Can carbon capture from air shift the climate change equation?

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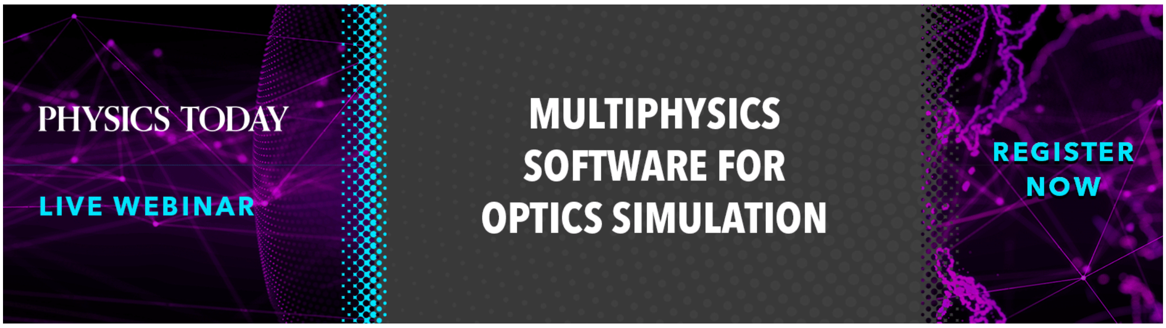

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Critics dismiss the idea of scrubbing meaningful amounts of carbon dioxide from the air, but proponents say the approach could be scaled up for the job.

Of all the schemes for rescuing the world from the worst effects of climate change, perhaps none seems more quixotic than extracting carbon dioxide directly from the air. Yet at least three companies have developed working capture systems and lined up serious investments to deploy them. All plan to make money on the venture, by selling the gas for production of chemicals, fertilizers, and synthetic fuels and even for desalination, but they say their real goal is to alter the climate change equation.

Although CO_2 removal is conceptually straightforward, using it to address the climate change problem is an enormous challenge. Yet dramatically reducing or eliminating net global carbon emissions is vital if the world is to stay below the 2 °C temperature increase from preindustrial levels that scientists say is the threshold for the direst impacts of climate change. That task is formidable: 37 gigatons of CO_2 were emitted in 2017, according to a projection by the Global Carbon Project. The sum is likely to grow in coming years as developing countries use more energy.

Trying to counter such massive emissions with direct-air capture (DAC) seems incredible to some. The atmospheric concentration of the gas is just over 400 ppm, up from around 277 in the preindustrial era. At 100% capture efficiency, 2500 molecules of air must be scrubbed to capture one molecule of CO_2. "In order to remove CO_2 from an ambient airstream, you need a device whose physical proportions are immense," says MIT physicist Robert Jaffe, who poses DAC as a problem in his book *The Physics of Energy* (2018). "If we walk through a simple calculation, the results are daunting."

For example, a coal-fired power plant that meets the needs of a city the size of Cambridge, Massachusetts, would emit 1.6 million tons of CO_2. Regardless of the specific removal process, Jaffe says, simply moving the volume of air necessary to capture that amount would require a DAC plant 100 meters high by 600 meters long, with its fans blowing constantly day and night at 2 meters per second. Jaffe assumed a capture efficiency of 50% and an atmospheric CO_2 concentration of 500 ppm, perhaps an ambient level at which solutions such as DAC are seriously considered, he says. (Jaffe's hypothetical power plant produces 150 MW of electricity; a typical US coal-fired power plant produces about 1 GW.)

Direct-air capture is not to be confused with capturing CO_2 post-combustion at the source of fossil fuel emissions, a technology that has been deployed in a few places around the world. (See PHYSICS TODAY, May 2013, page 23.) The concentration of CO_2 in flue gas is far higher—up to 15% for coal plants—than in the atmosphere. Even so, thermodynamics requires that the capture and compression of the gas will consume about 16% of the power plant's useful energy output, says Jaffe. Post-combustion capture from flue gas isn't expected to become viable unless governments impose a substantial price on CO_2 emissions.

In its influential 2011 report *Direct Air Capture of CO_2 with Chemicals*, the American Physical Society estimated it would cost $600 to capture a ton of CO_2 directly from the air and require erecting 30-km-long plants for every gigawatt-size coal plant. DAC advocates say the report did a disservice by dismissing DAC as a viable option for mitigating climate change.

Among the DAC advocates is Peter Eisenberger, a Columbia University physicist and cofounder of Global Thermostat. His company, based in New York City, is one of three startups that claim they can or soon will be able to capture CO_2 with DAC at a cost well below half of APS's figure. To date, however, the Swiss company Climeworks is the only one that can document cost in a commercial setting. Its plant supplies a greenhouse with 900 tons of CO_2 annually to boost crop yields by accelerating photosynthesis. Coincidentally, the cost comes

CLIMEWORKS' DIRECT-AIR capture plant supplies 900 tons of carbon dioxide a year to a commercial greenhouse in Hinwil, Switzerland.

to $600 a ton. For comparison, CO_2 used by the US oil and gas industry for enhanced oil recovery can be purchased from naturally occurring underground reservoirs for $30–$40 per ton.

All the companies' cost estimates include only the cost of capturing the CO_2 and not the cost of permanent underground storage. A 2015 National Academies of Sciences, Engineering, and Medicine report estimated the cost of sequestration will be $10–$20 per ton of CO_2.

Proponents of DAC say it will be a far more efficient method of CO_2 removal and far less land-intensive than another alternative, reforestation. Although other methods of CO_2 removal have been proposed, the UN Intergovernmental Panel on Climate Change, in its most recent assessment, judged those to have "biogeochemical or technological limitations to their potential on the global scale." By one estimate, by Richard Houghton of the Woods Hole Research Center, more than 2×10^6 km^2 would have to be reforested to have a significant effect on climate change. The state of Alaska is 1.7×10^6 km^2. And the world loses about 100 000 km^2 each year to deforestation.

From CO_2 to fuels

All DAC systems work by forcing huge volumes of air through devices called contactors, where the CO_2 molecules are adsorbed by chemical compounds. The chemicals are either hydroxides or amines. All require heat to release the concentrated CO_2, with far higher tem-


CLIMEWORKS

peratures needed for hydroxide systems. Electricity is required for the large fans; natural gas or electricity can provide the heat. In the case of amines, waste heat from industrial processes can be used.

Carbon Engineering (CE) is a Canadian firm founded by Harvard University physicist David Keith. The company has been operating a pilot-scale DAC plant in Squamish, British Columbia, since 2015; it captures 1 ton of CO_2 a day. In CE's two-chemical-loop process, the air is passed through contactors containing an aqueous potassium hydroxide. When CO_2 is captured, it forms potassium carbonate, which is sent to a fluidized bed reactor, where it reacts with calcium hydroxide. The resulting potassium hydroxide returns to the contactors, and solid pellets of calcium carbonate are moved to a calciner and heated to 900 °C to release the CO_2. The lime that's left is hydrated and returned to the bed reactor.

A June article in *Joule* by Keith and his colleagues presented a detailed engineering analysis for a DAC plant that could handle 1 million tons per year. That's about the amount of CO_2 emitted each year by 200 000 vehicles.

Keith's paper puts the cost per ton at \$94–\$232, depending on energy costs and the end use of the CO_2. The highest-cost DAC plants would supply pressurized CO_2 for shipment or geologic sequestration. The lowest-cost plant would serve as the front end of a gas-to-liquids plant that would produce synthetic fuels to replace or be blended with gasoline, diesel, or aviation fuels.

Keith says CE's board will decide in the next several months whether to build a combined DAC and synthetic fuels plant to validate all the steps in the process. The plant would produce 100 barrels or so a day. It's possible that the Canadian or US government might put up some funding.

The next step, a commercial plant producing 2000 barrels a day of fuels and capturing 300 000 tons of CO_2 per year, will cost roughly \$300 million, Keith says. Financing depends on finding both a buyer for the fuels and a supplier of low-cost renewable energy, preferably one that will take an ownership stake in CE.

The economics of CE's fuels venture and how carbon-neutral the fuels will be depend mostly on the price and carbon content of the electricity needed to produce the fuels' hydrogen component. CE plans to use mainly renewable energy in splitting water for hydrogen. Keith says CE will produce fuels for about \$1 a liter: \$0.70 for splitting water and \$0.15 apiece for the DAC and fuels-synthesis processes. Petroleum products cost about \$0.60 a liter.

Keith acknowledges that synthetic fuels can't compete with petroleum products in unregulated environments. But in niche markets, notably California, a low-carbon fuel standard (LCFS) sets limits on the carbon-intensity of fuels sold there. Measured in grams of CO_2 per megajoule, the current limit will be gradually tightened so that increasing numbers of electric vehicles and a growing fraction of renewable fuels such as biodiesel and ethanol will be in the mix.

The federal renewable fuel standard, on which the corn ethanol industry depends, provides further incentive for low-carbon synthetic fuels. And a new federal tax credit taking effect this year provides incentives for capturing and storing or reselling CO_2.

Adapting catalytic converters

A different chemical process, using amine sorbents, is being deployed by two companies: Climeworks and Global Thermostat. In GT's process, 2 m^2 arrays of contactors laden with CO_2 are physically transferred to a second stage, where the gas is driven out under partial vacuum by 85 °C steam. The relatively low temperature lowers energy costs by using waste heat generated by electricity plants and other industrial processes.

GT has operated a 1000-ton-per-year CO_2 DAC pilot plant since 2010. Cofounder Eisenberger says he expects to achieve a cost of \$100 per ton at the company's first commercial facility, nearing completion in Huntsville, Alabama. The plant doesn't use waste heat; if it were available there, he says, CO_2 could be captured at \$75 per ton. The 3000-ton-per-year machine, housed in two shipping containers, is for a major beverage bottler.

Eisenberger expects his process to drop to \$50 a ton in a few years. The savings would result from incremental improvements as more devices are built and from further refinements to the contactors. The cost could be cut in half again as the price of solar electricity falls.

GT has adapted vehicle catalytic converters to serve as contactors. The converters' narrow channels entrain flow at 5 meters per second parallel to the contacting surface, minimizing turbulence, Eisenberger says. That's more than twice the flow rate of 2 meters per second that Jaffe used in his calculations, he notes, and at least double what's possible with CE's and Climeworks' contactors.

Eisenberger says other projects with end users in plastics, fertilizers, and fuel are at various stages of commercialization. GT's process also works for flue gas, and deals are in the works for flue-gas capture plants in the 100 000-ton-per-year range, he says.

Climeworks, based in Zurich, Switzerland, with 60 employees, is the sole company to date with a commercial plant in operation. Valentin Gutknecht, director of business development, says it was the first to produce fuels from DAC. It has sold several plants with capacities up to 50 tons of CO_2 per year to the automaker Audi for synthetic fuels R&D and demonstration. Climeworks is commissioning a commercial system for a carbonated beverage producer.

Unlike GT's versions, Climeworks' amine-based contactors aren't moved once they're loaded with CO_2. Instead, the fans are stopped after several hours and the amine solution is heated in place to 100 °C to release the captured gas.

Climeworks is supplying the CO_2 for a collaboration in Iceland known as Carbfix. The European Union–funded project injects concentrated CO_2 into a basaltic geologic formation. There it reacts with the rock to form a calcite mineral. Drawing on the country's plentiful geothermal heat, the project boasts carbon-negative status. The company is supplying some of the CO_2 needed for the Nordic Blue Crude air-to-fuels plant to be completed in 2020. Carbfix will tap Norway's abundant hydroelectric power to produce about 56 000 barrels of synthetic fuels a year.

The system from Climeworks is modular, and any number of its 50-ton-per-year, self-contained contactor units can be combined. From its current $600 per ton, cost will decline further with technology improvements and mass production, Gutknecht says. "We know this isn't a cost level that will have a significant effect on global climate. For that we are working on a rigorous roadmap to achieve a cost level of $100 per ton by 2030." He's confident that $200 per ton can be achieved within two to three years.

GLOBAL THERMOSTAT'S pilot plant captures 1000 tons of CO_2 per year using modified automotive catalytic converters.

Altruistic motives

Climeworks, GT, and CE are all finalists for the Virgin Earth Challenge, a $25 million prize offered by UK billionaire Richard Branson to the first company that can demonstrate for 10 years an economically viable method for DAC and permanent removal of CO_2.

Each company is pursuing parallel commercial and altruistic paths. "We absolutely think we can finance plants and make money," says Keith of his fuels venture. "I'm not saying it's easy; there's a lot of ways to fail. But I do think it's possible."

The market for CO_2 is easily $1 trillion, Eisenberger says. "This is doable at an economically viable cost," he says, particularly if solar electricity declines to $0.01/kWh, as he predicts. "We believe the path to address climate change is to make it economically profitable," he says. "Our model is to use the CO_2 from the air and make plastics, carbon fiber, concrete, and make money while we sequester it."

Gutknecht says Climeworks is a cost-competitive solution in some regions for bottling companies, greenhouses, and other markets. "But that won't have a significant effect on the climate and this is ultimately what we want to do and why we exist as a company," he says. "If we are to remove billions of tons, we need some form of carbon tax or carbon trading and pricing at a level at which we can really deploy our systems." The carbon price needed for profitable operation is $100 per ton, he says.

To date, nations that have imposed carbon taxes or emissions trading systems collectively represent about 15% of the world's CO_2 emissions. The price or price-equivalent in all but a handful of those countries is at or below $25 per ton, according to the World Bank. The US has no national tax or emissions trading system, although California and a few other states do.

The DAC pioneers say they're not discouraged by the immensity of the challenge. "We don't see any deployment limits," says Gutknecht. Removing 4 billion tons of CO_2 per year, about 1/10 of current emissions, could be done with 80 million of the company's contactors, each comparable to a car in size and material requirements.

Eisenberger agrees, noting that DAC is one of the few solutions to the climate problem that doesn't have significant negative side effects. The entire global output of CO_2 could be captured by 10 million of GT's 4000-ton-per-year, shipping-container-sized plants, he says. The total landmass requirement would be 5000 km^2. Reducing CO_2 emissions alone won't be enough to prevent the worst effects of climate change because the gas lasts so long in the atmosphere. "There's no drain in the bathtub," Eisenberger says.

Lingering questions

Climate scientist James Hansen cautioned, though, that DAC won't provide a get-out-of-jail-free card for the world. Commenting on Keith's *Joule* paper in a 12 June blog post, Hansen noted, "Unfortunately, the new news on carbon capture costs provides no support for the notion that we can solve the climate problem without fossil fuel phase-out. On the contrary, the Keith et al. study reinforces our concerns."

An issue is the disparity between the costs claimed by Keith and Eisenberger and the APS report's estimates. Robert Socolow, the Princeton University physicist who proposed and co-chaired the APS committee that wrote the report, says there are several design differences between the generic hydroxide-contactor DAC plant that the panel considered and CE's design. "I am happy that David [Keith] . . . placed the APS report side by side with his paper," he says. "Until now, the entire discussion about costs has been about total costs. And David's paper moves the discussion to the cost of specific components."

Critics of the APS report complain that costing was performed by chemical industry experts applying standard industrial methodology. "They didn't listen to why their fundamental way of thinking about it was wrong," says Eisenberger. The APS committee, he says, ignored the possibility of "innovation, invention, and change." But Socolow counters that an entire chapter of the report was devoted to innovations and changes required for competitive DAC.

Of the APS study, Keith says, "I think you can't just take a bunch of experts and hope to suddenly figure out the cost of a technology that hasn't been developed yet, just by doing scaling analysis. If we could do that, venture capital companies would make a lot more money because they'd know in advance whether it would work."

Keith says his technology has advanced incrementally, not by breakthroughs. He compares it to photovoltaics, where costs continue to decline.

"I've read a lot of stories in PHYSICS TODAY about new fancy solar techs, but it's not what happened. It's not the reason that you can now buy solar panels for 40 cents a watt. It's a bunch of pretty unremarkable stuff that doesn't get reported," he says.

Socolow cautions that a full cost accounting of DAC must include the ratio of CO_2 that's needed to capture CO_2. If the energy is supplied from coal-powered plants, the ratio may even approach 1. "You can emit a CO_2 molecule for each one you capture," he says. Keith's paper puts the ratio of CE's process at about 0.1, and he agrees it would make little sense to use carbon-intensive power to make fuels.

David Kramer PT