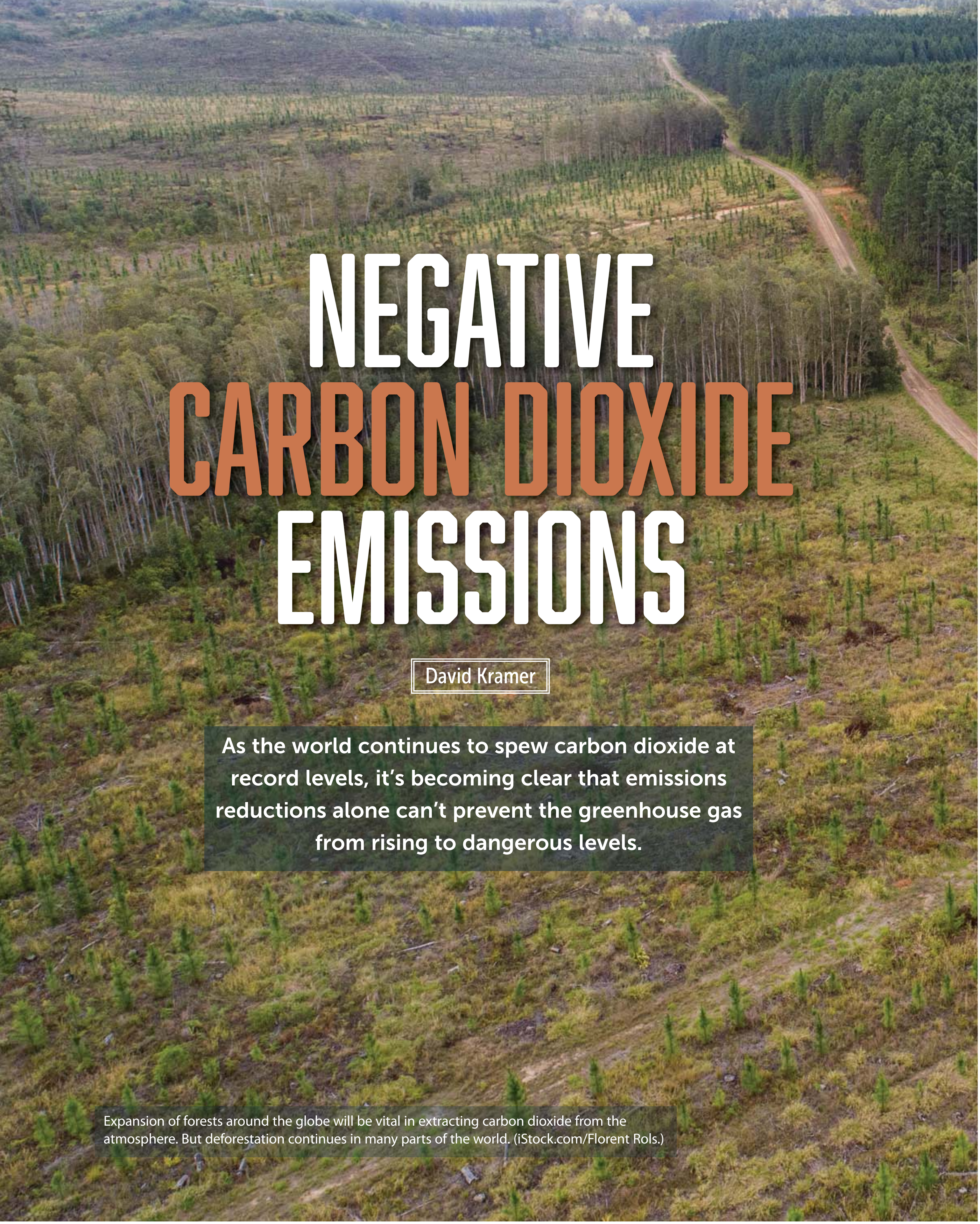
Negative carbon dioxide emissions

David Kramer

Citation: Physics Today **73**, 1, 44 (2020); doi: 10.1063/PT.3.4389
View online: https://doi.org/10.1063/PT.3.4389
View Table of Contents: https://physicstoday.scitation.org/toc/pto/73/1
Published by the American Institute of Physics



NEGATIVE CARBON DIOXIDE EMISSIONS

David Kramer

As the world continues to spew carbon dioxide at record levels, it's becoming clear that emissions reductions alone can't prevent the greenhouse gas from rising to dangerous levels.

Expansion of forests around the globe will be vital in extracting carbon dioxide from the atmosphere. But deforestation continues in many parts of the world. (iStock.com/Florent Rols.)

David Kramer is news editor of PHYSICS TODAY.

In December 2015 in Paris, 186 nations pledged their best efforts to keep the average global temperature “well below” 2 °C from its preindustrial average, with a goal to not exceed a 1.5° increase. But with carbon dioxide emissions increasing year after year and President Trump rescinding the Paris treaty, many climate scientists say it’s likely inevitable that the world will overshoot the atmospheric CO_2 level that could keep temperatures in check.

Annual global CO_2 emissions, currently about 37 gigatons, climbed 0.9% from 2018 to 2019, according to projections by the Global Carbon Project. That follows a 2.7% jump in 2018. China, which produces more than one-quarter of the world’s total emissions, has committed to leveling off its CO_2 output, but not until 2030. Demand for electricity in India, now the third largest emitter, is expected to double over the next 20 years, and coal is expected to remain the major contributor, according to BP’s 2019 *Energy Outlook*. The need to reduce CO_2 emissions is made more urgent by the difficulty of reducing agricultural sources of nitrous oxide and methane, greenhouse gases that contribute the equivalent of 10–20 Gt of CO_2 per year.

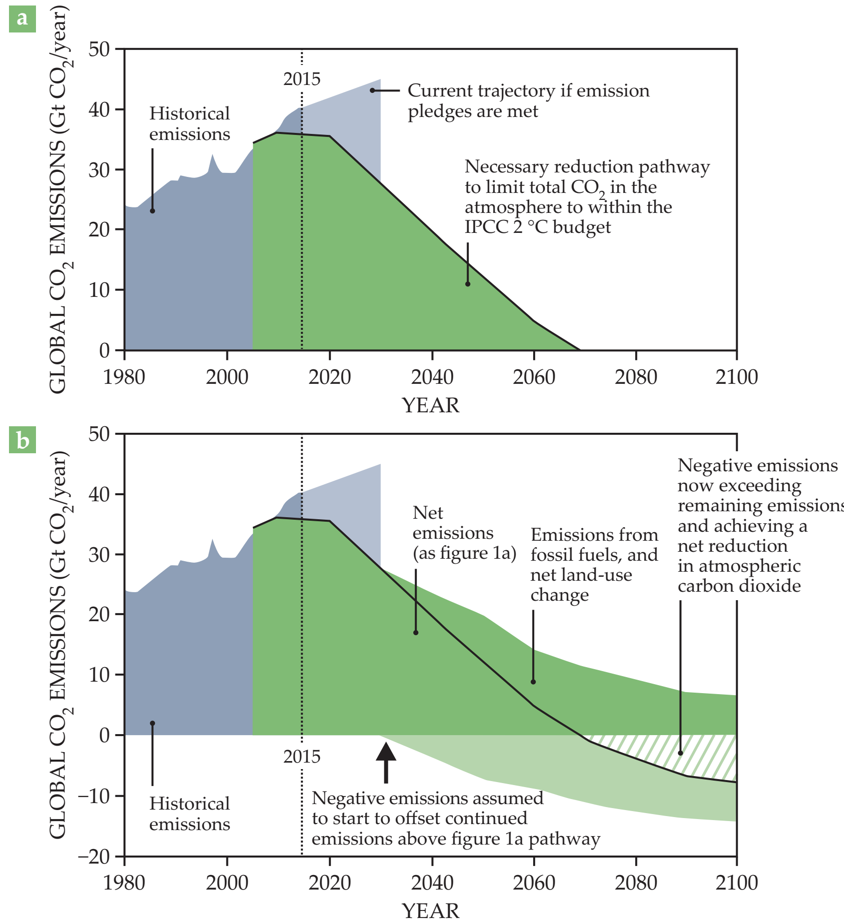
From its preindustrial level of 280 parts per million, atmospheric CO_2 has risen to roughly 410 ppm and is increasing at a rate of 2.5 ppm annually. It’s uncertain what the CO_2 concentration will be if and when a 1.5° or 2° increase occurs, because warming will continue even if emissions were immediately brought to zero. About half of anthropogenic CO_2 is removed from the atmosphere by oceans and terrestrial sinks within 30 years, but the other half will endure for centuries or more, according to the United Nations’ Intergovernmental Panel on Climate Change (IPCC). Positive feedback loops from the warming that has already occurred include the effects of shrunken ice cover in the Arctic and methane emissions from melting permafrost.

Estimates of when the world will top safe CO_2 levels have varied over time. A 2013 IPCC forecast said the 1.5° threshold could be breached as soon as 2021. In a 2018 report, the panel estimated that Paris commitments, even if followed by more stringent emissions reductions in 2030, won’t be sufficient to limit warming to 1.5°. Some studies suggest that existing emissions have already committed the world to a greater than 33% chance of 1.5° warming or more, whereas others suggest the world may have 20 more years at current emissions rates before blowing past the mark.[1]

Bringing CO_2 concentrations back to safe levels, many scientists believe, will require the extraction of a significant amount of CO_2 from the atmosphere. There are two ways to mitigate CO_2-caused warming: geoengineering to curb the amount of solar radiation reaching Earth's surface, and removing excess CO_2 from the atmosphere. Known as negative emissions technologies (NETs), the various methods that take the second approach form the subject of this article.

The role of NETs

The February 2019 National Academies of Sciences, Engineering, and Medicine committee report *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda* concluded that achieving Paris goals without retarding economic growth will likely require that 10 Gt of CO_2 be extracted from the atmosphere annually by 2050, and that figure will need to increase to 20 Gt annually by 2100. The committee said that a combination of currently available NETs could be ramped up to the 10 Gt level by 2050, but constraints—chiefly the availability of land—might limit their potential to just half that amount.



ESTIMATED GLOBAL REDUCTION (a) in CO_2 emissions required to limit temperature increases to 2 °C above preindustrial levels. The gray shaded area at the top shows projected emissions through 2030 if all current emission reduction pledges from the 2015 Paris agreement were to be met. In fact, emissions have continued to grow and are projected to reach record levels in 2019. **(b)** Gradual reduction in CO_2 emissions that could be possible with a significant and growing contribution of negative emissions technologies, beginning around 2030. Note that immediate large reductions to emissions are also required. (Source: European Academies Science Advisory Council policy report 35, 2018, adapted from K. Anderson, G. Peters, *Science* **354,** 182, 2016.)

Those NETs, which could be implemented for \$100 or less per ton of CO_2, are reforestation, afforestation (establishing forests on land not previously forested), improved forest management, agricultural and coastal management practices that add carbon to soils and sediments, and bioenergy with carbon capture and storage (BECCS). "We have the technology today. It's not crazy expensive and it adds up to gigatons," says National Academies committee member Jennifer Wilcox of Worcester Polytechnic Institute.

Capturing and storing CO_2 in such quantities will be a massive undertaking. Julio Friedmann, senior research scholar at Columbia University's Center for Global Energy Policy, regards the 10 Gt target as comparable to the mass of annual global oil and gas production. "We have to create an industry the size of the oil and gas industry that runs in reverse. And we're on the clock. If we could do that over 200 years, I'd be a lot more relaxed. But we've actually got 30 years to do that."

Steven Koonin, a New York University physicist and noted skeptic of the climate science consensus, agrees that "anyone who aspires to stabilize emissions in the next 50 years has got to be thinking about negative emissions technologies." He also puts the required scale at tens of gigatons per year of CO_2 by 2050.

The National Academies panel warned that afforestation, reforestation, and BECCS would compete with each other and with food production for finite arable land. BECCS, which the committee found had the potential to remove up to 3.5 Gt/year, likely will also be held back by the inability to gather all the necessary biomass economically.

Additionally, meeting the full capture potential from improved agricultural practices would require either a revolutionary breakthrough in agricultural productivity or wholesale changes in diets, including greatly reduced meat consumption and reduced food waste, the National Academies report said. Demand for wood will constrain improvements to forest management. Further limitations will come from resistance to adopting improved farming practices and from continued coastal development that reduces wetlands and marshes; both of those constraints will hold back the potential for increasing carbon uptake in soils and sediments.

In marked contrast to the National Academies findings, the European Academies Science Advisory Council said in a February 2018 report that NETs are unlikely to remove even several gigatons of CO_2 per year after 2050. "Negative emission technologies may have a useful role to play but, on the basis of current information, not at the levels required to compensate for inadequate mitigation measures," the report stated. Low technological readiness, high costs, and negative effects on terrestrial and marine ecosystems are factors weighing against NETs, it said. The world should instead focus efforts on halting the loss of forests and the degradation of lands that are adding to the greenhouse gas burden, and on deploying carbon capture and storage at power plants and other point sources of CO_2 emissions.[2]

Natural solutions

Research published in October 2017 by the Nature Conservancy and other institutions indicated that a combination of natural measures could provide more than one-third of all climate mitigation measures—including emissions reductions—necessary from now to 2030 to keep warming below the 2° mark, and it would cost \$100/ton or less. Most of that potential is from reforestation, avoided deforestation, and improved forest management. Lesser contributions would come from improving agricultural management practices, restoring wetlands and coastal areas, and other practices.

Those measures collectively would remove 11 Gt of CO_2 annually and could be implemented without affecting food production, according to the study. Up to one-third of the natural measures could be accomplished for \$10/ton or less. The researchers assumed that CO_2 emissions are held level for the next decade and then plunge to just 7% of current levels by 2050.[3]

More controversial but well-publicized findings were published by researchers led by Thomas Crowther of ETH Zürich in July. Increasing the world's forest cover by nearly 900 million hectares—an area equivalent to the entire US—could increase storage by 205 Gt, about one-quarter of the total atmospheric CO_2 pool, the authors asserted. Enough suitable land is available to accommodate as many as the one trillion new trees without impinging on global food supply or urban areas, they said.[4]

Others dispute those findings. "My biggest objection to the [ETH] paper is the notion that a billion hectares is just sitting there doing nothing," says Rob Jackson, a Stanford University professor who chairs the academic collaboration Global Carbon Project. "There is no discussion of land disturbances, water requirements, or of how you would incentivize land ownership" to achieve the reforestation. For example, although it might be possible to carry out large-scale tree planting in the western US, where so much of the land is publicly owned, government would have to provide costly incentives to landowners in the eastern half of the country to reforest their property.

Friedmann also questions the ETH results. "From an energy perspective, from a land perspective, from a nutrient perspective, from what we understand about tree physiology, it doesn't make sense. I don't understand the basis on which they would make the claim," he says. "Second, we haven't figured out how to stop chopping down trees yet."

No one argues that planting more trees won't be part of the solution, though. Nearly all the modeled pathways to achieve the Paris goals that were assessed by an IPCC special report on lands released in August 2019 require land-based mitigation and land-use changes consisting of different combinations of reforestation, afforestation, reduced deforestation, and bioenergy. The IPCC report also noted that options for storing more CO_2 in soils and vegetation don't lock up carbon indefinitely. When vegetation matures or when soil carbon reaches saturation, CO_2 removal declines toward zero. The accumulated carbon in vegetation and soils is at risk from future loss triggered by flood, drought, fire, pest outbreaks, and poor management.[5]

New forests and their improved management could soak up 2.5 Gt/year, the National Academies report said. Worldwide adoption of improved agricultural practices could increase

SILICON KINGDOM HOLDINGS

ARTIST'S CONCEPT OF AN "ARTIFICIAL TREE," a direct air capture system in development by Arizona State University and investors. The translucent spiral structure contains an ion exchange resin that when dry has an affinity for CO_2. Once saturated, the spiral structure is lowered into the cylinder, where moist air causes the CO_2 to be released and captured.

CO_2 capture in soils by 3.5 Gt/year, the report said. Those measures include reduced- and no-tillage farming, planting seasonal cover crops, converting marginal croplands to perennial grasses and legumes, adding manure and compost to soils, and improving the management of grazing lands.

Bioenergy with carbon capture and storage

BECCS is a hybrid of natural and technological approaches. The first step involves growing biomass to remove CO_2 from the atmosphere. Rather than the biomass staying in place as in the case of planting trees, it is harvested and subjected to one of several processes—combustion, fermentation, thermochemical conversion such as pyrolysis or gasification, or microbial conversion—that release the original carbon as CO_2, which is then captured and stored. Energy thus generated could produce either electricity or, through electrolysis, hydrogen. Cost estimates for the processes range from \$80 to \$150 per ton of CO_2 captured and stored. "I think \$100 is a totally fair number to

CARBON ENGINEERING

CARBON ENGINEERING has demonstrated its direct air capture technology at its Squamish, British Columbia, pilot plant. The company has a partnership with Occidental Petroleum to design a plant capable of scrubbing 1 million tons of CO_2 per year.

throw around," says Daniel Sanchez, an engineer at the University of California, Berkeley, who studies CO_2 removal methods.

As with other NETs requiring land conversion, BECCS will be constrained by agriculture, land degradation, water scarcity, and ecological concerns. Competition with food production and other sustainability concerns are likely to limit BECCS to 0.5–5.0 Gt/year, according to the IPCC. "If this is a technology the world wants to pursue seriously, we can get to one billion tons of CO_2 put underground each year," says Sanchez. "Beyond that you get into tremendous uncertainties about how we use and manage our lands." In their modeling, Sanchez and his colleagues developed a global inventory of marginal agricultural land—areas that come into production only part of the time. They narrowed that further to include only lands located above known geological storage reservoirs.[6]

A 2016 DOE report found the US could produce at least 1 Gt of dry biomass from agricultural, forestry, waste, and algal materials each year without adversely affecting the environment or food production. That biomass could produce enough biofuel or biopower to displace a little less than a third of US petroleum output.

The economics of unsubsidized electricity generation from biomass aren't favorable. The process is only about 25% thermally efficient, compared with the 42% efficiency of natural gas power generation. (The efficiency of both can be increased in combined cycle plants, where waste heat is harnessed.) Natural gas is cheaper than biomass, and capital costs for BECCS are more than four times those for a gas plant, the report said.

While relatively straightforward in concept, BECCS has been demonstrated on an industrial scale in only a handful of places. The largest such demonstration is the US Department of Energy–funded Illinois Industrial Carbon Capture and Storage Project, in which 1 million tons of CO_2 per year is being captured from corn fermentation at an Archer Daniels Midland ethanol plant and injected into a sandstone formation more than 2100 meters underground. But Niall Mac Dowell, who leads the clean fossil and bioenergy research group at Imperial College London, says BECCS is ready for prime time. "Pretend you are the US government. If you give me a long-term contract for removing CO_2 from the atmosphere for \$100 per ton, I guarantee that I can finance a BECCS project on that basis."

The BECCS technology has an inherent advantage over solely land-based approaches to CO_2 capture, says Mac Dowell. "When you put a ton of CO_2 into geology, it is permanently removed. Locking it up in a tree is inherently leaky. You could have a forest fire, a lightning strike, and someone could decide in 100 years to not do it anymore." Managing forests incurs additional perpetual costs, he adds.

If BECCS is used to produce biofuels by pyrolysis, the coproduct biochar can be added to soils for long-term carbon storage. For dedicated biochar production, the pyrolysis liquids and volatiles can be burned to generate electricity or process heat.

Biochar has the benefit of improving soils for growing crops or biomass. But its potential is limited, says Jackson: "I don't believe [biochar] is feasible at the gigaton scale. As a tool to improve degraded soils, it has a lot of advantages. But as a tool to be applied across millions of hectares, I don't see how we would do it. Spread it by helicopter? Plow it into lands on national forestlands?"

Direct air capture

Extracting CO_2 directly from the atmosphere using giant fans and chemical processes has been attracting a lot of attention in the past year. At least four fledgling companies are developing variations of the technology, known as direct air capture (DAC). (See PHYSICS TODAY, September 2018, page 26.) In May, Carbon Engineering, based in British Columbia, Canada, announced a joint venture with Occidental Petroleum to develop an engineering design for a plant capable of scrubbing 1 million tons of CO_2 from the atmosphere each year. Construction is expected to commence in 2021. Occidental and Chevron Corp were among investors providing a total of $68 million in new equity financing last year. In June, New York–based Global Thermostat announced that ExxonMobil had invested an undisclosed amount to scale up Global's DAC technology.

Oil companies and DAC may seem to be odd bedfellows, but the relationship is symbiotic. In addition to providing direct financing, the petroleum industry creates a ready-made market for the captured CO_2, which is needed for enhanced oil recovery. Also known as tertiary recovery, EOR forces pressurized CO_2 into depleted reservoirs to extract otherwise unrecoverable oil. Since it is miscible in petroleum, CO_2 also lowers the viscosity of the oil, which improves its flow to extraction wells.

Susan Hovorka, a geologist with the University of Texas at Austin, says oil and DAC should mix. "It's a perfectly reasonable step toward getting the NETs portfolio commercialized."

"If we want to do something like DAC on a gigaton scale, we can't do it without the help of the energy companies," agrees Wilcox. "It will take an immense workforce and will transition the jobs workers now have to doing this. The workers will require the same exact skill sets."

Wilcox is skeptical of DAC's feasibility, however. "It's really fundamental chemical engineering, and a really hard separations process," she says. "Most of those pushing the field are physicists. That's fine, but I feel like they are missing a big piece, like the process engineering. You can do a techno-economic analysis and say something costs x dollars per ton, but until you actually build it and prove it and show it, it's, like, not real."

Global Thermostat officials say its process can extract CO_2 for $100/ton, though it has yet to demonstrate it at scale. Wilcox says paper studies indicate costs of $100 to $150 a ton are feasible in the long run, but the Swiss company Climeworks is the only DAC pioneer to have sold commercial systems. The largest produces 900 tons of CO_2 per year for a greenhouse in Hinwal, Switzerland, at a cost of $600/ton. That was the exact cost estimated by the American Physical Society in a 2011 report on DAC.[7]

Climeworks hopes to lower that cost to $200/ton in the next three years, says spokesperson Louise Charles, and ultimately to $100. Steve Oldham, CEO of Carbon Engineering, told a Washington, DC, conference in October that the company's cost is "way, way, way less than $600 per ton." Howard Herzog, senior research engineer at the MIT Energy Initiative, notes the distinction between gross and net costs of DAC. If all the energy used to drive the Climeworks process is carbon-free, for example, gross and net costs would be the same. But if natural gas fuels Climeworks' power, then its net CO_2 removal cost would be well over $1000 a ton, he says.

Wilcox believes DAC may be more relevant in a post-2050 world, when forest fires, droughts, sea-level rise and the other negative impacts of climate change have reached the point where $300/ton for CO_2 extraction may not look so expensive.

Friedmann, a DAC enthusiast, thinks the technology will provide half of CO_2 capture needs. He says high cost is the only hurdle DAC faces. "That's okay. We know how to drop the cost of things," he says, citing the dramatic reduction in the cost of photovoltaics over the past several decades.

Large-scale deployment of DAC, however, will require enormous amounts of energy. One study published in July found DAC could constitute as much as a quarter of the world's total energy demand[8] by 2100. Energy is required not only to power the fans that continuously force air to flow past contactors that contain adsorbing chemical compounds, but also to provide heat to extract the CO_2 from the saturated compounds. Compressing and transporting the purified CO_2 to storage sites adds to energy requirements. Depending on the adsorbing compound used—currently either amines or hydroxide solutions—waste heat from industrial processes might supply a portion of the need.

Klaus Lackner, director of Arizona State University's Center for Negative Carbon Emissions, aims to reduce energy consumption with an "artificial tree" that uses wind to move air past chemical contactors. The trees' "leaves" contain an ion exchange resin that has a high affinity for CO_2 when dry. Once saturated with CO_2, they are moved to an enclosed wet environment, where the gas is released and concentrated.

In April 2019, Arizona State announced an agreement with a group of investors including Lackner to build and deploy 12-column clusters of the devices that will remove 1 ton of CO_2 per day. At full scale, such farms will be capable of capturing 3.8 million tons of CO_2 annually, at the familiar cost of $100 a ton, according to the university. All DAC approaches feature far smaller geographic footprints and water requirements relative to land-based NETs. For example, a forest of artificial trees capable of capturing as much CO_2 as the Amazon rain forest would be 500 times smaller than the natural version, says Wilcox.[9]

Storage

Although not a NET itself, CO_2 storage is intrinsic to both DAC and BECCS. Experts say the pore space in sedimentary rocks around the globe is more than enough to sequester all the CO_2 that humanity could ever want to remove from the air. DOE has estimated that the total storage capacity in the US alone ranges between 2.6 trillion and 22 trillion tons of CO_2.[10] China has enough storage to hold 600 years' worth of its current emissions.[11] Globally, the number is easily 20 trillion to 30 trillion tons, says Friedmann.

SOLIDIA TECHNOLOGIES

SAMPLES OF NOVEL CONCRETE in cylinders are tested by Solidia Technologies employees prior to curing with CO_2. Building materials present a route to permanently remove CO_2 from the atmosphere.

As of last year, just five dedicated geological CO_2 storage locations were operational worldwide, according to the Global CCS Institute. The longest-running is in the North Sea's Sleipner gas field, where since 1996, 1 million tons of CO_2 from Norwegian natural gas processing has been injected beneath the seabed every year, with no leakage. The sole dedicated geological storage site in the US is at the DOE-funded Illinois ethanol plant demonstration. The world's largest dedicated geological storage site, at Chevron's liquefied natural gas project in Western Australia, began operating in August. The company says it will sequester up to 4 million tons of CO_2 each year.

Compressing and injecting CO_2 makes up a small fraction of the total cost of BECCS or DAC. Sanchez says it will cost between \$1 million and \$33 million to drill a well capable of injecting 1 megaton of CO_2 annually. Assuming a 20-year lifetime for the well, that's less than \$1 per ton of CO_2. He estimates the total cost of storage, including operation, maintenance, monitoring, and verification, at around \$5/ton.

A report by the Congressional Research Service says that long-term average cost of CO_2 transport and storage should stay below the level of approximately \$12–\$15/ton in North America, due largely to the abundant capacity offered by deep saline formations.[11] Herzog's estimate is much higher: up to \$50/ton.

Incorporating CO_2 into building materials is another way to store captured CO_2. Solidia Technologies in New Jersey has developed a process it says could reduce the carbon footprint of cement and concrete production by 60%. Solidia's cement is cured with CO_2 instead of water, and that process forms calcium carbonate and silica to harden the concrete. About 0.5 Gt of CO_2 could be captured per year if the company's technologies were adopted by the entire precast concrete industry, says Solidia chief technology officer Nicholas DeCristofaro. Concrete made with the company's proprietary cement locks up about 300 kg of CO_2 per ton as it cures in a CO_2-rich environment. The manufacture of Solidia's cement itself also produces 30% less CO_2 than conventional Portland cement. (Cement production contributes about 8% of global CO_2 emissions.) Solidia's concrete curing process wouldn't work for the larger ready-mix concrete market.

CO_2 mineralization

Solidia concrete is an artificial version of CO_2 mineralization, a naturally occurring capture process also known as rock weathering. "It is technically mineralization to make concrete block with CO_2," says Phil Renforth, associate professor at Heriot-Watt University in the UK. The same chemical reactions occur on certain rocks, and they can be accelerated either by exposing a greater surface area of the rock to the atmosphere or by bringing CO_2-bearing liquid into contact with the rock at depth. Compared with storing CO_2 in geological formations, rock weathering chemically transforms the CO_2 into carbonates such as calcite, magnesite, dolomite, and quartz. If performed subsurface, mineralization can induce seismicity of the sort that has occurred with wastewater injection from oil and gas hydrofracturing.

Mineral carbonation requires rocks rich in calcium, magnesium, or iron cations, such as peridotite, basaltic lava, and ultramafic and mafic rocks containing olivine. Peter Kelemen, a Columbia University geochemist, says enough mantle rock is located within a few kilometers of Earth's surface to permanently capture hundreds of trillions of tons of CO_2.

When finely ground, olivine-rich rock can absorb up to its weight in CO_2. For more common basalt and volcanic material, the ratio is about 20%. Renforth says as much as 10 Gt of rock mining and grinding per year is feasible by 2100. For comparison, about 50 Gt of rock is extracted globally each year by the aggregate industry.

Mineralization may be cost-competitive with direct air capture systems, the National Academies committee said. But it warned that mining and spreading the rock would create enormous volumes of waste that could contaminate water, air, or both.

Renforth says the required particle fineness will depend on the reactivity of the rock. Negative emissions would, of course, be reduced by the CO_2 generated to extract and crush the rock, transport it to the application site, and distribute it. Cost estimates vary widely from a low of $20 to hundreds of dollars per ton of CO_2 extracted, he says.

Kelemen says he and coinventors have filed a patent application on a process for weathering magnesium-rich rocks that involves heating up the carbonated rock to drive off the CO_2 for capture, and then recycling the rock. Once again, the cost is projected at $100 per ton of CO_2 captured.

In a marine environment, mineralization might raise the alkalinity of the ocean surface and thereby increase its CO_2 capture capacity. The process would offer an added benefit of countering the CO_2-caused ocean acidification that is damaging coral reefs and other sensitive marine ecosystems.

One 2017 study suggested that dissolving huge quantities of finely ground olivine particles (10 μm) in ice-free coastal areas—roughly 9% of the entire ocean surface—could extract 800 Gt of carbon (3000 Gt of CO_2) by 2100. Olivine mining would have to be increased by two orders of magnitude to achieve that level, the researchers said, and CO_2 emissions from crushing operations could offset as much as 20% of the gas captured. Pollution from impurities such as silica, iron, and heavy metals also is possible.[12]

Taking action

Implementing NETs at the necessary scale will require increased R&D to improve the understanding of mineralization, to mature DAC, and to better determine the effects of land-based approaches on food production and ecosystems, among other needs. The National Academies report suggested a detailed portfolio of NETs R&D totaling as much as $1 billion annually. In September the think tank Energy Futures Initiative offered a 10-year, $10.7 billion R&D and demonstration program to bring CO_2 removal to commercial readiness.[13]

But it will take more than R&D alone to bring some NETs, including DAC, to fruition, says Friedmann. "We know the recipe; we've done it over and over again. We have sustained, long-lived R&D programs that drop the price enough that we start making policy. And we expand policies to align with markets. That is exactly what we did for solar, wind, and nuclear, and batteries."

To nurture wind and solar, states enacted renewable portfolio standards, while the federal government offered investment tax credits and production tax credits. Adoption was then spurred on by stimulus money during the last recession, loan programs, and feed-in tariffs (long-term purchase contracts to renewable energy producers that are based on the cost of the technology).

"It's not necessarily what is technically achievable; it's about the political will, and the extent to which governments, especially the US, are willing to provide economic incentives to leave CO_2 in the earth or to put it back in the earth," says Wilcox. "It's not all going to happen by advancing technology and getting costs down."

Notably, in the US a measure known as 45Q, first enacted in 2008 to incentivize the capture of CO_2 for EOR, was expanded last year to make eligible both CO_2 captured and stored and CO_2 captured for other uses. The tax credit will increase to $50/ton for stored and $35/ton for CO_2 that's put to use. The tax credit could exceed the cost of capture for industries producing ethanol, ammonia, and hydrogen, according to the report by the Energy Futures Initiative. It estimated that 45Q could stimulate storage or utilization totaling 50–100 Mt of CO_2 per year, depending on public acceptance, the availability of pipelines and storage sites, and other factors.

Bipartisan, bicameral legislation known as the Utilizing Significant Emissions through Innovative Technologies Act and introduced in February 2019 would authorize increased R&D on CO_2 capture and utilization, ease regulatory hurdles on construction of CO_2 pipelines, and further extend 45Q. The Senate bill was reported out of committee and awaits floor action. But as of press time, none of five subcommittees with jurisdiction in the House have considered the measure.

REFERENCES

1. Z. Hausfather, *Analysis: How Much "Carbon Budget" Is Left to Limit Global Warming to 1.5C?*, Carbon Brief (2018).
2. European Academies Science Advisory Council, *Negative Emission Technologies: What Role in Meeting Paris Agreement Targets?*, policy report 35 (February 2018).
3. B. W. Griscom et al., *Proc. Natl. Acad. Sci. USA* **114**, 11645 (2017).
4. J. F. Bastin et al., *Science* **365**, 76 (2019).
5. Intergovernmental Panel on Climate Change, *Climate Change and Land* (2019).
6. P. A. Turner et al., *Clim. Change* **148**, 1 (2018).
7. R. Socolow et al., *Direct Air Capture of CO_2 with Chemicals: A Technology Assessment for the APS Panel on Public Affairs*, American Physical Society (June 2011).
8. G. Realmonte et al., *Nat. Commun.* **10**, 3277 (2019).
9. J. Wilcox, "A new way to remove CO_2 from the atmosphere," TED talk, 10 April 2018.
10. P. Folger, *Carbon Capture and Sequestration (CCS) in the United States*, Congressional Research Service (9 August 2018). Available at https://fas.org/sgp/crs/misc/R44902.pdf.
11. Global CCS Institute, *The Global Status of CCS 2018*, https://indd.adobe.com/view/2dab1be7-edd0-447d-b020-06242ea2cf3b.
12. E. Y. Feng et al., *Earth's Future* **5**, 1252 (2017).
13. Energy Futures Initiative, *Clearing the Air: A Federal RD&D Initiative and Management Plan for Carbon Dioxide Removal Technologies* (September 2019).

PT