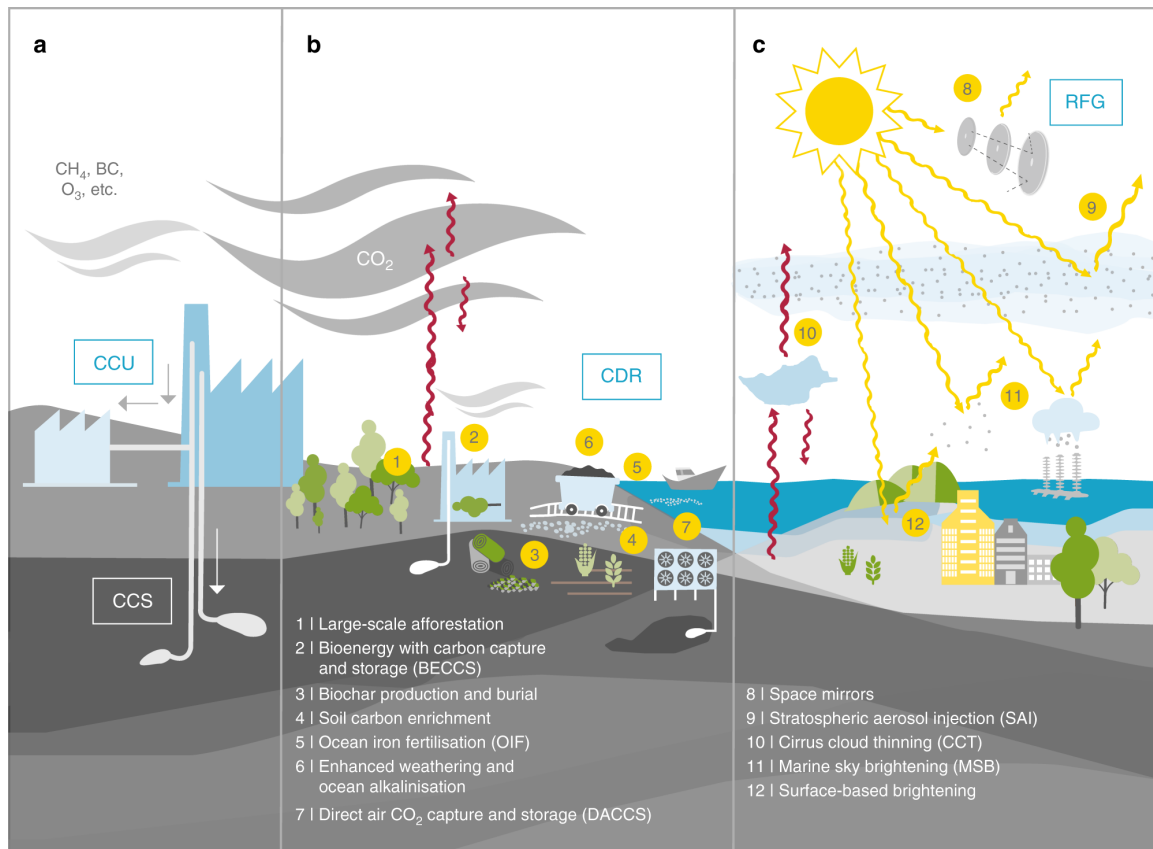
What Is Technological Carbon Dioxide Removal?

As the climate crisis worsens, scientists, engineers and technology companies are looking toward innovation to mitigate the impacts of climate change. Removing carbon directly from the atmosphere, sometimes referred to as negative emissions or carbon dioxide removal (CDR), involves a range of technologies. For the purposes of this report, technological CDR includes advanced technological innovations to remove CO₂ emissions from the atmosphere. These technologies include but are not necessarily limited to:

- Bioenergy with carbon capture and storage (BECCS)
- Biochar
- Ocean iron fertilization
- Direct air carbon capture and storage (DACCS) or utilization
- Enhanced weathering and ocean alkalization

See Figure 1 below for how the technologies relate to other options to remove or capture carbon. Direct air capture involves taking CO₂ out of ambient air. BECCS is the process of transforming trees and crops into power or fuel by essentially retaining CO₂ embodied in biomass that previously took CO₂ out of the atmosphere. Biochar, developed from burning biomass and using it to improve soil quality, sequesters CO₂ in the soil. Enhanced weathering and ocean alkalization involve the process of dispersing reactive minerals on land or the ocean to absorb CO₂.

Figure 1: Carbon Management Options



Source: Nature²

This paper includes a heavy focus on direct air capture (DAC) because it is the CDR technology that is most advanced and will likely be the most effective and economical over the long run. At times, we also discuss carbon capture utilization or storage (CCUS) at length. Even though CCUS keeps CO₂ from entering the atmosphere, it does not achieve emissions *reductions* as it does not take carbon out of the air. However, CCUS has numerous similarities with DAC and has experienced important economic, political, and marketplace breakthroughs in recent years.

Carbon removal alone will not draw down enough CO₂ emissions to reach our climate goals. A vast array of solutions is needed to solve climate change: Renewables, alternative transportation sources, fuel efficiency, and reforestation are all required. However, technological CDR is another key contributor to add to this list, as it can provide a vital interim solution until the world economy can fully decarbonize.

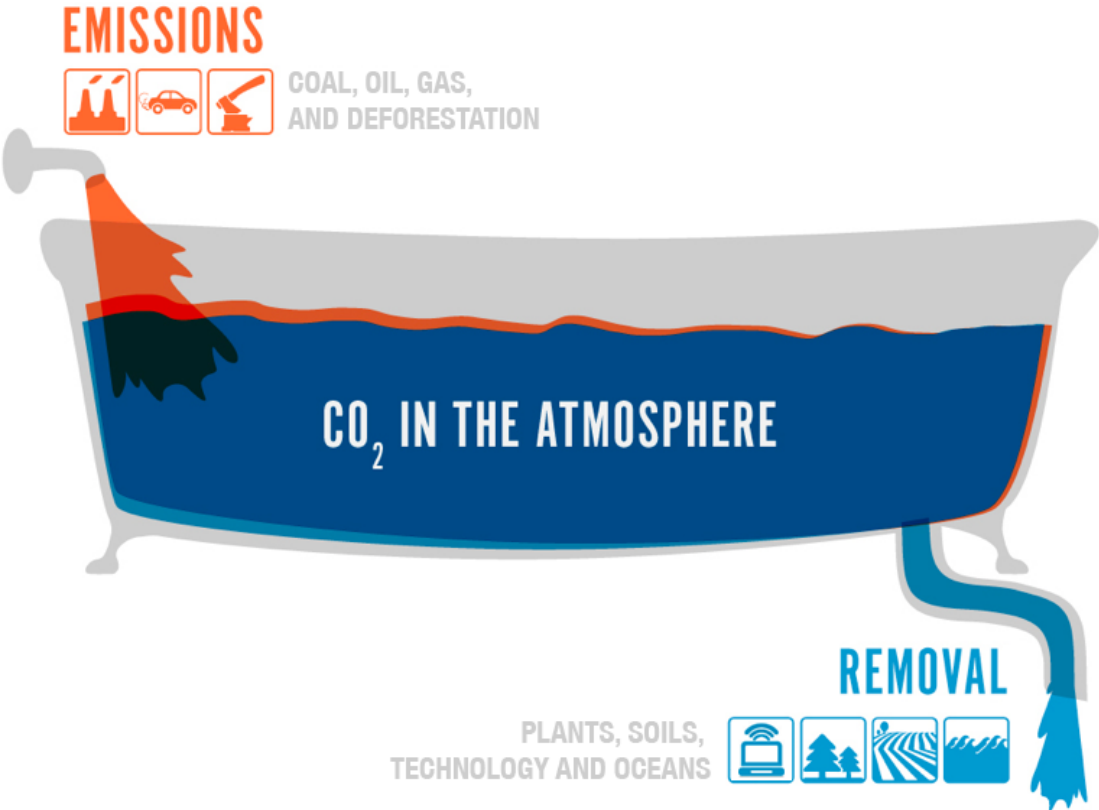
The Urgency to Act

The recent Special Report on Global Warming of 1.5°C from the Intergovernmental Panel on Climate Change (IPCC), which is the UN body that analyzes climate science, highlighted the urgency with which the world will need to act to limit damages caused by climate change and to limit the increase in warming to 1.5°C above pre-industrial levels. The report makes special mention of carbon removal alongside emission reductions, stating clearly that technological CDR is necessary for both moving to net-zero

² Lawrence, Mark, et al. "Evaluating climate geoengineering proposals in the context of the Paris Agreement temperature goals." *Nature Communications*. September 13, 2018. <https://www.nature.com/articles/s41467-018-05938-3>

emissions and for producing net-negative emissions to compensate for any overshoot of 1.5°C. The pathways studied in the report rely on different levels of carbon removal (ranging from 100-1,000 Gt CO₂ over the 21st century for scenarios with limited or no overshoot), but all rely on it to some extent. The report notes that technological CDR deployed at such a scale is unproven, and is a major risk to our ability to limit warming to 1.5°C. The report also notes that the feasibility and sustainability of technological CDR could be enhanced if a portfolio of carbon-removal approaches is pursued.

Figure 2. Emissions and Removal



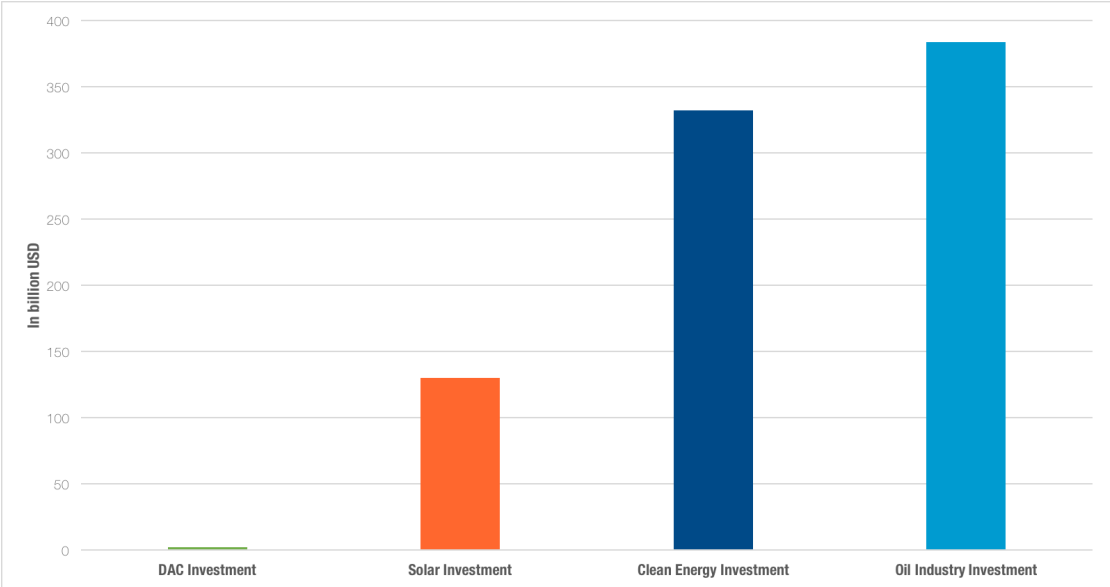
I. Carbon Removal in the Real Economy

Interest in CDR among entrepreneurs and investors has grown significantly in the past decade, and particularly after the IPCC published its 2018 report.

As CDR technology evolves and experts reach a consensus that the world must creatively incorporate a variety of solutions in mitigating climate risks, companies see an opportunity to both become profitable and offer solutions to fighting climate change. Firms have raised capital, conducted research, and tested their technologies. But widespread commercialization is still distant. For instance, so far only one company – Climeworks AG, which is based in Switzerland – has an operating commercial DAC plant. Two companies in North America – Global Thermostat and Carbon Engineering – are nearing commercialization in this space. Another startup, Infnitree – based in Cold Spring Harbor, New York and founded in 2014 – is also developing DAC technology, but is lagging behind the others in the commercialization process.

Despite the lack of public investment in CDR technology, progress among the DAC companies reflects the promise of this technology. However, the nascent industry faces many challenges: For DAC to have a significant impact on emissions, it must be wide-scale and economical. See Figure 3 below: The three leading DAC companies have raised almost \$170 million since 2009, a paltry amount compared to capital expenditures of other industries. The success of these DAC companies is crucial for the viability of the industry for the longer term. If they do not achieve an economic scale, investors may become even more cautious. Should the companies succeed, it would open the door for more entrants and an influx of capital. However, the scale needed is massive – a study led by Jan Minx of Germany’s Mercator Research Institute on Global Commons and Climate Change says that in order to capture the necessary amount of CO₂ to keep warming at 1.5°C to 2°C through the end of the century, the world would need to build “several hundred” facilities every year between 2030.³

Figure 3. Direct Air Capture Investment (2009-18) Versus Other Industries (2018)



Note: DAC number is based on capital received from investors

³ Minx, Jan, et al. “Negative emissions – Part 1: Research landscape and synthesis.” *Environmental Research Letters*. May 22, 2018. <https://iopscience.iop.org/article/10.1088/1748-9326/aabf9b>

Sources: News reports, company data, BNEF, Barclays

Some companies are exploring using enhanced weathering, BECCS, and biochar to both cut CO₂ and make profits, but despite a handful of success stories, most operations have not yet gone far beyond the research stage. Researchers point out that these technologies are not ready for large-scale use due to high costs and unintended negative environmental impacts.

This section looks at the economic opportunities in the different carbon removals technologies, which ones hold the most promise, the leading companies, and what actions investors are taking.

DAC Companies Look to Utilization

A lot has gone well for direct air capture – policymakers are showing more interest, startups are developing the technology, costs are high but falling, and one DAC company (Climeworks AG) has commercialized and captured the imagination of both supporters and critics of CDR.

Despite this progress, a question loomed over the nascent industry about how companies could generate profits in the long term by capturing CO₂. Companies are looking to use the carbon they take from the air and turn it into commercial products they sell. Climeworks is already progressing in this area. The growing success of Climeworks, both technologically and financially, will likely inform other DAC initiatives, such as Global Thermostat and Carbon Engineering, and companies looking to profit with carbon capture. As of the third quarter of last year, Climeworks had raised more than \$51 million and constructed nine DAC facilities in six countries.⁴ In Iceland, Climeworks' facility has stored CO₂ it captures in basalt rock, and the company has struck a deal with Coca-Cola's subsidiary in Switzerland for CO₂ use in its soda drinks. This partnership provides the opportunity for Climeworks to commercialize the CO₂ it removes from the atmosphere, helping it meet its goal of capturing one percent of global CO₂ emissions by the middle of next decade. As of now, however, the company is taking only a modest amount of CO₂ out of the air – 1,100 metric tons annually at its three plants that are now running.⁵ Estimates say that 400 DAC facilities are needed to draw down one percent of emissions from the atmosphere.⁶ As noted earlier, Minx's study projects that hundreds need to be constructed each year to pull enough CO₂ out of the air to keep warming to 1.5 degrees.

Why Can't the Industry Move Faster?

Even though a number of companies are now testing CDR technology, overall investment remains low, particularly when considered in the context of the myriad climate challenges. Firms in this nascent industry need outside funding because their technology has, for the most part, not gone beyond the pilot phase and reached commercialization. Entrepreneurs are currently in the process of seeking a sustainable business model. "High cost barriers to entry prevented companies from pushing forward on innovation, which in turn prevented the technology from getting cheaper," said Jesse Jenkins, a leading scholar on climate change and clean energy.⁷

⁴ Sampson, Joanna. "Climeworks raises funding to commercialise CO2 removal technology." *Gasworld*. August 28, 2018. <https://www.gasworld.com/climeworks-raises-funding/2015328.article>

⁵ Rathi, Akshat. "Climeworks has opened a third plant capturing carbon dioxide from the air." *Quartz*. October 1, 2018. <https://qz.com/1407687/climeworks-has-opened-a-third-plant-capturing-carbon-dioxide-from-the-air/>

⁶ Siegel, RP. "The Fizzy Math of Carbon Capture." *Grist*. October 10, 2018. <https://grist.org/article/direct-air-carbon-capture-global-thermostat/>

⁷ Kahn, James. "Can Updated Tax Credits Bring Carbon Capture Into the Mainstream?-Greentech Media." Carbon Utilization Alliance. February 26, 2018. <https://www.cua.earth/news/2018/2/26/can-updated-tax-credits-bring-carbon-capture-into-the-mainstream-greentech-media>

Based on conversations with a variety of stakeholders, investors are eyeing companies working on carbon removals but see minimum “deal-quality”—there is not yet a strong enough business case to invest in companies and the industry is not yet near maturity. Private equity, venture capitalists, wealthy individual donors, angel investors, integrated companies and governments have all contributed to funding companies working with CDR technology, whether they are corporations, start-ups, or university pilot programs, but many still lack sufficient funds and are only slowly seeing commercial prospects. The ghost of the 2008 economic recession and losses in renewable energy for venture capitalists early this decade still hover over the financial sector, prompting potential investors to remain cautious. Traditional venture capitalists veer toward industries such as pharmaceuticals and software, both of which provide relatively short payback periods. By contrast, carbon removal requires large-scale infrastructure investments and growth and profits will occur over long-term horizons. Given that the tax credit for DAC just recently went into effect, it is too early to tell how much of an impact this measure will have overall. In the next few years, demonstrating the feasibility of the technology and how costs could be reduced will be key developments to watch.

Companies’ success with using DAC technology to convert CO₂ into commercial products that turn a profit in the coming years and decades will depend on the overall economics of the marketplace, the levels of risk investors are willing to take on new companies, and what policy levers are implemented to hasten deployment. Nonetheless, given the growing interest, enthusiasts of the technology believe the industry is on the cusp of reaching a turning point, saying that once the economics are favorable and the right policy levers are in place, the marketplace will be “de-risked”—established companies will see their products become more widespread and newer firms will also enter the marketplace. Others, however, are less optimistic, noting the financial hurdles may be too high to overcome and the trepidation of established companies, such as oil companies or cement makers, to integrate CDR technologies in their businesses may take longer than anticipated. Moreover, the capital-intensive nature of the CDR industry suggests to some stakeholders that technologies will be deployed slowly.⁸

New Research Sheds Light on Price of Carbon

Currently, Global Thermostat, Carbon Engineering and Climeworks are the leaders in DAC because of their early investments in this space, their financial support, and name recognition. Climeworks, based in Switzerland, is already operating commercial DAC plants, but on a small scale. The relative success of these three companies indicates that commercial operation is possible, but also shows the large number of obstacles the industry must overcome before becoming self-sustainable and having an impact on reducing global carbon emissions.

Carbon removal would become economically feasible on a large scale if there is a price on carbon at the federal level in the United States. Even if carbon pricing comes to realization, it’s unclear what overall costs would be. So far, the literature is sparse on how much carbon removal will cost, but recent groundbreaking research has shed light in this area, a big development for industry and investors. Global Thermostat and Carbon Engineering say they are nearing the threshold of \$100 per ton, making DAC close to becoming an economic reality.⁹ Carbon Engineering last June published an article in the scientific journal *Joule* describing its process for DAC and its ability to reduce costs to below \$100 per ton. The company’s analysis, which is the first paper with a breakdown of engineering costs for DAC, shows that

⁸ Ahmad, Fatima. “CO₂ Utilization: A Look Ahead.” Center for Climate and Energy Solutions. January 2017. https://www.c2es.org/document/co2-utilization-a-look-ahead/#_ednref16

⁹ Keith, David. “Climate Change Breakthrough: Large-scale capture of atmospheric CO₂ shown to be feasible and affordable.” Carbon Engineering. June 7, 2017. <http://carbonengineering.com/climate-change-breakthrough/>

the DAC process is cheaper than previously believed. If correct, the company's estimates, along with Global Thermostat's, should shift expectations that DAC can become economical in the foreseeable future. Before Carbon Engineering's article, a 2011 study from the American Physical Society was the main source for the price of DAC, saying that the cost would be near the \$600 per ton range level, concluding that it is "not currently an economically viable approach to mitigating climate change."¹⁰ But that estimate was inaccurate, the researchers now admit. Despite the optimism surrounding the \$100 per ton cost, companies currently still face unfavorable economics, as the National Academies of Sciences noted.¹¹ NAS, though, said that with federal investment of \$180-\$240 million per year, the price would fall below \$100 per ton within the next two decades.¹²

Combining Renewable Energy With DAC

Besides its high costs, another criticism of DAC stems from its intense energy use. DAC plants must use low- or zero-carbon energy in order to counteract CO₂ benefits. The negative emission potential of DAC increases when facilities use renewable energy for power, making DAC a more viable long term option to combat climate change. With the falling price of renewables (see Figure 4 below), the business case of utilizing solar, industrial waste or renewable heat becomes more attractive for DAC facilities. "The availability of cheap renewable energy provides an opportunity to implement negative emissions that were previously considered uneconomic," said a group of researchers writing in Carbon Brief.¹³ "DAC, for example, can provide some of the flexibility that is needed for system integration of renewables."

Figure 4. Annual Decline of Solar Prices, Increase in Installations

¹⁰ "Direct Air Capture of CO₂ with Chemicals." American Physical Society. June 1, 2011.

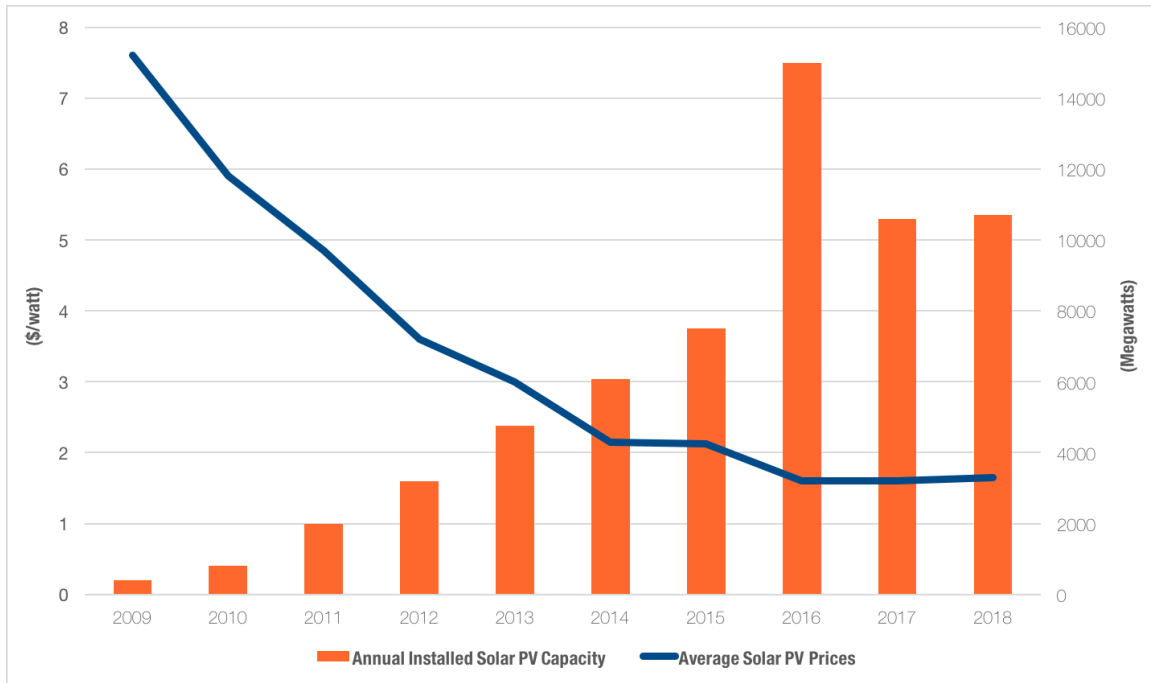
<https://www.aps.org/policy/reports/assessments/upload/dac2011.pdf>

¹¹ "Technologies That Remove Carbon Dioxide From Air and Sequester It Need to Play a Large Role in Mitigating Climate Change, Says New Report; Some of These Technologies Can Be Deployed Now, But Additional Ones Are Needed to Meet Climate Goals." The National Academies of Sciences, Engineering, and Medicine. October 24, 2018.

<http://www8.nationalacademies.org/onpinews/newsitem.aspx?RecordID=25259>

¹² "Negative Emissions Technologies and Reliable Sequestration: A Research Agenda." National Academies of Sciences, Engineering, and Medicine. 2018. <https://www.nap.edu/catalog/25259/negative-emissions-technologies-and-reliable-sequestration-a-research-agenda>

¹³ Wohland, Jan, et al. "Combining renewables with direct air capture for 'net negative' emissions." *CarbonBrief*. July 11, 2018. <https://www.carbonbrief.org/combining-renewables-with-direct-air-capture-for-net-negative-emissions>



Sources: SEIA, Wood Mackenzie

DAC Companies in North America

For DAC to scale up as a solution to climate change, a wide variety of actors that can monetize the technology is necessary. Moreover, the number of facilities needs to reach a global scale. However, as noted, so far the list of DAC companies is small. Global Thermostat and Carbon Engineering are the two main North American companies currently utilizing DAC. Given that taking CO₂ out of the air and permanently storing it underground is costly, their business models depend on using the CO₂ to create a market by converting it into materials for plastics, synthetic fuels, beverages, or other commercial products – similar to what Climeworks is intending to do. The viability of this business plan depends on the captured CO₂ contributing to valuable mass-market products. Both companies are nearing commercialization – Global Thermostat with a DAC plant in Huntsville, Alabama and Carbon Engineering with one in Squamish, British Columbia.

Economic Criticisms of Direct Air Capture

From a business perspective, DAC has come under criticism. Critics argue that carbon capture utilization and storage (CCUS) holds more promise for developing sustainable business models. CCUS involves capturing CO₂ from an emitting source (such as a power plant) and turning it into a marketable product or sequestering it underground. DAC companies can essentially construct facilities anywhere, but the technology is more expensive – DAC facilities pull CO₂ that is dispersed throughout the atmosphere, making it difficult to capture large volumes at one time. This factor is important regarding both its environmental impact and business potential. In order for DAC to be successful, it needs to suck large volumes out of the atmosphere by achieving scale, which is challenging due to its high costs. By contrast, in the CCUS process, the concentration of CO₂ is higher than what a DAC plant can pull out of the atmosphere. This could make CCUS more economical than DAC because it can capture higher volumes of CO₂ to use in commercial products. It is also faster, simpler and requires less energy. With CCUS, instead of using the CO₂ captured for commercial products, companies may also store the CO₂

underground, as can firms using DAC. However, the CCUS process is more controversial since critics argue it helps extend the life of fossil fuel plants. Globally, there are approximately 43 carbon capture and sequestration plants that are either operating, under construction or being developed.¹⁴ In the United States, the main large-scale carbon capture and sequestration power facility is the Petra Nova power plant near Houston, Texas, which has reportedly captured 90 percent of emissions.¹⁵ When putting the economics aside, it is important to note that DAC and CCUS provide different functions. DAC is crucial to remove carbon from the atmosphere, particularly if the world “overshoots” on emissions. CCUS cannot perform the same function of reducing atmospheric concentrations of CO₂.

The CCUS industry has seen a large rise in entrants, in large part because it has been around for decades and has received billions of dollars in public investment. Analysts see CCUS growing even more sharply in the coming years. For instance, the consultancy McKinsey and Company and CO₂ Sciences, Inc. estimate that the annual market size for the development and commercialization of CO₂-based products could reach \$1.1 trillion by 2030, cutting 10 percent of global emissions annually. Stakeholders who spoke to Climate Advisers for this paper suggest that the McKinsey estimate is conservative. However, as of now, despite the potential, new firms are facing difficulties – similar to DAC companies – raising enough capital from investors and finding a stable customer base for their products. Moreover, CCUS has come under criticism from some environmental groups that argue the carbon capture process does not achieve negative emissions and instead benefits incumbent fossil fuel interests.

A good bit of commonality exists between DAC and CCUS. Some startups developing conversion technology are looking to team up with DAC companies to provide them with CO₂. Moving forward, the economics for each individual startup will determine whether they use CO₂ from DAC facilities or from an industrial source. Ultimately, all the companies in this space are seeking to create a “circular carbon economy,” which entails taking CO₂ out of the atmosphere (or keeping it from ever entering the atmosphere in the first place) and then re-using it. The Ellen MacArthur Foundation defines the circular carbon economy as follows: “It entails gradually decoupling economic activity from the consumption of finite resources, and designing waste out of the system.”¹⁶

Limited Economic Potential of CDR Technologies Outside of DAC

Outside of DAC, the economic potential from other CDR technology in the short to medium term is limited. The number of companies utilizing enhanced weathering, ocean iron fertilization, BECCS or biochar is small at the moment. These methods, with a few exceptions, are not yet profitable and need more research. Moreover, some have seen their own controversies and criticisms because of questions about their environmental impact.

Currently in the United States, there is only one large-scale BECCs facility, which was funded with \$141 million through the American Economic Recovery and Reinvestment Act of 2009.¹⁷ The project, called Illinois Industrial Carbon Capture and Storage, is a collaboration between the Department of Energy and ADM, and captures one million metric tons of CO₂ per year at a corn ethanol facility. The biofuel plant

¹⁴ “The Global Status of CCS.” Global CCS Institute. 2018. <https://indd.adobe.com/view/2dab1be7-edd0-447d-b020-06242ea2cf3b>

¹⁵ “Two DOE-Supported Projects Receive Awards for Carbon Capture Technologies.” Office of Fossil Energy. December 7, 2017. <https://www.energy.gov/fe/articles/two-doe-supported-projects-receive-awards-carbon-capture-technologies>

¹⁶ “What is a circular economy?” Ellen MacArthur Foundation. <https://www.ellenmacarthurfoundation.org/circular-economy/concept>

¹⁷ Mooney Chris. “The quest to capture and store carbon and slow climate change just reached a new milestone.” The Washington Post. April 10, 2017. https://www.washingtonpost.com/news/energy-environment/wp/2017/04/10/the-quest-to-capture-and-store-carbon-and-slow-climate-change-just-reached-a-new-milestone/?noredirect=on&utm_term=.66cdddee4344

strips out the CO₂ as the corn is converted to ethanol. The CO₂ is then stored underground. The ADM scheme is different than other BECCS projects, which include power plants burning wood to produce electricity and capturing the CO₂.

BECCS is a crucial part of the suite of CDR solutions necessary to limit warming to 1.5 degrees, according to the IPCC. Infrastructure constraints – such storage sites and access to transportation for CO₂ and biomass – and the fact that widescale utilization would require land and water use reflect the myriad challenges that BECCS faces in order for commercialization to occur. According to the Proceedings of the National Academy of Sciences, about 30 percent of the United States' biomass could be used for BECCS. At that level, BECCS projects would remove 100 megatons of CO₂ annually, the equivalent of 1.6 percent of the emissions reductions needed by 2030. The IPCC has continued to highlight the importance of BECCS, but its reports have given it less relevance over time, the result of its continued high costs, the large scale necessary to make a meaningful impact on emissions, and the emergence of other technologies and strategies to combat climate change.¹⁸

Enhanced weathering, the process of dispersing reactive minerals on land or the ocean to absorb CO₂, is energy intensive and costly. Companies looking to monetize enhanced weathering may have to factor in the costs of mining and crushing the rock. Moreover, transporting and distributing the rock to spread on cropland may also further escalate costs, while also increasing the environmental footprint of the project. There are, however, some means of enhanced weathering that do not involve mining or crushing rock. Other issues to consider are the natural process of weathering absorbing CO₂ slowly and the fact that it is best done in humid areas. A study by the Potsdam Institute for Climate says enhanced weathering could become economical at between \$60 to \$200 per ton, depending on the type of rock. Altogether, a number of large hurdles are in the way of enhanced weather becoming realized on a large scale. Thorben Amann of Hamburg University's Institute for Geology, Center for Earth System Research and Sustainability pointed out how costly one version of enhanced weathering is: "To sequester one billion tons of CO₂, more than three billion tons basalt would have to be spread, a mindboggling amount equal to almost half of the current global coal production. Grinding the rocks and spreading the powder over roughly one-fifth of global cropland would be necessary, which is believed to be feasible, but -- due to the gigantic amount of rocks involved -- the costs eventually add up."¹⁹

Biochar Market Holds Promise, Set to Grow

Biochar, a product that is developed from burning biomass and using it to improve soil quality. Companies see biochar as both a climate change solution – CO₂ is sequestered in the soil for hundreds of years – and a commercial product. Companies investing in the technology predict biochar becoming a multi-billion industry in the coming decade. The biochar market is still nascent, but it is working its way into the mainstream with new scientific research and technology.

The market for biochar has grown significantly in recent years as knowledge of its potential to sequester carbon has gained more traction. Growers, mostly farmers, purchase biochar to spread on their cropland to increase its productivity, help it retain water, and absorb CO₂. The demand for biochar (some refer to it as engineered biocarbon) is on the rise among farmers wanting to improve the health of their soil. Consultancy Grand View Research sees the biochar market growing by 13 percent annually to reach \$3.15

¹⁸ Aton, Adam. "Forests are 'really central' to 1.5 C." E&E News. October 9, 2018.

<https://www.eenews.net/climatewire/stories/1060101837/>

¹⁹ Potsdam Institute for Climate Impact Research. "Enhanced weathering of rocks can help pull CO₂ out of the air". ScienceDaily. March 6, 2018. <https://www.sciencedaily.com/releases/2018/03/180306101711.htm>

billion by 2025.²⁰ The customer base may expand to retail, turf, nursery, ornamental, and government. The environmental benefit of biocarbon is clear: Given that carbon is stored in the soil for hundreds of years, it does not circle back into the atmosphere. The combination of its environmental and economic value should allow biochar to grow in value and marketability over the longer term.

Companies are taking advantage of this demand increase. One main example is Cool Planet, a Colorado-based company that produces a biochar-based soil amendment in California. The company's product is sold commercially, and it has received funding from large donors and is seeking additional investment. In Cool Planet's Series A funding last year, which totaled \$20 million, North Bridge Ventures and Augustin Coppel in Mexico gave the largest injections, while others such as family offices and venture capitalists also provided funding. Founded in 2009, Cool Planet initially invested in fuels technology along with biocarbon research and testing. In 2014, when petroleum prices dropped sharply, management decided to abandon the project for a large-scale fuel plant and fully pivoted to agriculture and biocarbon. With industry seeking to reduce greenhouse gas emissions and bolster the health of soils, Cool Planet believes its technology intersects both of those goals. It is currently in talks with big agriculture companies to displace the use of peat, which is not environmentally friendly since it releases CO₂ when it is burned.

This year, Cool Planet plans to build a plant in Alexandria, Louisiana, to manufacture its biochar-based soil amendment. It wants to expand, too, by building facilities in Georgia, Wisconsin, Oregon and Colorado. These locations would allow the facilities to be close to both the biomass source to produce the biochar and close to customers. The facilities would allow Cool Planet to produce enhanced biochar on a large scale. By contrast, most biochar currently on the market is chunky and dusty, which is less productive for users.

One recent policy development may help accelerate development for biocarbon products, underpinning demand. The Agriculture Improvement Act of 2018, the so-called Farm Bill, passed with overwhelming bipartisan support in the U.S. Congress and included provisions for pilot programs to help farmers increase carbon in their soil, the first time the government has ever supported sequestering carbon in soil.²¹ The law does not mention biochar specifically but creates an environment that should bolster its market longer term. Even so, there are numerous technological, feedstock, and logistical challenges surrounding creating a consistent and robust biochar market.

²⁰ "Biochar Market Size Worth \$3,146.1 Million by 2025". Grand View Research. May 2017.

<https://www.sciencedaily.com/releases/2018/03/180306101711.htm>

²¹ Eideberg, Callie. "How the farm bill changes the future of climate and water conservation." Environmental Defense Fund. December 12, 2018. <http://blogs.edf.org/growingreturns/2018/12/12/farm-bill-climate-water-conservation/>

II. Political State of Play in the United States

Advanced CDR technology solutions now enjoy rare bipartisan policy support in Washington, D.C. The best example of this is seen in the recently reformed tax credit known as 45Q, an incentive to support the deployment of carbon management projects in the United States. The legislation, introduced in 2017 as the FUTURE Act, received broad bipartisan support in Congress, from governors and other state leaders, and a diverse coalition of industry, labor, and environmental supporters.²² The revamped 45Q tax credit boosts the amount of money available to companies willing to capture and store carbon emissions in geologic formations or use CO₂ to extract oil from existing wells. And crucially, the credit now includes DAC.

The emergence of this broad type of political support for carbon removals in the United States means there is an opportunity to capitalize on the momentum brought by existing legislation and develop further measures to act on climate change. Currently, carbon removals may be the only climate measure able to pass political muster in this country. However, despite recent progress, political uncertainty is a major concern with CDR technology, which reinforces the hesitancy of private sector and investor action.

This section looks at the history of 45Q, the bipartisan consensus surrounding technology for carbon removals, the major organizations behind carbon removals, and new ways government can facilitate the acceleration of this technology.

Government Support Critical

Given that not enough capital in the industry yet exists for widespread adoptions of CDR, government support is critical and will likely remain so for the foreseeable future. As the industry is capital-intensive and requires high up-front costs, government can provide support in various ways until costs fall to a manageable level for stakeholders and the technology is deployed at a large scale. Political resolve from across the ideological spectrum will likely continue to exist for advancing innovation in technological CDR. Section 45Q is only one of many potential policy levers to accelerate carbon removals. The opportunities and challenges now are leveraging this bipartisan support to adopt a broader range of federal policy incentives and programs that would speed the development and deployment of carbon removals. Besides reducing carbon emissions, technological CDR can support and create new domestic jobs, bolster national security, and cut the nation's trade deficit. Stakeholders argue that a wide variety of government action is essential for accelerated deployment: Research and development funding, along with other key actions, can provide an environment where entrepreneurs can profit and bring their technologies to the market as soon as possible.

Stakeholders see a variety of areas where the government can work to share market risks with commercial participants. Government can help with funding research and development. The technologies need more capital than a research lab but are considered too risky for most funders. By providing direct funding, governments can spread risks for companies and provide the opportunity to scale up the technologies until they become commercially viable. Simply put, investment in research can facilitate decreases in price and overall costs. Tax credits, whether through a revamped 45Q or a new credit, would stimulate innovation and provide certainty to the industry.

²² "Furthering carbon capture, Utilization, Technology, Underground storage, and Reduced Emissions Act". 115th Congress. July 12, 2017. <https://www.congress.gov/bill/115th-congress/senate-bill/1535/text>

Another lever is government procurement. With the federal government or states taking the lead with buying products made from CO₂, they can provide companies with a stable customer base in their initial commercial phase.

Carbon pricing is the most effective tool the government could implement to help entrepreneurs and investors in this space. Implementing a pricing mechanism is a critical government action that would provide support to the entire industry. Although some companies are confident that they will be profitable regardless of a price on carbon, such government action would send a strong signal to companies and investors for longer-term planning.

45Q's Broad, Bipartisan Support

The 45Q provision found widespread bipartisan support, an anomaly in today's increasingly polarized politics. Co-sponsors of the FUTURE Act in the Senate included Democrats Heidi Heitkamp from North Dakota and Sheldon Whitehouse from Rhode Island, and Republicans Shelley Moore Capito of West Virginia and John Barrasso of Wyoming. Mike Conaway, Republican of Texas, sponsored the companion bill in the House. The 45Q provision first emerged in the Energy Improvement Extension Act of 2008, but it was mainly geared toward enhanced oil recovery and critics pointed to the credit value being too low. As a result, discussion to enhance its effectiveness started at the beginning of this decade. In 2015, the Obama administration sought to correct the credit's shortcomings and the following year, Heitkamp and Whitehouse introduced legislation to expand 45Q. It did not make it through Congress at that time. In 2017, however, the FUTURE gained traction among both Democrats and Republicans and was ultimately folded into the Bipartisan Budget Act of 2018 during the 115th Congress.

The amended Section 45Q in the 2018 Budget Bill increased the value of the tax credit by \$30 to \$50 per ton for permanent sequestration, while raising the credit for enhanced oil recovery (EOR) by \$25 to \$35 per ton. It also removed the cap of 75 million tons on the amount of CO₂ that can be injected underground. Just as critical, the credit expands the types of technology that qualifies. DAC and conversion of CO₂ into commercial products are now permitted for the credit, rather than only EOR, which ultimately leads to higher emissions when the oil is burned.

While CDR is not universally loved—some on the left fear focusing on removal will alleviate pressure on polluters to mitigate their emissions—carbon removal is the most popular climate solution in Washington at the moment. Most climate advocates and liberal policymakers now understand that deploying environmentally-sound carbon removal technologies at scale is essential for meeting ambitious longer-term climate goals. “In establishing the level of the tax incentive for CO₂ capture, the 115th Congress has tacitly placed a value on avoiding CO₂ in the atmosphere,” said Energy Futures Initiative.²³ Fossil fuel companies and conservative policymakers, meanwhile, support investments in new CDR technologies since they could help companies that produce hydrocarbons meet climate targets while also creating jobs. The conservative-leaning think tank ClearPath estimates that hastened deployment of carbon capture technology, with help from the government, can add 780,000 jobs and almost \$200 billion to U.S. GDP by 2040.²⁴ The International Energy Agency says that the credit could “trigger the largest surge in carbon capture investment of any policy instrument to date,” adding \$1 billion in investment over the next six

²³ “Advancing Large Scale Carbon Management: Expansion of the 5Q Tax Credit.” Energy Futures Initiative. May 2018. https://static1.squarespace.com/static/58ec123cb3db2bd94e057628/t/5b0604f30e2e7287abb8f3c1/1527121150675/45Q_EFI_5.2_3.18.pdf

²⁴ Ong, Justin. “Making Carbon a Clean commodity.” *Clearpath*. September 20, 2018. <https://clearpath.org/jay-and-richs-take/making-carbon-a-clean-commodity/>

years and as much as 30 million tons of CO₂ capture capacity.²⁵ Experts argue that heavy industries will be the main beneficiaries of the tax credit. The impact on companies building DAC facilities may be muted in the short term, however, unless costs do in fact drop below \$100 per ton during the eligibility timeframe.

A long list of stakeholders from along the political spectrum backed the 45Q measure, helping revamp the credit after seven years of negotiation. A broad coalition of NGOs and industry players, along with labor groups, backed the measure, which portends the likelihood of continued coordination. A number of oil companies favored 45Q. ClearPath lobbied conservative lawmakers, and Carbon180 was a major player on the liberal side. Others that backed the measure include the Bipartisan Policy Center, the Carbon Capture Coalition, Energy Futures Initiative, Rhodium Group, Spitfire Strategies and the World Resources Institute.

These organizations have mostly taken a pragmatic approach to influence federal policy to bolster efforts to reduce carbon. They have worked with industry, scientists, academics, and other NGOs to foster more research and scholarship in this area, as well as support technology and climate science. With the new Democratic House of Representatives and climate change in the news on a daily basis, progressive organizations are optimistic that climate will rise on the Washington agenda and allow for progress on carbon removal policy, such as direct funding for DAC, increased Department of Energy activity in this space, expansion of existing tax credits, and support for public-private partnerships.

Leading conservative organizations are likely to remain in favor of more federal policy steps to support carbon capture technologies, including DAC. They take a different approach to climate than environmental groups, believing carbon capture is not only beneficial to fight climate change, but can also improve the market for coal plants and enhance the economics of incumbent fossil fuel industries. Conservative outfits, generally speaking, seek to bring about environmental improvements through technology. Some companies in the oil industry have become advocates of using carbon capture/removal technology, which allows companies to raise their ambition surrounding climate change and reduce their overall carbon footprint. RoyalDutch Shell and Chevron, for example, along with other major international oil companies, have developed CCUS projects that capture emissions at their operations and inject them into rock or below the surface, permanently sequestering the CO₂. The Oil and Gas Climate Initiative, a voluntary group of major oil companies, has allocated more than \$1 billion to technologies to reduce emissions, with about half of the amount invested in CCUS.²⁶ As industry players continue to come under pressure from investors and governments to cut emissions while also meet the demand for growth, companies will continue to look for technologies for carbon mitigation. However, carbon capture at oil and gas facilities is a high-cost operation, and it is dependent on government subsidies, prompting pushback from environmentalists who see oil and gas initiatives as greenwashing exercises. The oil industry has countered by taking interest in CDR technology—Chevron and Occidental have invested in Carbon Engineering, the first significant partnership between energy companies and a developer of DAC.²⁷

²⁵ Bennett, Simon and Stanley, Tristan. “US Budget bill may help carbon capture get back on track.” International Energy Agency. March 12, 2018. <https://www.iea.org/newsroom/news/2018/march/commentary-us-budget-bill-may-help-carbon-capture-get-back-on-track.html>

²⁶ “Oil and Gas Climate Initiative holds workshop on the potential of Carbon Capture, Use and Storage in the Gulf Region,” Oil and Gas Climate Initiative. November 5, 2018. <https://oilandgasclimateinitiative.com/oil-and-gas-climate-initiative-holds-workshop-on-the-potential-of-carbon-capture-use-and-storage-in-the-gulf-region/>

²⁷ “Carbon Engineering Announces Investment from Oxy Low Carbon Ventures and Chevron Technology Ventures to Advance Innovative Low-Carbon Technology.” Carbon Engineering. January 9, 2019. <http://carbonengineering.com/carbon-engineering-announces-investment/>

Criticisms of 45Q

While 45Q is a positive bipartisan development and is indicative of political support for CDR technology, the credit has come under criticism for a variety of reasons, and momentum behind its passage needs to be maintained in order to achieve a material reduction in CO₂ emissions and for companies to utilize the technology as best they can. For 45Q to significantly stimulate investment and to meet expectations in capturing large amounts of CO₂, it is dependent on a variety of issues, such as “public acceptance, the ability to transfer tax credits, the availability of CO₂ pipeline infrastructure, and the readiness of storage sites.”²⁸

One major criticism of 45Q is that it mostly helps established entities. Tax credits do not provide an incentive structure for startups that are in the pre-revenue stage to innovate. New entrants benefit more from a direct funding injection from the government for research and development. On the other hand, some critics question whether the changes in 45Q are in fact large enough to stimulate CDR deployment. Although the 45Q provision is geared toward stimulating the market for carbon management technologies for the longer term, continued regulatory uncertainty still makes both investors and entrepreneurs cautious. Despite the tax credit energizing the industry, the U.S. Internal Revenue Service (IRS) has yet to clarify how companies can claim the credit under the rule. Not until the IRS provides proper guidance will a flood of investment occur. There is also the issue of the sunset provision on 45Q. It expires at the end of 2023, and projects – which are large and capital-intensive – need to be constructed by then to be eligible for the credit. Backers of 45Q argue that it needs to be amended and reshaped to optimize its effectiveness for both industry and carbon management.

Given the difficulties for the sector to commercialize, both public and private action will remain crucial moving forward. The NAS’s recent paper stressed this point, highlighting how coordination between the government and private companies is necessary to support the advancement of all carbon removal technologies, particularly DAC. “There is no commercial driving force for developing direct air capture technologies,” NAS said. “Therefore, developing a low-cost direct air capture option will require sustained government investment.”²⁹

Besides 45Q, other pragmatic carbon removal legislation was proposed during the 115th Congress. Although these initiatives did not pass, they could provide a blueprint for lawmakers to stimulate innovation in technological CDR. For instance, the same sponsors of the FUTURE Act introduced the USE IT Act to build on the momentum of the expansion of 45Q. This bill – first introduced in March 2018 in the Senate by Barrasso and reintroduced in the 116th Congress this month – seeks to accelerate the advancement of research and development for DAC and carbon utilization technologies, while also supporting infrastructure for transporting CO₂.³⁰ H.R. 4096, introduced by Democrat Grace Meng of New York, looked to authorize the Secretary of Energy to develop a prize competition to help accelerate the advancement of carbon removal technology.³¹ With Democrats in Congress and 2020 candidates challenging President

²⁸ “Advancing Large Scale Carbon Management: Expansion of the 45Q Tax Credit.” Energy Futures Initiative. May 2018. https://static1.squarespace.com/static/58ec123cb3db2bd94e057628/t/5b0604f30e2e7287abb8f3c1/1527121150675/45Q_EFI_5.2_3.18.pdf

²⁹ “Negative Emissions Technologies and Reliable Sequestration: A Research Agenda.” The National Academies of Science, Engineering, and Medicine. October 2018. <https://www.nap.edu/resource/25259/Negative%20Emissions%20Technologies.pdf>

³⁰ “Utilizing Significant Emissions with Innovative Technologies Act.” 115th Congress. May 24, 2018. <https://www.congress.gov/bill/115th-congress/senate-bill/2602?q=%7B%22search%22%3A%5B%22USE+IT+Act%22%5D%7D&r=1>

³¹ “Carbon Capture Prize Act.” 115th Congress. October 23, 2017. <https://www.congress.gov/bill/115th-congress/house-bill/4096/all-actions>

Donald Trump on climate as a key focus of their broader agenda, technological CDR could become a major part of the Party's climate platform.

III. Implications and Analysis

Scientists and other climate experts agree that the world needs to raise its ambition quickly in order to remove CO₂ and other greenhouse gases and avert deep climate crises in the future. As part of a global strategy, accelerated deployment of CDR technology is critical. The IPCC has recognized the need to be proactive in order to limit warming to 1.5 degrees Celsius above pre-industrial levels. CDR technology for climate management will grow in importance over the years and decades as the effects of climate change worsen and the technology is adopted by more actors. The scale at which this technology is deployed and its ultimate impact on the economy and meeting climate challenges will remain highly uncertain for some time.

In the United States, technological approaches using man-made methods to remove CO₂ from industrial facilities and the atmosphere have become part of the climate conversation and may be on the cusp of becoming economic on a wide scale.

Provisions to accelerate the use of CDR technology can satisfy both political parties, environmentalists, heavy emitters, investors, entrepreneurs and the general public. Environmental advocate NGOs and Democrats can continue to back CDR technology given its importance in long-term climate management. Republicans are excited that new technologies can reduce the climate footprint of heavy emitters such as oil and gas companies at a reasonable cost. This bipartisan consensus can continue to achieve positive developments in the CDR space.

To take advantage of the current environment, the U.S. government could do the following to help meet U.S. climate goals and foster the commerciality of CDR:

- **Extend the 45Q tax credit beyond January 1, 2024 to broaden the number of actors that can apply for the credit.** By expanding the time window, Congress would provide greater certainty to industry and investors so they can advance projects.
- **Regulators should develop standards and safeguards for industry and government to follow.** Given that CDR technologies carry various economic, environmental, logistical and land-use risks, the U.S. government will need to provide vigorous safety studies, and the Environmental Protection Agency (EPA) and the Department of Interior (DOI) should develop rules for industry to follow. At the same time, companies will need to establish a set of guardrails and norms to gain public trust and consistency.
- **Invest in continued research, development, and demonstration of CDR technologies so they can be deployed as soon as possible.** R&D funding for a wide array of technology, which NAS stressed is critical, can improve performance, decrease risks for investors, lower costs, and spur innovation.
- **Collaborate with industry.** Public-private partnerships are essentially risk-sharing agreements that can help industry players find support before they develop viable business models. National labs, universities and research institutions have the ability to provide capital and expertise to private industry. Collaboration allows for public leadership in fighting climate change while also emboldening private companies to be part of the solution while gaining financial rewards.

- **Stimulate innovation by developing a prize competition.** Like the X-Prize competition, a contest for innovators in the CDR space would provide a platform for companies to exhibit their technologies and expand their networks. Crucially, a competition would also inform policymakers and the general public about why this technology is important for climate management.
- **Government procurement of products that are made with CO₂.** This process would provide a customer base for companies utilizing CO₂ for commercial products and allow the government to reduce its carbon footprint.
- **Establish a federal price on carbon, whether through a carbon tax, carbon fee and dividend, or cap-and-trade system.** A price on carbon would facilitate further innovation, provide certainty for industry, and put a value on the CO₂ that is captured.
- **Provide tax credits for midstream infrastructure products so CO₂ can be transported from where it is captured to demand centers.** A study in the Proceedings of the National Academy of Sciences shows that low-interest government loans could provide the necessary pipeline infrastructure to help cut CO₂ emissions by an extra 31 million tons of CO₂ per year.³²
- **Collaborate with other countries to share critical technology and expertise with them, particularly emerging markets where dependence on fossil fuels is growing.** The United States can do this by developing collaborative initiatives to help develop policies elsewhere. Such action could provide U.S. companies access to key markets overseas. The U.S. government could provide finance and incentives for R&D. To make this work, the United States can work through the G20 or bilateral and multilateral partnerships.
- **The U.S. government should work within the UNFCCC to elevate CDR technology within the Paris process.** This can ensure that CDR is not excluded as an option for Nationally Determined Contributions (NDCs) under the 2015 Paris Agreement and further make CDR part of the mainstream narrative for permissible solutions.

³² Kelly, Morgan. "Funded by new tax credits, U.S. carbon-capture network could double global CO₂ headed underground." Princeton Environmental Institute. September 25, 2018. <https://www.princeton.edu/news/2018/09/25/funded-new-tax-credits-us-carbon-capture-network-could-double-global-co2-headed>

ANNEX

A Taxonomy of Carbon Dioxide Removal Technologies and Associated Risks

Carbon dioxide removal technologies may involve a range of environmental, socioeconomic, and economic risks. Environmental risks, for example, range from potential damage to natural ecosystems and biodiversity loss to food insecurity and production of non-CO₂ gases. Here we outline these risks for the major CDR technologies discussed in this paper.

Bioenergy with carbon capture and storage (BECCS)

BECCS is the process of growing biomass, such as switchgrass, which captures carbon dioxide through photosynthesis, burning it to produce electricity or liquid fuels, and capturing the carbon dioxide emissions associated with combustion for underground storage.³³

BECCS poses a series of environmental and socioeconomic risks due to its land and water requirements. Large-scale deployment can displace natural ecosystems, such as forests and grasslands, damaging wildlife and resulting in significant biodiversity loss.³⁴ Similarly, large-scale deployment can decrease land availability for food production, resulting in increased prices and regional shortages.³⁵ At the same time, BECCS can strain freshwater resources, contributing to water scarcity and negatively affecting freshwater ecosystems.

Whether BECCS is carbon negative, neutral, or positive is case-dependent. Factors to consider include emissions and changes to albedo from land-use change; competition with reforestation or afforestation; nitrous oxide emissions from nitrogen fertilizer use; transportation emissions if the growing and processing sites are not co-located; carbon losses during capture; and potential leakage from geological storage.³⁶

³³ See, for example, European Academies Science Advisory Council, “Negative Emissions Technologies: What Role in Meeting Paris Agreement Targets?” (Halle, Germany: German National Academy of Sciences Leopoldina, 2018).

³⁴ Phil Williamson, “Comment: Scrutinize CO₂ Removal Methods” *Nature* 530 (2016).

³⁵ Sivan Kartha and Kate Dooley, “The Risks of Relying on Tomorrow’s ‘Negative Emissions’ to Guide Today’s Mitigation Action” (Somerville, Massachusetts: Stockholm Environment Institute, 2016).

³⁶ Committee on Geoengineering Climate et al., “Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration” (Washington, DC: National Academies Press, 2015); Pete Smith et al., “Biophysical and Economic Limits to Negative CO₂ Emissions” *Nature Climate Change* 6 (2016); Mark G. Lawrence et al., “Evaluating climate geoengineering proposals in the context of the Paris Agreement temperature goals” *Nature Communications* 9 (2018).

Figure 5: Carbon Dioxide Removal Technologies and Selected Concerns

	Environmental and socioeconomic concerns	Climate-related concerns
Bioenergy with carbon capture and storage (BECCS)	<ul style="list-style-type: none"> • Ecosystem displacement • Biodiversity loss • Food insecurity • Water scarcity 	<ul style="list-style-type: none"> • Emissions from land-use change and throughout the BECCS process • Albedo change • Competition with other negative emissions techniques
Biochar	<ul style="list-style-type: none"> • Air quality • Possible land-intensiveness • Possible food insecurity 	<ul style="list-style-type: none"> • Emissions from land-use change and throughout the biochar process • Albedo change • Potential instability • Competition with other negative emissions techniques
Ocean iron fertilization (OIF)	<ul style="list-style-type: none"> • Unpredictable and potentially severe effects on ocean ecosystems • Disruption to fisheries 	<ul style="list-style-type: none"> • Largely temporary storage • Nitrous oxide and methane emissions
Enhanced weathering (EW) or ocean alkalization	<ul style="list-style-type: none"> • Negative effects on terrestrial or ocean ecosystems • Air and water pollution associated with large-scale mining 	<ul style="list-style-type: none"> • Some emissions from mining and transport
Direct air carbon capture and storage (DACCS)	<ul style="list-style-type: none"> • Some land use • Possible water use • Possible mining effects 	<ul style="list-style-type: none"> • Losses during transportation and storage • Possible carbon intensiveness of energy source

Biochar

Biochar results from the process of heating biomass under low-oxygen conditions (pyrolysis) and serves as a carbon-rich and decomposition-resistant additive to soils that can improve agricultural yield.³⁷ There is broad disagreement about the climate, environmental, and socioeconomic benefits and risks of biochar production and burial.³⁸ Climate-related concerns include emissions from land-use change; albedo change due to the effect of darkened soil; the variability of biochar stability; the question of whether biomass sites are co-located with pyrolysis sites; and the competition between biochar and other land-based negative emissions techniques, such as BECCS, for land and water resources (whether BECCS or biochar is more climate-effective is case-dependent). Meanwhile, environmental and socioeconomic concerns include the potential for land-intensiveness (which is typically low but varies), as well as the effect of particulate matter, which biochar can release during production, transport, and distribution, on air quality.³⁹ Food insecurity is likewise a concern due to the potential for land competition with food production.⁴⁰

Ocean Iron Fertilization (OIF)

³⁷ European Academies Science Advisory Council, “Negative Emissions Technologies.”

³⁸ Kartha and Dooley, “The Risks of Relying on Tomorrow’s ‘Negative Emissions’ to Guide Today’s Mitigation Action”; Jan C. Minx et al., “Negative emissions—Part 1: Research landscape and synthesis” *Environmental Research Letters* 13 (2018).

³⁹ Pete Smith and Julio Friedmann, “Bridging the Gap: Carbon Dioxide Removal” in *The Emissions Gap Report* (United Nations Environment Programme, 2017).

⁴⁰ Committee on Geoengineering Climate et al., “Climate Intervention.”

Fertilizing the ocean with iron could promote the growth of algae, which absorb carbon dioxide. It is generally recognized that ocean iron fertilization is deeply problematic, with environmental risks outweighing the potential for negative emissions. The negative and unpredictable environmental effects of ocean fertilization can include toxic algal blooms; increases in ocean acidity; decreases in oxygen; disrupted nutrient cycling; and disrupted food webs, including fish, seabirds, and ocean mammals.⁴¹ Fertilization can also unpredictably disrupt the yields of fisheries.⁴² Meanwhile, the overall climate benefit is limited, given that fertilization can produce additional gases, including nitrous oxide and methane, and can result in carbon storage that is largely temporary, with carbon returning to the atmosphere rather than being sequestered in the deep ocean.⁴³

Enhanced Weathering (EW) and Ocean Alkalinization

Enhanced weathering is the process of dispersing crushed silicate or carbonate minerals over land to accelerate the absorption of carbon dioxide. Meanwhile, ocean alkalinization is the process of dispersing alkaline minerals in the ocean, changing ocean chemistry and increasing carbon dioxide uptake.⁴⁴ Enhanced weathering and ocean alkalinization have not yet been demonstrated at scale but raise several concerns. The mining and transport necessary for these techniques could have a significant environmental footprint and require a significant amount of energy.⁴⁵ In addition, the dispersal of minerals in enhanced weathering could negatively affect terrestrial ecosystems as well as groundwater and rivers, while the dispersal of minerals in ocean alkalinization could negatively affect marine ecosystems.⁴⁶

Direct Air Carbon Capture and Storage (DACCS)

DACCS captures carbon from ambient air through a chemical process and stores it underground. Although the technique has not yet been demonstrated at scale, it has elicited fewer climate, environmental, or socioeconomic concerns than other negative emissions technologies.⁴⁷ Climate-related concerns revolve around carbon losses during transportation and storage; they also revolve around the energy intensiveness of DACCS, which could offset its climate benefit unless the energy source is clean. Environmental and socioeconomic concerns revolve around water use, which could be significant for some technologies; mining that may be required for input materials; land use, which would be relatively minimal aside from any associated clean energy infrastructure; and negative environmental effects that have not yet been anticipated or considered.⁴⁸

Key Funding from the Department of Energy

⁴¹ European Academies Science Advisory Council, “Negative Emissions Technologies”; Williamson, “Comment: Scrutinize CO₂Removal Methods”; Minx et al., “Negative emissions—Part 1: Research landscape and synthesis”; Fuss et al., “Negative emissions—Part 2: Costs, potentials and side effects”; Lawrence et al., “Evaluating climate geoengineering proposals in the context of the Paris Agreement temperature goals.”

⁴² European Academies Science Advisory Council, “Negative Emissions Technologies”; Williamson, “Comment: Scrutinize CO₂Removal Methods”; Fuss et al., “Negative emissions—Part 2: Costs, potentials and side effects.”

⁴³ Fuss et al., “Negative emissions—Part 2: Costs, potentials and side effects”; Williamson, “Comment: Scrutinize CO₂Removal Methods”; Lawrence et al., “Evaluating climate geoengineering proposals in the context of the Paris Agreement temperature goals.”

⁴⁴ Committee on Geoengineering Climate et al., “Climate Intervention”; “European Academies Science Advisory Council, “Negative Emissions Technologies.”

⁴⁵ Fuss et al., “Negative emissions—Part 2: Costs, potentials and side effects.”

⁴⁶ Minx et al., “Negative emissions—Part 1: Research landscape and synthesis”; Fuss et al., “Negative emissions—Part 2: Costs, potentials and side effects.”

⁴⁷ Williamson, “Comment: Scrutinize CO₂Removal Methods”; Lawrence et al., “Evaluating climate geoengineering proposals in the context of the Paris Agreement temperature goals.”

⁴⁸ Smith and Friedmann, “Bridging the Gap: Carbon Dioxide Removal”; Fuss et al., “Negative emissions—Part 2: Costs, potentials and side effects.”

One major contributor to companies in their early stages of carbon management technologies has been the U.S. Department of Energy's Office of Fossil Energy. Since Fiscal Year 2010, Congress has appropriated a total of more than \$5 billion to the DOE for activity related to carbon capture, a reflection of a remarkable area of political agreement during a time in which Democrats and Republicans have been starkly divided.⁴⁹ During this time period, the Office of Fossil Energy funded nine "later-stage," large projects to test the commercial viability of CCS, and also provided grants to smaller projects.⁵⁰ It is important to note that although these are not negative emissions projects, they highlight the role the U.S. government can play in facilitating advancement of technology that mitigates CO₂ emissions. American Recovery and Reinvestment Act of 2009 was instrumental in stimulating project funding, which is aimed at reducing the financial and technical risks of commercial CCUS.

In 2018, the Office of Fossil Energy funded roughly \$85 million in projects for carbon management through the National Energy Tech Laboratory and has announced \$30 million more for projects to advance technologies that bring down the cost of CO₂ capture. The funding has gone to a mix of private companies, research institutions and universities, with the likes of Ohio State, Arizona State, and SRI International, a nonprofit started by Stanford University, receiving injections last year.⁵¹

Fossil Energy has stated its long-term goals in the carbon capture area. By funding projects for both public and private partners, it aims to bring down the cost of carbon capture, with the goal of "second-generation" technologies resulting in CO₂ at less than \$40 per ton during 2020-25. It also has ambitions to extend research for even more advanced technologies to bring the price below \$30 per ton by 2035.⁵²

Fragmented Industry

Currently, the industry surrounding carbon removal and carbon utilization technology is fragmented. Although a handful of firms have reached or are near commercialization, there is no one dominant player that will dictate the direction of the industry. This dynamic provides opportunities for new companies, which have room to innovate and carve out their own niche. Potential customers have the opportunity to experiment with new businesses, and there may be less competition at this stage for entry, particularly in local and regional markets. On the downside, investors may balk at funding newer and smaller companies, hesitating in particular due to the fact that companies--and the entire market--have yet to mature. There is also the lack of one voice speaking for what the industry needs from policymakers with regards to regulation and legislation.

Potential Growth in Using CO₂ in Cement and Concrete

A large number of companies in this space see opportunities in converting captured CO₂ into cement and concrete. They are banking on growing demand for their products resulting from increases in population, infrastructure upgrades and urbanization mixed with the greater ambition to fight climate change. The cement industry, which contributes approximately 5-7 percent of global emissions, has a total market value of \$1.3 trillion. So far, though, CCUS companies have penetrated only a small fraction of the cement

⁴⁹ Folger, Peter. "Carbon Capture and Sequestration (CCS) in the United States." Congressional Research Service. August 9, 2018. <https://fas.org/sgp/crs/misc/R44902.pdf>

⁵⁰ "Advanced Fossil Energy: Information on DOE-Provided Funding for Research and Development Projects Started from Fiscal Years 2010 through 2017." US Government Accountability Office. September 21, 2018. <https://www.gao.gov/products/GAO-18-619>

⁵¹ Office of Fossil Energy. <https://www.energy.gov/fe/listings/fe-press-releases-and-techlines>

⁵² Carbon Capture R&D. Office of Fossil Energy. <https://www.energy.gov/fe/science-innovation/carbon-capture-and-storage-research/carbon-capture-rd>

sector, which is typically slow to adopt changes. This slow pace of adoption among incumbent industries is used by critics of CCUS and DAC point out that they are likely to affect emissions only at the margins.

The Carbon XPRIZE

Despite industry fragmentation, companies utilizing carbon capture have found an industry community in the Carbon XPRIZE competition, which is sponsored by NRG and Cosia. The competition's purpose is to inspire "radical new approaches and breakthroughs in science, engineering, policy and business." By raising the profile of these companies and their technologies to investors, the XPRIZE seeks to accelerate the commercial use of these technologies to cut emissions.

The contest has highlighted how the industry is both competitive and collaborative. The companies in the competition reflect how much capital is necessary to reach commercialization. The finalists for the XPRIZE are competing for \$20 million. Yet, the ten XPRIZE finalists need a total of \$60 million in funding to cover capital and development costs to build out pilot programs. A majority of the companies have yet to move beyond the lab pilot phase. Two are labeled as early commercial, another a commercial pilot, while only one is in the "growth" phase. (See the Annex for profiles of some of the finalists). The competition, which consists of three rounds over four and a half years, is now in the "testing and certification" phase, where finalists show their technologies to judges. One of the judge's criteria is whether the companies use more CO₂ in their products than they emit when they consume energy – essentially showing that it is developing a carbon negative technology.

The XPRIZE has provided a platform for companies that may have otherwise not received much attention. Even companies that are no longer in the competition have benefitted from the publicity from participating in it. The competition has elevated the visibility of the different types of technology available and the promise of the sector's role in mitigating the effects of climate change. "The prize will prove that CO₂ can be a valuable asset—a building block for a wide variety of products that we use every day."⁵³

DAC, NET, and CCUS Company Profiles

Global Thermostat

The main U.S.-based company with DAC facilities is Global Thermostat. The company, whose CEO is Graciela Chichilnsky, launched the company with Peter Eisenberger, formerly a physicist with ExxonMobil. Chichilnsky won the Nobel Peace Prize with Al Gore when she served on the UN IPCC, while Eisenberger became frustrated at Exxon that the oil major would not move beyond fossil fuels.

Since it began as a startup in 2010, Global Thermostat has raised \$51 million. It has not disclosed its private investors, but it reportedly has the backing of a U.S. energy company and Edgar Bronfman Jr, the former chairman and CEO of Warner Music.⁵⁴ It has received public money, including a \$250,000 grant in 2017 from the New York State Energy Research and Development Authority. Global Thermostat, along with Georgia Tech and Algenol, was also awarded \$2 million from the U.S. Department of Energy. A number of companies have used Global Thermostat's technology to reduce emissions. For instance, Algae Systems, a renewable energy company, produces carbon negative fuels with Global Thermostat's equipment by injecting CO₂ into its algae and producing biochar, diesel and jet fuel.⁵⁵

⁵³ XPrize Foundation. <https://carbon.xprize.org/prizes/carbon/faq>

⁵⁴ Gunther, Marc. "Startups have figured out how to remove carbon from the air. Will anyone pay them to do it?". *The Guardian*. July 14, 2015. <https://www.theguardian.com/sustainable-business/2015/jul/14/carbon-direct-air-capture-startups-tech-climate>

⁵⁵ Fehrenbacher, Katie. "An algae startup emerges with a pilot plant in Alabama". Global Thermostat. <http://globalthermostat.com/wp-content/uploads/2014/08/algae-startup.pdf>

With carbon removal now considered a necessary part of the climate solution, the company is seeing more opportunities from investors. The company's CEO said that after the IPCC published its report in October, Global Thermostat received investment offers totaling \$200 million in just one day. This development shows how the IPCC report and the growing urgency surrounding climate should help jump-start the industry.⁵⁶

Global Thermostat, with its steady funding over the years, is nearing commercialization. Since 2010, it has run demonstration plants at SRI International in California, and currently, it is building its first commercial plants in Huntsville, Alabama, with operating costs at \$150 per ton. But the company expects costs to drop and is targeting \$50 per ton, with help from selling CO₂ to soda companies to inject into carbonated drinks. Having beverage producers as clients can position Global Thermostat to reach commercialization. The company says that with the combination of its customer base – which will purchase CO₂ – and the federal government tax credit, it can soon reach the \$50 per ton figure, the level at which it can scale up its technology. One of the advantages of the company's cost structure is that it uses low amounts of electricity in its capture process, instead mostly utilizing leftover process heat to power its facilities.⁵⁷

The Alabama plant can currently suck only 4,000 tons annually out of the air, hardly enough to move the needle in combating climate change. The company claims, though, that less than 400 of the company's plants could reduce annual global emissions by one percent, the total emitted by 60 million cars. The company is aiming to grow globally: It now has 35 patents in 147 countries and plans to sell CO₂ captured for water desalination, synthetic fuels and polymers along with beverages. "We expect global adoption and we will favor scaling up in developing nations where most of the growth of the world economy will be located," said Graciela Chichilnsky.⁵⁸

Carbon Engineering



Figure 6: Carbon Engineering's Direct Air Capture System

Carbon Engineering Ltd., based in British Columbia, is nearing the commercialization phase, using DAC to either sequester the CO₂ underground or use it to produce transportation fuels. The company has received almost \$70 million in private funding since its inception in 2009.⁵⁹ The U.S. Department of Energy has contributed funding, as well as the government of Canada. Carbon Engineering has been able to survive the lab-to-marketplace transition because the company has patient, strategic investors who are committed to long-term success of carbon removal. Its Founder is David Keith, a Harvard professor, and one of the company's investors is Microsoft's Bill Gates. In January, oil giants

Chevron and Occidental announced that they are investing in Carbon Engineering, giving significant backing to the company's bottom line and the commercial viability for DAC for the longer term.

⁵⁶ Magill, Bobby. "Carbon Removal Firms see Opportunity in U.N. Climate Report." Environmental & Energy Report. *Bloomberg*. October 12, 2018. <https://www.bna.com/carbon-removal-firms-n73014483159/>

⁵⁷ Siegel, RP. "The Fizzy Math of Carbon Capture." *Grist*. October 10, 2018. <https://grist.org/article/direct-air-carbon-capture-global-thermostat/>

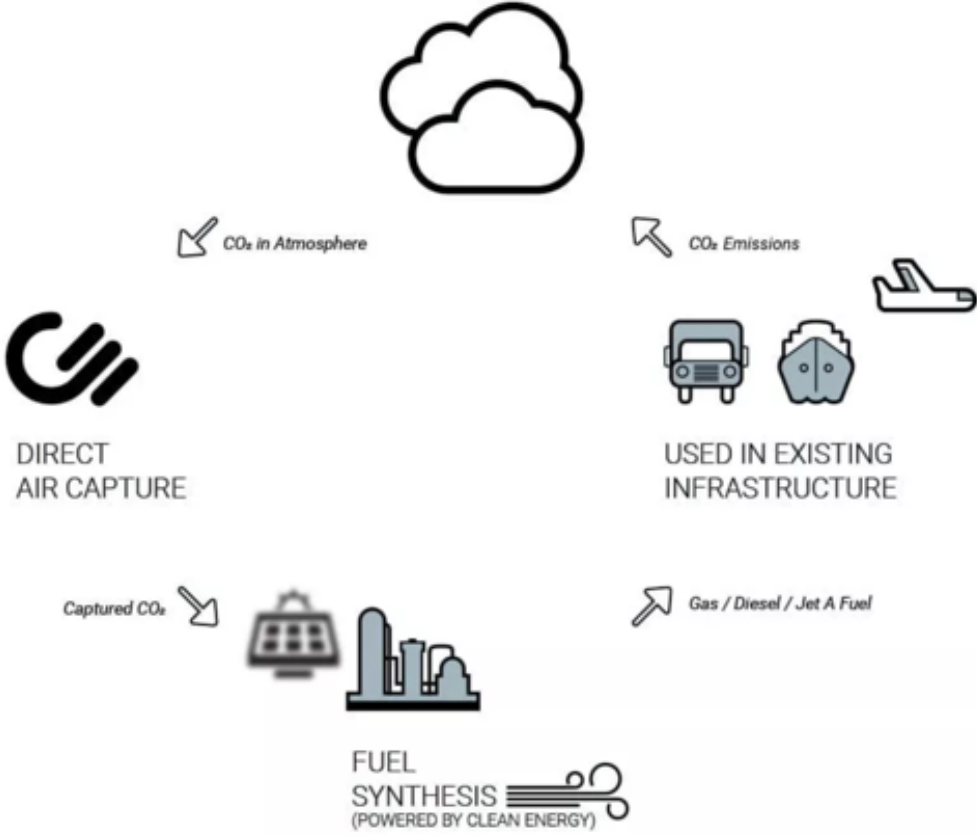
⁵⁸ du Besse, Alessandro. "The Global Thermostat can fight climate change. Interview with Graciela Chichilnsky." *Impakter*. April 4, 2018. <https://impakter.com/global-thermostat/>

⁵⁹ Carbon Engineering. "Carbon Engineering concludes USD \$68 million private investment round and proceeds with commercialization of carbon dioxide removal technology." *Carbon Engineering*. March 21, 2019. <https://carbonengineering.com/carbon-engineering-concludes-usd68-million-private-investment-round/>

Carbon Engineering’s first direct air capture pilot began in 2015, and in 2017, the company started using carbon to synthesize liquid transportation fuels. It currently has a pilot program in British Columbia and it is aiming to build a large-scale plant there by 2022.

When Carbon Engineering’s technology is used to take CO₂ out of the atmosphere and store it underground, the process will create negative emissions. Another market opportunity for Carbon Engineering’s DAC technology is to use the captured CO₂ for commercial products, specifically transportation fuels. Even though utilizing the carbon as fuel means it gets re-emitted, the company says that its product is a low-carbon, environmentally friendly alternative to traditional production of fossil fuels.

Figure 7. Carbon Engineering’s Air-to-Fuels System



Source: Carbon Engineering

Carbon Engineering is eyeing establishing a foothold in the California market, where the state’s Low Carbon Fuel Standard (LCFS) makes it economically viable to inject carbon underground or sell fuel synthesized from CO₂.

As noted earlier, Carbon Engineering received a lot of attention last June when it published an article in the scientific journal *Joule* describing its process for DAC and its ability to reduce costs to below \$100 per ton. The company’s analysis, which is the first paper with a breakdown of engineering costs for DAC, shows that the DAC process is cheaper than previously believed. If correct, the company’s estimates, along with Global Thermostat’s, should shift expectations that DAC can become economical in the

foreseeable future. In the paper, the authors describe each step involved in DAC and note what hardware is needed throughout the process. When the researchers consider the amount of energy used in the process and the overall capital expenses, they calculate the overall costs, concluding that the range is from \$94 to \$232 per ton.

However, the authors acknowledge the shortcomings of estimating costs at this point in the process toward commercialization:

It is difficult to estimate the cost of a technology prior to its widespread deployment. CE [Carbon Engineering] has spent several tens of millions of dollars developing DAC technology, yet our performance and cost estimates still carry substantial uncertainty. Our process design choices were substantially driven by a goal of reducing development risk and reducing the capital cost of early plants, rather than by minimizing energy use or ultimate levelized cost. CE adopted a conservative approach to cost and performance estimation, driven, in part, by controversy around the feasibility and cost of DAC. The process described here should therefore be seen as a low-risk starting point rather than a fully optimized least-cost design.⁶⁰

When this study was published, Carbon Engineering and DAC technology, in general, received an increasing amount of positive press. For instance, a headline in *The Atlantic* said: “Climate Change Can Be Stopped by Turning Air Into Gasoline.” In the article, Keith explained his company’s goals: “What we’ve done is build a [direct-air capture] process that is—as much as possible—built on existing processes and technologies that are widespread in the world. That’s why we think we have a reasonable possibility of scaling up.”⁶¹

With the low-carbon transportation fuels made from the CO₂ sucked out of the air, Carbon Engineering hopes to develop a diverse customer base and has taken a step in that direction with its new partnerships with Chevron and Occidental. How realistic the costs that Carbon Engineering cited in *Joule* and its plans to scale up are difficult to assess at this moment. Critics caution that analyzing such a complex and new process will take time. The company is seeking additional funds to take the final steps to commercialization.

CarbonCure

Founded in 2007 and an XPRIZE finalist, CarbonCure is one startup company in the CCUS space that is seeing growth. Its technology takes recycled CO₂ sourced from an industrial emitter and injects it into concrete when it is mixed. This process improves the strength of the concrete. Besides strengthening the concrete, this technology is attractive to customers because it can cut costs while also reducing a company’s carbon footprint. It is now being used in over 100 concrete plants in North America. Toronto’s Brampton Brick and Virginia’s Vulcan Materials were two of the first to utilize CarbonCure’s technology.

CarbonCure’s advantage versus its peers is that it is more than a decade old, making it a relatively mature company in this sector, and it has received a steady stream of funding and is building a customer base. The company has received funding from a variety of sources, with the total reaching at least \$9.3 million after five rounds of funding. In 2013, BDC Venture Capital – which has more than \$1 billion under management – Eagle Cliff Partners, Innovacorp, 350 Capital, along with strategic investors, injected \$3.5 million into CarbonCure, helping the company transition to commercialization. In 2015, Pangea Ventures

⁶⁰ Keith, David. “A Process for Capturing CO₂ from the Atmosphere.” *Joule*. June 7, 2018.

[https://www.cell.com/joule/fulltext/S2542-4351\(18\)30225-3](https://www.cell.com/joule/fulltext/S2542-4351(18)30225-3)

⁶¹ Robinson, Meyer. “Climate Change Can Be Stopped by Turning Air Into Gasoline.” *The Atlantic*. June 7, 2018.

<https://www.theatlantic.com/science/archive/2018/06/its-possible-to-reverse-climate-change>

funded CarbonCure with \$3 million, while in September of 2018 Bill Gates' Breakthrough Energy Ventures announced investment in the company.

With the funding from Breakthrough, it plans to develop international partnerships and expand its portfolio of technologies that use CO₂ as a value-added material in concrete manufacturing. The company says the biggest challenge to its growth is the cement industry's reluctance to change quickly. Currently, there are 6,500 concrete plants in the U.S. and Canada. With its technology being utilized at only 100 plants so far, the company believes it has a large upside, but the gap also reflects how few in the concrete industry have installed this technology.

Blue Planet

Based in California and founded in 2006, Blue Planet converts CO₂ to carbonate and then turns it into limestone rock, which is then incorporated into concrete. This process allows Blue Planet to secure clients that can use the product in buildings, sidewalks and bridges. This way, the CO₂ is permanently sequestered in infrastructure instead of being released into the atmosphere. In California, Blue Planet's products have been used on projects at the San Francisco-Oakland Bay Bridge. It is also working with cement manufacturers in Mexico and Canada, along with power plants in Wyoming.

Blue Planet is looking to government procurement for growth. California, for instance, uses 240 million tons of concrete every year but imports most of it. By using Blue Planet's products, the state could reduce emissions and save costs. By 2024, the global ready-mix concrete market could reach almost \$1 trillion. Because of the expansions of airports, bridges, roads, along with construction of new buildings, Blue Planet is in position to grow. The company also has big-name support: Actor Leonardo DiCaprio is on its advisory board.

Calera

A Silicon Valley startup, Calera has aimed to configure its operations around repurposing CO₂ as concrete. It has received funding from Khosla Ventures Venture Capital, the Department of Energy and Hercules Capital. The company, founded by Brent Constanz (now the CEO of Blue Planet), received a large amount of funding early on, including \$50 million from Khosla, but there has been little news about the company in recent years. The company has reportedly pivoted from mixing CO₂ in cement to "using the material to make fiber cement boards used in bathroom tile backing or exterior siding." Last decade, when Calera touted its technologies and received funding from the DOE, one prominent scientist criticized it, alleging that its operations would actually increase CO₂ emissions.

Solidia Technologies

Solidia Technologies is another company that is using CO₂ in cement and concrete. It has reached the commercialization stage and has a long list of funders, including the Oil and Gas Climate Initiative. Other investors include BASF, Bright Capital, Kleiner Perkins Caufield and Byers, BP, Total Energy Ventures and a number of individuals. The company was founded in 2008, and its technology was first developed at Rutgers University. As of the end of 2017, it had raised \$60 million in funding.

Carbon Upcycling Technologies

Launched four years ago and based in Calgary, Carbon Upcycling Technologies is turning CO₂ into a product to prevent erosion in infrastructure. Its competitive advantage derives from making infrastructure more efficient. In 2017, CUT saw positive revenues from its corrosion protection product, and this year it launched an additive for the plastics market. CUT, an X-Prize finalist, has found clients such as Costco,

McDonald's, Dunkin' Donuts, Red Lobster, and Starbucks franchises. Contractors in Miami-Dade, Florida and Portland, Oregon have also used the company's technology.

C2CNT

Based in Northern Virginia and an X-Prize finalist, C2CNT converts CO₂ into carbon nanotubes, a product that can be used for numerous purposes, such as construction, energy storage, and strengthening industrial materials. Its customers are in the steel, cement and construction industries.

The company's CEO, a chemistry professor at George Washington University, estimates that each ton of CO₂ is worth a quarter of a million dollars. It is not seeking venture capital but is instead looking for strategic partnerships. Capital Power, a power producer based in Edmonton, acquired an equity interest in C2CNT in May.

C4X

An X-Prize finalist, C4X is incorporated in both Canada and China. Its technology converts CO₂ into chemicals and plastics. It is now in the commercial pilot state, with customers that are manufacturers of plastics, lithium-ion batteries, and automotive parts. The fact that it is in the lithium-ion market bodes well for C4X with the growing demand due to rising sales of electric vehicles. C4X is seeking corporate investment in order to scale up its technology. Its main focus is China, where it has partnered with the country's largest cement maker and also power companies. But it is also looking to expand in North America. In Canada, C4X has partnered with Ford Motor Company of Canada and Walkerville Brewery.

Newlight Technologies

Based in Huntington Beach, CA and founded in 2003, Newlight Technologies has reached the early commercial stage, but still needs \$15 million in funding. Since 2013, when it started scaling up its technology, it has raised almost \$41 million. The company's technology turns either methane or CO₂ emissions from farms, landfills, flaring and power plants into biodegradable plastics. With consumers wanting to move away from plastic made from fossil fuels, Newlight believes its technology has considerable upside potential. Newlight shows that converting greenhouse gases to plastics is economically viable. The company already has agreements to supply some 74 billion pounds of its product for the next two decades. Customers include big names such as Dell, Virgin Mobile, and IKEA.

CERT

Made up of scientists and engineers at the University of Toronto, CERT has developed a system to convert CO₂ into chemical feedstocks. An XPRIZE finalist, CERT is seeking to construct a field pilot and is seeking about \$6 million in funding for capital and development costs, with existing funding from the Canadian and Ontario governments. It has received support from a European oil major and a large tech company. Currently, it is seeking strategic partnerships with emitters such as energy producers or steel and cement manufacturers looking to derive value from captured CO₂, as well as petrochemical manufacturers with existing supply chains to sell low-carbon chemical feedstock products. As of now, CERT does not have any customers.

Carbon Upcycling UCLA

An XPRIZE finalist, Carbon Upcycling UCLA is a group of engineers at the University California, Los Angeles (UCLA) that has developed technology to convert CO₂ into CO₂Concrete. The product serves as a low-cost functional replacement for traditional concrete. It has received some funding from UCLA, but more from philanthropists and DOE's Office of Fossil Energy. For instance, the Anthony and Jeanne Pritzker Family Foundation gave the company \$1.5 million last year. With support from the DOE, the

CO₂Concrete process is being upscaled for demonstration at an operating coal power plant. CO₂Concrete is now in the process of raising \$10 million for full-scale commercialization activities.