Methods for removing carbon from the atmosphere

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A rendering of Carbon Engineering's large-scale carbon dioxide removal plant, which will use direct air capture. Photo: Carbon Engineering Ltd.

The Intergovernmental Panel on Climate Change (IPCC) asserts that limiting global warming to 1.5˚C could avert the most catastrophic effects of climate change. In its recent report, it laid out four means of achieving this —and all of them rely on removing carbon dioxide from the atmosphere. This is because even if we cut most of our carbon emissions down to zero, emissions from agriculture and air travel would be difficult to eliminate altogether. And since carbon dioxide that's already in the atmosphere can affect climate for hundreds to thousands of years, the IPCC maintains that carbon dioxide removal (CDR) technologies will be critical to get rid of 100 to 1000 gigatonnes of CO2 this century.

How can carbon dioxide be removed?

There are a variety of CDR strategies, all in different stages of development, and varying in cost, benefits and risks. CDR approaches that employ trees, plants and soil to absorb carbon have been used at large scale for decades; other strategies that rely more on technology are mostly at the demonstration or pilot stages. Each strategy has pros and cons.

Afforestation and reforestation

As plants and trees grow, they take carbon dioxide from the atmosphere and turn it into sugars through photosynthesis. In this way, U.S. forests absorb 13 percent of the nation's carbon emissions; globally, forests store almost a third of the world's emissions.

Reforestation in Southern Oregon. Photo: Downtowngal

Planting additional trees could remove more carbon from the atmosphere and store it for a long time, as well as improve soil quality at a relatively low cost—$0 to $20 per ton of carbon. Afforestation involves planting trees where there were none previously; reforestation means restoring forests where trees have been damaged or depleted.

Afforestation, however, could compete for land used for agriculture just as food production needs to increase 70 percent by 2050 to feed the growing world population. It could also affect biodiversity and ecosystem services.

And although forests can sequester carbon for decades, they take many years to grow and can become saturated in decades to centuries. They also require careful management because they are subject to human and natural impacts such as wildfires, drought and pest infestations.

Soil carbon sequestration

The carbon that plants absorb from the atmosphere in photosynthesis becomes part of the soil when they die and decompose. It can remain there for millennia or it can be released quickly depending on climatic conditions and how the soil is managed. Minimal tillage, cover crops, crop rotation and leaving crop residues on the field help soils store more carbon.

Italian ryegrass as a cover crop after maize harvest in S. Africa. Photo: Alan Manson

The IPCC, which considers soil carbon sequestration to have the ability to reduce CO2 at the lowest cost—$0 to $100 per ton—estimates that soil carbon sequestration could remove between 2 and 5 gigatonnes of carbon dioxide a year by 2050. By comparison, the world's power plants released 32.5 gigatonnes of CO2 in 2017.

Soil carbon sequestration could be deployed immediately, and would improve soil health and increase crop yield; moreover it would not stress land and water resources. But while soil stores large amounts of carbon in the beginning, it can become saturated after 10 to 100 years, depending on climate, soil type and how it is managed.

If we burn plants for energy at a power plant and capture and store the resulting emissions, the CO2 the plants previously absorbed is removed from the atmosphere. The CO2 can then be used for enhanced oil recovery or injected into the earth where it is sequestered in geologic formations.

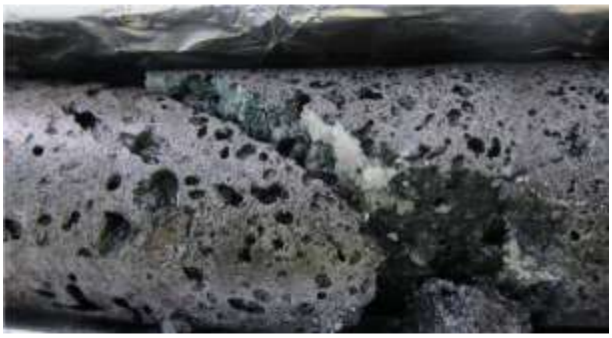
The IPCC estimates that BECCS could remove between 0.5 and 5 gigatonnes of carbon a year by 2050. To absorb enough carbon to keep the world at 2˚, however, energy crops would need to be planted over an area of land up to three times the size of India, according to one estimate; and even smaller amounts of BECCS would compete with land needed for food production. One study concluded that large-scale BECCS could cause global forest cover to fall 10 percent and require twice as much water as is currently used globally for agriculture. BECCS could also end up impacting biodiversity and ecosystem services, and generating greenhouse gas emissions through farming and fertilizer use.

At this point, BECCS is expensive. Right now, there is only one working BECCS project in the world—an ethanol plant in Decatur, IL that has captured and stored over 1.4 million tons of CO_2. Because there are so few research projects and BECCS is untested on a large scale, it is still in an early stage of development. While current cost estimates for BECCS range between $30 and $400 per ton of CO_2, studies project that costs could drop to $100 to $200 per ton of carbon by 2050. Nevertheless, BECCS is considered one of the most potentially effective carbon dioxide removal strategies for providing long-term carbon storage.

The National Academies of Sciences, Engineering and Medicine projects that given what we know today, afforestation and reforestation, soil carbon sequestration, and BECCS, along with sustainable forestry management practices (such as thinning forests and prescribed burns) could be scaled up to capture and store 1 gigatonne of carbon a year in the U.S. and 10 gigatonnes globally. However, this would require huge changes in agriculture, forest and biomass waste management.

Carbon mineralization

This strategy exploits a natural process wherein reactive materials like peridotite or basaltic lava chemically bond with CO_2, forming solid carbonate minerals such as limestone that can store CO_2 for millions of years. The reactive materials can be combined with CO_2-bearing fluid at carbon capture stations, or the fluid can be pumped into reactive rock formations where they naturally occur.



Calcite, a carbonate mineral, forming in basalt. Photo: Sigrg

Scientists at the Earth Institute’s Lamont-Doherty Earth Observatory have been working on carbon mineralization for several years, and are finding ways of speeding up the natural reaction to increase CO_2 uptake and permanently store it. Lamont research professor David Goldberg and his colleagues, for example, are studying the feasibility of storing 50 million tons or more of CO_2 in basalt reservoirs in the Pacific Northwest. Over 20 years, the project would inject CO_2 from industrial sources, such as manufacturing and fossil fuel power plants, into basalt 200 miles offshore, on the eastern flank of the Juan de Fuca Ridge. There, beneath 2600 meters of water and another 200 meters of sediment, the basalt reservoir contains pore spaces that would fill up as the CO_2 mineralizes into carbonate limestone. In this area, the basalt reacts quickly and mineralization could potentially take only two years or less. Goldberg's team has analyzed factors including how to transport the CO_2, how it would react chemically, and how the site could be monitored over time.

The next step is to launch a pilot project there to store 10,000 tons of CO_2. "A pilot project is critical to move the ball forward for basalt offshore carbon mineralization, both for technical and regulatory reasons," said Goldberg. It would enable the researchers to experiment with different kinds of injections—for example, whether they should be continuous or intermittent—and answer questions such as 'how fast does the pore space fill up?' which can only be tested in the field. In addition, a pilot project is key to understanding the regulatory implications of carbon mineralization, since no regulations currently exist. Canada and the U.S. would only begin creating a regulatory framework when they have a pilot project. Goldberg says they're still looking for funding for a pilot project, but "There's a lot of interest."

Since 2012, CarbFix, an Icelandic project that Goldberg also worked on, has been capturing carbon and mineralizing it at the country's largest geothermal power plant run by Reykjavik Energy. While the plant runs on geothermal renewable energy, it still emits a small amount of CO_2; CarbFix injects 12,000 tons of CO_2 yearly into the ground for $30 per ton.

Because carbon mineralization takes advantage of natural chemical processes, it has the potential to provide an economical, non-toxic and permanent way to store huge amounts of carbon. However, there are still technical and environmental questions that need to be answered—according to the National Academies report, carbon mineralization could possibly contaminate water resources or trigger earthquakes.

Direct air capture

Direct air capture sucks carbon dioxide out of the air by using fans to move air over substances that bind specifically to carbon dioxide. (This concept is based on the "artificial tree" work of Klaus Lackner, director of the Center for Negative Carbon Emissions at Arizona State University, who was for many years the director of the Earth Institute's Lenfest Center for Sustainable Energy.) The technology employs compounds in a liquid solution or in a coating on a solid that capture CO_2 as they come into contact with it; when later exposed to heat and chemical reactions, they release the

CO2, which can then be compressed and stored underground. The benefits of direct air capture are that it is actually a negative emissions technology—it can remove carbon that's already in the atmosphere, as opposed to capturing new emissions being generated—and the systems could be located almost anywhere.

At a coal plant, about one in ten molecules in exhaust gas is CO2, but CO2 in the atmosphere is less concentrated. Only one in 2,500 molecules is CO2, so the process for removing CO2 is more expensive compared to capturing carbon from fossil fuel plants. Direct air capture started out at $600 per ton of carbon; currently it costs $100-$200 a ton—still expensive, in part because there are no economic incentives (such as a carbon tax) or secondary environmental benefits (such as enhanced soil quality) to removing CO2 from the air. Improving the technology so that CO2 can be captured more efficiently, and/or selling the captured CO2 can bring the price down. Three companies—Swiss Climeworks, Canadian Carbon Engineering, and American Global Thermostat—are working on this.

Climeworks's first commercial plant near Zurich captures 1,000 metric tons of CO2 a year, which is used in a greenhouse to boost crop yields by 20 percent. In 2017, the company installed a direct air capture unit as a demo at Reykjavik Energy's Icelandic plant to capture a small amount of CO2 that then gets stored underground by CarbFix.

Reykjavik Energy's Hellisheidi plant in Iceland with direct air capture. Photo: Sigrg

Climeworks now has 14 direct air capture facilities built or under construction in Europe; its Italian plant uses the captured CO2 to make methane fuel for trucks.

Carbon Engineering, which boasts Bill Gates as an investor, has a plant in western Canada that can capture one million tons of CO_2 a year. It projects that at large scale, it could remove CO_2 for $100 to $150 per ton. Its goal is to use the CO_2 to make carbon-neutral synthetic hydrocarbon fuels, which would further lower its cost. The company maintains that a facility using this “Air to Fuels” process, once scaled up, could produce fuel at less than $1 dollar a liter.

Global Thermostat, which is building its first plant in Huntsville, AL, is aiming to get its price down to $50 a ton by selling the captured CO_2 to a soda company. The company would build small on-site “capture plants” at the soda maker’s facilities, thus reducing costs for energy and transportation.

One study projected that direct air capture could suck up 0.5 to 5 gigatonnes of CO_2 a year by 2050 with possibly 40 gigatonnes by 2100. However, large scale direct air capture could eventually have environmental impacts stemming from the extraction, refining, transport and waste disposal of the minerals that capture the carbon emissions.

While direct air capture has great potential for carbon dioxide removal, it is still at an early stage of development. Fortunately, it is getting some Congressional support in the form of the FUTURE Act (the Furthering carbon capture, Utilization, Technology, Underground storage, and Reduced Emissions Act). The act doubles the tax credits for capturing and permanently storing carbon dioxide in geological formations and using it for enhanced oil recovery; for companies that convert carbon to other products such as cement, chemicals, plastics and fuels; and provides a $35 tax credit per ton of CO_2 via direct air capture.

Enhanced weathering

Rocks and soil become weathered by reacting with CO_2 in the air or in acid rain, which naturally occurs when CO_2 in air dissolves in rainwater. The rocks break down, creating bicarbonate, a carbon sink, which is eventually carried into the ocean where it is stored. Enhanced weathering speeds up this process by spreading pulverized rock, such as basalt or olivine, on agricultural land or on the ocean. It could be crushed and spread on fields and beaches, and even used for paths and playgrounds.

Enhanced weathering could improve soil quality, and as the alkaline bicarbonate washes into the ocean, it could help neutralize ocean acidification. But it could also potentially alter soil pH and chemical properties, and affect ecosystems and groundwater. Mining, grinding and transporting the rock would be costly, require a lot of energy and produce additional carbon emissions as well as air pollution. Due to the many variables and the fact that most assessments of enhanced weathering have not been tested in the field, cost estimates vary widely.

Ocean alkalinization, considered a type of enhanced weathering, involves adding alkaline minerals, such as olivine, to the ocean surface to increase CO_2 uptake and counteract ocean acidification. One study estimated that this strategy could sequester between 100 metric tons to 10 gigatonnes of CO_2 a year, for costs ranging from $14 to over $500 a ton. Its ecological impacts, however, are unknown.

Ocean fertilization

Phytoplankton off the coast of Finland. Photo: Stuart Rankin

Ocean fertilization would add nutrients, often iron, to the ocean to prompt algal blooms, which would absorb more CO_2 through photosynthesis. However, by stimulating the growth of phytoplankton—the basis of the food chain—ocean fertilization could affect local and regional food productivity. Vast algal blooms could also cause eutrophication and result in dead zones depleted of oxygen. In addition to its possible ecosystem impacts, it also has less potential to sequester carbon over the long term.

Coastal blue carbon

Salt marshes, mangroves, sea grasses and other plants in tidal wetlands are responsible for more than half of the carbon sequestered in the ocean and coastal ecosystems. This blue carbon can be stored for millennia in the plants and sediments. However, wetlands are being destroyed by runoff and pollution, drought and coastal development—a soccer field-sized area of seagrass is lost every half hour. Restoring and creating wetlands and managing them better could potentially double their carbon storage. Healthy wetlands also provide storm protection, improve water quality and support marine life.

There are few estimates of the carbon removal potential of blue carbon, but the costs would be low to zero.

And some ideas for the future

Combinator, an organization that funds promising startups, has put out a call for any working on new types of carbon dioxide removal technologies, none of which have yet been tested outside of a lab. Specifically, they are looking for projects in four areas:

Modifying the genes of phytoplankton would enable them to sequester carbon in areas of the global ocean that lack the nutrients needed for photosynthesis.

Electro-geo-chemistry uses electricity from renewable sources to break saline water down to produce hydrogen (which can be used for fuel) and oxygen, which, in the presence of minerals, produces a highly reactive solution. This solution absorbs carbon dioxide from the atmosphere and turns it into bicarbonate.

Enzyme systems speed up chemical reactions that could change carbon dioxide into other useful organic compounds. Y Combinator would like to create enzyme systems that can do this outside of living cells to simplify carbon fixation.

The last idea involves creating 4.5 million little oases in deserts to host phytoplankton that would absorb CO_2. They would also provide fresh water and support vegetation that could also suck up carbon.

What's needed to advance carbon dioxide removal?

Each CDR technology is feasible at some level, but has uncertainties about cost, technology, the speed of possible implementation, or environmental impacts. It's clear that no single one provides the ultimate solution to climate change.

“Carbon dioxide removal alone cannot do it,” said Kate Gordon, a fellow at the Columbia Center on Global Energy Policy. “If there’s one thing the IPCC report really underscores is that we need a portfolio—we need to reduce emissions dramatically, we need to come up with more renewable energy options to replace fossil fuels, we need to electrify a lot of things that are currently run on petroleum and then we need to do an enormous amount of carbon removal.” In the near term she would like to see more deployment and ramping up of tried and true strategies, such as tree planting trees and more sustainable agricultural practices.

Grassland conservation in South Dakota Photo: USFWS

In fact, a new study just determined that planting trees and improving management of grasslands, agricultural lands and wetlands could sequester 21 percent of the U.S.’s annual greenhouse gas emissions at relatively low cost.

Developing the other carbon dioxide removal strategies further is going to take substantial amounts of money.

“The climate philanthropy community actually needs to recognize this as part of the climate solution—it’s really important that [CDR] becomes part of that portfolio,” said Gordon. “We also need a pretty significant federal R&D budget dedicated to these strategies so we can start improving the technology and get a better grasp on how much it does cost to do each of these things, how effective they are and how safe they are.”

Establishing a financial incentive to remove carbon such as a carbon tax or penalties for emitting carbon would help as well.

“This is the next frontier of the energy, climate and technology conversation,” said Gordon. ”We need to be ahead of this thing if we want to stay competitive—if we want to continue to have most of the world’s clean energy and advanced energy patents…Otherwise we’ll be buying it from somebody else, because someone’s going to do it.”