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Climate Solutions Series

Carbon Dioxide Removal Solutions

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THE ISSUE

This brief is the sixth and final in a series on achieving net-zero global greenhouse gas emissions by 2050. The CSIS Energy Security and Climate Change Program hosted six events followed by resource briefs related to each event. For more information on the series, see our ***website****.*

THE CHALLENGE

According to the Intergovernmental Panel on Climate Change, both dramatic reductions in carbon dioxide (CO_2) emissions and the large-scale removal of CO_2 from the atmosphere will be necessary to stabilize the climate by 2050 and have a chance of keeping temperature rise below 1.5 degrees Celsius above pre-industrial times.[1] The amount of CO_2 removal (CDR) or negative emissions required depends on the extent and speed to which emissions are reduced and how far temperature "overshoots" the 1.5-degree target. Critically, the longer it takes to reduce emissions, the greater the need for CDR. The IPCC estimates that a future with low energy demand and a rapid transition to zero-carbon fuels could require removing an average of 1.25 billion tons of CO_2 per year by 2100, whereas a fossil fuel-dependent future could require ramping up to 20 billion tons of CO_2 removed each year by the midcentury and beyond.[2]

Unlike other climate change technologies and investments, CDR is not about stopping emissions from going into the atmosphere but instead removing them from the atmosphere. Also, unlike some of the other solutions discussed in this series, CDR technologies are not focused on providing a good like electricity or an industrial product. Some CDR solutions have co-benefits, but many primarily exist for the purpose of removing CO_2, which is not currently valued at an appropriate level in policy or society. Comparing to other technologies for cost-competitiveness, then, is difficult. Some have suggested treating carbon removal as a public good or service akin to garbage removal or street sweeping, highlighting that it is a necessary service whose success should not be judged by its economic competitiveness.[3]

CDR methods cover a range of technologies and solutions, each with their own unique technological, economic, or policy challenges. Many of these options are still theoretical or at pre-commercial scale and still require research and development to assess whether they will ultimately be feasible.

First, technological solutions for removing CO_2 from the atmosphere are at an earlier stage of development than more commonly known emission reduction technologies such as wind, solar, nuclear, etc. For many decades, development and deployment of emission reduction technologies have been prioritized over removal technologies. As it becomes clearer that there is a need for negative emissions in any scenario that achieves the 1.5-degree target, the important role for CDR to work alongside efforts to reduce emissions, particularly in addressing the emissions from hard-to-abate sectors such as aviation and shipping, has gained traction.[4]

Second, CDR efforts, especially technological options, face the same siting and land use questions that other technologies have to address. Therefore, public perception will shape how easily these solutions can be implemented. At present, the general public does not understand what does and does not result in the removal of CO_2 from the atmosphere. An October 2020 poll of U.S. adults found that almost three-quarters had heard very little about CDR and, when asked about whether different technologies counted as carbon removal methods, majorities often got it wrong.[5] For example, 68 percent of respondents believed recycling was a carbon removal method and 65 percent said the same about installing solar panels.

A key for CDR acceptance will be educating the public not only on what is not CDR but also what the CDR options entail. In the same poll, there was little opposition to CDR solutions, but many did not have strong opinions.[6] The methods that required the least technology, such as planting new forests, saw the most support. The more technology that was involved—using technology to capture carbon from the atmosphere or speed up carbon mineralization in rocks, for example—the greater the percentage of respondents who were unsure or unfamiliar.

GETTING FROM HERE TO THERE

CDR is a nascent field—more so than any other topic we have covered in this series—and thus, much of what will be discussed in this brief is theoretical or at very small scale. Solutions fit into three categories: natural, technological, and hybrid. Natural solutions often involve growing more organisms that naturally absorb CO_2. Technological solutions rely on machines to remove carbon from the atmosphere, while hybrid solutions use technology or biological changes to supplement the natural CO_2 removal processes. There are many different CDR techniques, so this is not an exhaustive list but rather one that is representative of some of the larger categories of solutions. In addition, much like the other solutions covered in this series, successful CDR will likely involve a portfolio of several solutions rather than one dominant approach.

TECHNOLOGY

Natural solutions take advantage of the ability of natural systems to absorb CO_2 from the atmosphere. These include forests, agricultural soil, and wetlands. Oceans also absorb considerable CO_2, but ocean-based solutions will be discussed in a separate section. Natural solutions are also the readiest category of solutions because they are already in use today. A 2017 study estimates that cost-effective natural solutions can deliver 37 percent of CO_2 reductions needed to align with the Paris Agreement by 2030, assuming global CO_2 emissions continue on a business-as-usual pathway.[7] Reforestation of an area that has previously been logged and afforestation to create new forests both increase the number of trees, each of which can absorb about 0.02 metric tons of CO_2 per year at full maturity.[8] On the scale of a single tree, that is not significant, but the world's forests absorb as much as 30 percent of annual anthropogenic CO_2 emissions.[9]

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On agricultural lands, the soil absorbs carbon through methods including photosynthesis from plants and the ongoing decomposition of organic matter in the soil.[10] Planting cover crops can increase the carbon sequestration function in these soils because the organisms in the soil feed on the roots and shoots of the crops, which increases soil carbon.[11] Switching from annual to perennial grain crops can also increase carbon sequestration because the deep roots of these crops allow for more storage in the soil.[12] Planting can also decrease the natural emission of nitrous oxide, a greenhouse gas at least 265 times as potent as CO_2 but which spends much less time in the atmosphere.[13]

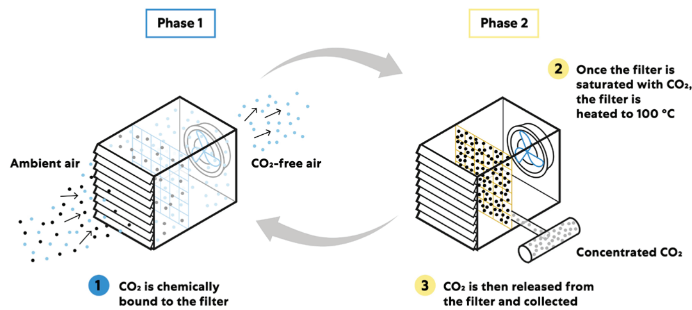
Wetlands have considerable potential to sequester carbon, often containing many times more carbon than agricultural soils.[14] Wetlands sequester carbon in trees and in soil much like forestry and agricultural practices do, but they can also store carbon-rich sediment that has eroded from catchments. Depending on their conditions, however, they also naturally emit some carbon and methane from decomposition. The anoxic nature of wetland soils slows decomposition, which slows the rate of carbon emissions, but the same conditions enable the emission of methane.[15] In general, wetland vegetation grows faster than decomposition emits CO_2, so wetlands are a net sink for GHGs, but there is variation depending on the type of wetland.[16] Natural wetlands have been lost to redevelopment for centuries, but the rate of losses in just the last 100 years is almost four times higher than the long-term rate over the last few centuries.[17] Restoring wetlands delivers not only carbon benefits but also bolsters local water resources, biodiversity, and flood prevention.[18]

One advantage of natural solutions is that several of them can be accomplished at low cost—namely, afforestation and reforestation can cost under $20 per ton of CO_2, and agricultural practices can cost under $100 per ton.[19] In addition, the co-benefits of natural solutions vary based on the type of solution but generally improve ecosystem health and harden natural areas to the impacts of climate change. However, as will be discussed later in this brief, the validity of some natural solutions has come under scrutiny.

One hurdle for natural solutions is that they can take time. Trees planted through reforestation or afforestation, for example, take years to grow, and therefore the CO_2 benefits will mount over time. Another issue these solutions face is that they can be somewhat geographically limited. Reforestation, for example, requires planting trees in an area where forests used to grow, and agricultural practices must be carried out on lands already used for growing crops. There is only so much land available to grow crops, so competition between natural solutions that do not produce resources inevitably conflicts with economic activities such as agriculture. The permanence of natural solutions can also be threatened by climate change, as disasters such as wildfires can release all the carbon stored in forests and soils in a very short amount of time. In 2020, for example, a series of wildfires in California emitted more CO_2 than the state's power plants.[20]

Technological solutions make use of technology to remove CO_2 from the atmosphere. Direct air capture is the major technology that fits this category. A 2018 literature review on the global potential for CDR found that direct air capture could scale up to 5 million tons of CO_2 removed per year by 2050 and even more later in the century.[21] A typical direct air capture installation pulls air into a machine and bonds the CO_2 to either a liquid solvent or a solid sorbent. The CO_2 is then separated and can be stored or used. Figure 1 shows an example of a solid sorbent system. Several projects around the world are injecting captured atmospheric CO_2 into geologic formations. However, new solutions are emerging, including bonding CO_2 with various minerals to create a cement-like building material.[22] These processes lead to negative emissions if the CO_2 is removed from the atmosphere, the technology is powered by zero-carbon energy, and the storage is properly maintained.

Figure 1: Solid Sorbent Direct Air Capture Process



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Direct air capture could scale up to 5 million tons of CO_2 removed per year by 2050 and even more later in the century.

CO_2 can be used in its natural state, including by injecting it into the ground or using it for soda carbonation, or can be transformed into products like fuels or inputs for fertilizer.[23] CO_2 use often results in the gas being rereleased to the atmosphere at some point in the process, meaning that using CO_2 captured from the atmosphere in this way is a carbon-neutral exercise rather than a carbon-negative one.

Direct air capture differs from carbon capture equipment attached to a point source such as a power plant or an industrial plant because while they both capture CO_2, point-source capture prevents adding CO_2 to the atmosphere while direct air capture subtracts CO_2 from the atmosphere. One advantage of direct air capture over traditional point-source carbon capture and most natural solutions is that it can be modular and can be sited anywhere, so building facilities on top of potential storage would avoid the costs of transporting the captured CO_2 across distances. However, much like point-source carbon capture, direct air capture requires power to function, and that must be zero-carbon power for truly negative emissions. In the United States, for example, an upper bound estimate for 2050 is that direct air capture could demand 3,733 terawatt-hours, or about 30 percent of the country's projected electricity demand in that year, to remove 2.3 billion tons of CO_2.[24]

Direct air capture projects are not yet widespread, but they do exist. There are 15 projects operating worldwide. Swiss company Climeworks operates a commercial plant that can remove 900 tons of CO_2 per year at $600 per ton.[25] Competitor Carbon Engineering estimates that its first commercial plant will remove CO_2 for $94-$232 per ton of CO_2 once it has been built.[26] Costs are expected to decline at least toward the low end of that estimate as developers learn from deployment and reach economies of scale. Scientists are also considering an analogous solution to extract CO_2 from seawater via an electrochemical process. This idea is at a much earlier stage than direct air capture but, if proven safe and effective, could complement the land-based efforts.

One issue that will be of increased importance if direct air capture is deployed at scale is that of land use. While the land required to build direct air capture equipment may not be significant, the extra energy needed to power these systems will require land. Wind and solar can require 10 times the amount of land per unit of power than coal or natural gas plants do, and the best wind and solar resources can often be in areas where their development receives significant local opposition.[27] Natural gas with carbon capture and nuclear energy both have smaller land requirements than wind and solar but could also provide zero-carbon power for direct air capture. This issue is clearly not specific to direct air capture, but it will be a consideration if direct air capture sees large-scale deployment and begins requiring large amounts of energy.

Hybrid solutions use technology to speed up natural processes. The primary hybrid CDR example is called bioenergy with carbon capture and storage (BECCS). The idea behind BECCS is that if trees or plants that sequester carbon are used to generate bioenergy and the resulting CO_2 emissions are captured, it results in "negative" emissions. There are concerns about the impact that increasing reliance on BECCS for energy may have on food systems and land use, but those potential impacts are driven by the biomass feedstocks used. Focusing primarily on waste biomass as a feedstock could capture between 2.5 and 5 billion tons of CO_2 per year by 2050 with minimal environmental impact.[28] Only one large-scale BECCS demonstration project that permanently stores captured CO_2 currently exists, but two projects in Norway are being developed as part of a larger, state-sponsored CCS initiative.[29]

There is another set of solutions that is not quite a hybrid solution but does not fit neatly into natural or technological solutions. This includes carbon mineralization and changes to the ocean environment. Certain types of rocks that contain minerals such as magnesium and calcium can absorb and turn CO_2 into solid carbonate. Naturally, this process absorbs about one gigaton of CO_2 from the atmosphere each year.[30] A solution that is potentially on the horizon involves intentionally speeding up or otherwise making broader use of this mineralization process, either by spreading these minerals over soils or by injecting captured CO_2 into mineral deposits. Using the minerals to directly capture and store CO_2 has the potential to increase the capture rate of these rocks to several gigatons per year, making it clear that this is not a very large-scale solution but may be one part of a broad solution set.[31]

Oceans currently absorb about 30 percent of CO_2 emissions, and some solutions similar to the carbon mineralization approach may prove beneficial to increase this capability while counteracting its largest issue, acidification.[32] One option is alkalinization, which involves grinding up alkaline materials such as calcium oxide or calcium hydroxide used in heavy industry and dispersing them into the ocean, increasing the alkalinity of the water. More alkaline water should absorb more CO_2 and should counteract the increasing acidity of the ocean caused by increasing atmospheric CO_2.[33] Another option would be depositing nutrients like iron into the ocean to stimulate the growth and photosynthesis of phytoplankton, which would then sequester more carbon. Undertaking these processes at a large scale would require further studies of how alkaline materials interact with sea life and how stimulating the growth of phytoplankton may affect marine ecosystems.[34]

POLICY

Policy is necessary to drive uptake of CDR, especially direct air capture, given the currently high costs and, frequently, the lack of resulting products or co-benefits. Much like in other sectors, policy will likely take two forms: research and development (R&D) funding or deployment policies and incentives.

Given how nascent the technological and hybrid solutions are, R&D funding is necessary to understand their potential and prove their viability. Governments have provided some funding for CDR solutions in the past, but the formalization of government support in dedicated research programs is a recent phenomenon. In an omnibus spending bill passed at the end of 2020, the U.S. Congress appropriated $447 million over the next five years for R&D in CDR, including a $100 million prize competition for direct air capture, as well as $800 million for carbon storage validation and testing and more than $100 million for carbon utilization.[35] A 2019 study from the National Academies of Sciences, Engineering, and Medicine proposed a research plan of approximately $1 billion per year that would enable research into technological, natural, and hybrid solutions.[36] This would represent about a 13 percent increase to the country's entire energy R&D budget from fiscal year 2019.[37]

A key step to incentivize the deployment of technological CDR is designing ways to pay for the capture and storage of CO_2 from the atmosphere. There is already an established market for pure streams of CO_2 for use in processes such as enhanced oil recovery or soda carbonation, but the volumes removed from the atmosphere necessary to help address climate change would swamp these markets as they exist now. The use of captured CO_2 to make fuels may prove to be a more viable route if they can compete with existing fuels. As stated above, while CO_2-derived fuels are a carbon-neutral venture and therefore do not ultimately contribute to a drawdown of atmospheric concentrations of CO_2, they could slow the growth of atmospheric CO_2 and help provide incentives for CDR.

In California, the Low-Carbon Fuel Standard (LCFS) imposes a declining cap on the carbon intensity of transportation fuels produced in the state. The program functions like a cap-and-trade program, providing credits to producers of qualifying low-carbon fuels in California that can then be sold to emitters for compliance. The average credit price has risen from $22 in January 2013 to just under $200 in October 2020.[38] The standard also awards credits to direct air capture projects in California or elsewhere with associated underground storage. While prices may fluctuate, the LCFS should provide an attractive funding stream for new projects, though they may or may not be located in California. This does not make CO_2-derived fuels competitive by itself, but it institutionalizes a value for negative emissions that most regulatory regimes do not include. If this policy does ultimately influence these CDR-based fuel supplies, other governments could follow California's example and set up their own markets. Governments could also establish a mandate for fuels made from captured CO_2—the United States could expand its Renewable Fuels Standard to include these fuels, and other governments could follow its lead.[39]

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Another way that governments can help create markets for the use of captured CO_2 is by leveraging their procurement power to buy captured CO_2 for use in products or fuels. In fiscal year 2017, the U.S. military consumed over 85 million barrels of oil.[40] If the U.S. military signed a contract for the supply of synthetic fuels made from CO_2 captured from the atmosphere for even a fraction of its fuel use, it could provide a significant signal to producers, create demand for CDR, and reduce its CO_2 emissions. Further, creating fuels from direct air capture on aircraft carriers or in remote areas would reduce the need to rely on fuel supply chains, reducing costs and potential vulnerabilities. The Rhodium Group estimates that a deployment of 9 megatons of direct air capture by 2030 could provide about 23 percent of the U.S. Department of Defense's fuel in 2030.[41] As noted elsewhere in this brief, CO_2-derived fuels do not lead to negative emissions, but creating markets for the use of CO_2 can help incentivize its capture, contributing to cost declines for the technology.

Valuing the storage, rather than the use, of the product is more complicated. One option is providing a tax credit for different parts of the process. In the United States, the 45Q tax credit usually associated with traditional, point-source carbon capture also provides a $35 per ton credit for direct air capture projects that remove at least 100,000 tons of CO_2 per year, and a $35 per ton credit is available to projects that convert captured CO_2 into fuels or other products.[42] However, a $50 per ton credit is also available to geologic storage projects. Given the costs of technological CDR, this will not fund projects entirely. But it does provide a steady funding stream.

In the natural solutions arena, governments can undertake restoration projects that increase natural CDR capacity while also creating jobs. The World Resources Institute has suggested a tax credit for reforestation similar to the 45Q credit for carbon capture or the investment tax credit for solar projects. The group posits that a properly designed campaign in the United States could remove 540 million tons of CO_2 over 20 years for $4-4.5 billion and create about 180,000 jobs.[43] This could also be applied to bolstering other natural CDR solutions, including restoring wetlands and incentivizing carbon-storing agricultural practices. Alternatives available to governments could also be to provide grants or even set up a program to directly employ workers to carry out these projects.

A controversial policy option is creating carbon markets that value CDR. Voluntary offset markets, which allow individuals or companies to pay projects that reduce or avoid emissions to "offset" their emissions, are controversial for several reasons. First is the problem of additionality, or whether the projects generating credits are actually avoiding emissions or are claiming the money for what they would have already done anyway.[44] Some natural solutions currently face questions about additionality, but direct air capture would likely not face this question because there is no clear justification for it other than capturing CO_2.

Second, the incentives created by carbon markets can come into question, too—marginalized communities have long argued that by allowing companies to buy offsets where they are cheapest instead of reducing their own emissions, carbon markets keep them from addressing the local environmental impacts they have on the communities where the pollution occurs.[45] Credits can also be manipulated for financial gain, as in 2010 when some businesses in China were accused of intentionally increasing their emissions so they could reduce them to generate sellable credits.[46]

A well-designed market that was able to address all of these problems could serve as a useful source of funding for projects that would otherwise be difficult to fund.

THE ROLE OF PRIVATE-SECTOR ENGAGEMENT

The developers of technological CDR solutions, while they may benefit from public R&D funding, are private companies. Many of the investors and customers for CDR projects are also private companies, and some are even large technology players or oil and gas companies. At present, there are only a few major technological CDR developers.

Direct air capture has seen high-profile support from oil and gas companies such as Chevron, ExxonMobil, and Occidental Petroleum. Chevron and Occidental have both invested in the Canadian company Carbon Engineering, while ExxonMobil is invested in the New York-based Global Thermostat.[47] These partnerships involve a combination of equity investments in the companies and partnerships for R&D. Occidental Petroleum is directly supporting the construction of a Carbon Engineering plant in Texas through a partnership with a private equity firm and, as of January 2021, United Airlines.[48] Instead of accepting funding from oil and gas companies, Climeworks has attracted customers such as the Swiss division of Coca-Cola and will provide captured CO_2 to a European consortium to make fuels from renewable electricity.[49]

Technology companies are investing in CDR through demand for negative emissions credits in an effort to deliver on carbon-neutral or carbon-negative commitments. The payments company Stripe has been purchasing carbon removal credits from four companies in the technological CDR value chain since 2019 and now offers its users the option to do so as well. In addition to offsetting the company's historical emissions, the company's stated intention for buying these credits is to help buy down the cost of technological CDR.[50] Technology giant Microsoft announced in 2020 that it would buy carbon removal from a combination of natural and technological CDR companies in an effort to become net-negative by 2030.[51] In January 2021, the company announced it had paid to remove 1.3 million tons of CO_2 from 26 projects.[52] E-commerce platform Shopify has agreed to buy CDR credits from Carbon Engineering and Climeworks, offering a similar reasoning to Stripe that the company is paying high rates now so that costs will fall.[53] With a growing number of companies committing to carbon neutrality, it is likely this list will grow as CDR capacity grows and customers gain confidence in its effectiveness.

CONCLUSION

Given the trajectory of global GHG emissions and how rapidly they must decline to meet climate goals, CDR will be necessary. Further, the longer it takes to substantially reduce emissions, the more important negative emissions will become. An array of natural, technological, and hybrid solutions is or can be made available, and each has its own costs and benefits. Natural solutions are available at a reasonable cost, and some are in practice today. Further R&D to drive down the costs of technological and hybrid solutions will help scale these solutions, and this is an area where public funding can help. Public understanding and acceptance of CDR can affect siting decisions and support for funding. Natural, technological, and hybrid solutions could all benefit from well-designed deployment policies, including tax incentives, direct employment, procurement policies, and markets or mandates. Private sector investments in CDR from oil and gas companies and technology companies are seeking to encourage the development of solutions, buy down the cost of the technology, and counteract historical emissions. ■

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