Fans draw ambient air into the Climeworks carbon-dioxide extraction facility near Hinwil, Switzerland.

EMISSIONS

We have the technology

Carbon capture and storage will be crucial for mitigating climate change and rebuilding the world's energy infrastructure.

BY KATHERINE BOURZAC

Above a waste-processing plant in the Swiss countryside towers a grid of 18 silver fans. This edifice, about the size of four shipping containers, is part of the first commercial system for capturing the greenhouse gas carbon dioxide (CO_2) from air. Built by Zürich-based firm Climeworks, the plant began operating in May.

Researchers who are studying climate-change mitigation think that carbon capture is crucial for meeting the goals of the 2015 Paris climate agreement. Its signatories have committed to preventing an average temperature rise worldwide of more than 2 °C above pre-industrial levels by the year 2100. But adopting renewable sources of energy and greater energy efficiency will not be enough. According to the 2014 Intergovernmental Panel on Climate Change report, mitigation will be more than twice as expensive — and, in more than half of models, impossible — without carbon capture and storage (CCS).

There are a few ways in which the planet-warming gas can be caught. Some, such as the system developed by Climeworks, remove CO_2 directly from the air; others trap such emissions at power plants before they ever reach the atmosphere. After it is captured, the carbon can be locked away for thousands of years in oil wells and other geological reservoirs, or put to use in fuel production.

A limited amount of CCS has been implemented so far: 17 large-scale projects that capture almost 40 million tonnes of CO_2 each year are in operation at present. Plants in the early and advanced stages of planning could increase the total amount by about another 30 million tonnes, but that's still several orders of magnitude away from what researchers understand to be necessary. Worldwide, 32 billion tonnes of CO_2 are emitted each year by the energy industry. To achieve climate-change mitigation at the lowest cost, and to meet the Paris limit on temperature rise, the world needs to do more. The International Energy Agency estimates that 4 billion tonnes of carbon must be sequestered a year by 2040, and by 2060, that amount must rise to 11.2 billion tonnes annually.

"We need hundreds of projects" to capture and sequester carbon, says Juerg Matter, a geoengineer at the University of Southampton, UK. But, he laments, "we have no coherent policy framework, no regulations, no economic incentives." CCS projects take years to build and they struggle to survive without supportive

CLIMEWORKS AG/JULIA DUNLOP

government policies. After all, says Howard Herzog, a CCS researcher at the Massachusetts Institute of Technology in Cambridge, without a price on carbon "it's always going to be less expensive to burn fossil fuels and emit CO_2."

Despite political and economic obstacles, the technology for capturing and sequestering carbon is improving. Energy companies worldwide are retrofitting power plants with CCS systems, and start-up companies are working on electricity generators that extract CO_2 as a standard part of their operation. Engineers are developing more-efficient ways to capture and purify the gas, and researchers are experimenting with the injection of CO_2 into geological formations to secure it long into the future.

GOING TO THE SOURCE

Energy companies and geologists have been storing CO_2 safely for decades, says Sally Benson, director of the Global Climate and Energy Project at Stanford University in California. Since the 1970s, oil companies have injected pressurized CO_2 into wells to free hard-to-extract deposits of oil. In fact, enhanced oil recovery is the main market for captured CO_2.

In January, the Petra Nova facility, the largest carbon-capture system to be added to an existing power plant, began operating near Houston, Texas. At the site in Thompsons, bulldozers shovel small mountains of coal, which will be burned to provide electricity to the surrounding area.

But the CO_2 produced in the process will not follow the usual path. Instead of billowing into the atmosphere, it will be captured, purified, pressurized and then delivered through a pipeline to an oil field. Each year, Petra Nova can capture 90% of the power plant's CO_2 emissions — as much as 1.6 million tonnes of the greenhouse gas.

US Secretary of Energy Rick Perry, a former governor of Texas, is a fan of the project. Speaking at an event on-site in April, Perry said: "I think that the solutions to many of the challenges that we have in the world today are displayed behind me." Unusually for a man who denies the role of anthropogenic CO_2 in climate change, Perry finds himself in agreement with many researchers who are obsessively concerned about climate change and the emissions that cause it. "We need several Petra Novas," says Niall Mac Dowell, who models low-carbon energy systems at Imperial College London. Building more such plants, he says, will help to bring their installation costs down, which will enable even more to be built.

Although enhanced oil recovery facilitates the continued burning of fossil fuels, it can achieve the net sequestration of CO_2 — the process typically locks more carbon atoms in the ground than are released when the recovered oil is burned. Mac Dowell estimates that enhanced oil recovery could, if properly regulated, tuck away 4–8% of the carbon needed to mitigate climate change.

It costs about US\$50 per tonne to nab the CO_2 from waste streams of power plants — a further expense that drives up the price of electricity. In a conventional carbon-capture set-up such as Petra Nova, power-plant emissions are run through large vats of chemicals called amines, which react with CO_2 to form a carbamate. When the solution becomes saturated, the vats are heated to release purified CO_2 — and that's where the extra cost comes in. Steam that would otherwise drive the generation of electricity must be diverted to heat the carbon-capture system, reducing the power plant's output by 20–30%. And around 10% of the CO_2 generated by the plants still escapes into the atmosphere — because of the cost, it's not practical to cycle the emissions through the solvent again to ensure that every molecule of CO_2 is captured.

Innovative technology, however, could make the purification of emissions less costly and more effective. NetPower, an energy start-up in Durham, North Carolina, is working on an unusual natural-gas-fired generator that is designed to remove CO_2 as part of its operation, and not as a costly add-on. In fact, the technology should produce no atmospheric emissions at all. For those reasons, NetPower is "the thrill of the year" in CCS circles, says Susan Hovorka, a geoscientist at the University of Texas at Austin. "They capture the CO_2 already at high pressure," she says — the state required for its injection into oil pipelines and for geological storage.

Conventional generators burn natural gas, heating water to produce steam that turns electricity-generating turbines. NetPower's design cuts out the steam, and instead heats and pressurizes CO_2 into a supercritical state (in which it exhibits properties of both a liquid and a gas) that can drive the turbines (see 'Clean fossil power'). The CO_2 that is produced when the natural gas is burned is then looped back into the system. As the CO_2 builds up, it is siphoned off, already purified and pressurized for injection into the ground for long-term storage. NetPower says that its early demonstration-scale generators are as efficient as the best existing natural-gas-powered generators, converting 59% of the fuel's energy into electricity. The company is building a fully operational 50-megawatt demonstration plant in La Porte, Texas, which will serve as a test bed for commercial-scale power plants.

"We have no coherent policy framework, no regulations, no economic incentives."

Further investment in fossil-fuel-powered technology may not seem a positive way forward for climate-change mitigation, but it is unlikely that decades of investment in fossil fuels would be abandoned immediately. And if natural gas could be burned cleanly, it would be a good adjunct to renewable power. Its use can be quickly ramped up or down, making it a reliable back-up for intermittent solar- and wind-based power generation.

NET NEGATIVE

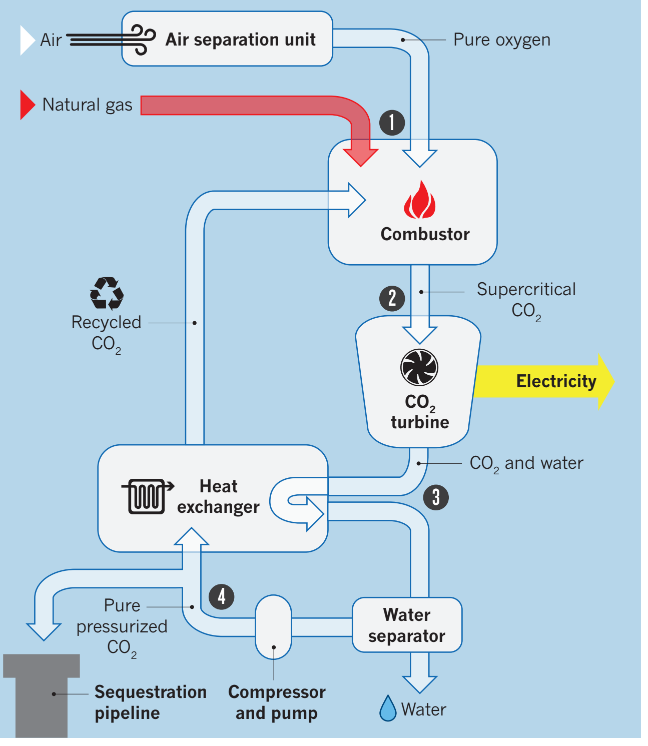
As well as capturing CO_2 at point sources, many researchers think that combatting climate change will require the removal of some of the CO_2 that is already in the atmosphere.

Extracting CO_2 from thin air is difficult. Coal flue gas is composed of 12% CO_2, and the exhaust gases from natural gas contain around

CLEAN FOSSIL POWER

Electricity can be generated from fossil fuels without producing any atmospheric emissions.

1 NetPower's system burns natural gas in pure oxygen in the presence of carbon dioxide. The CO_2, which is 95% of the gas mix, is heated and pressurized to a supercritical state.
2 In this state it can drive a fluid turbine to generate electricity.
3 Water present in the turbine's exhaust begins to condense in a heat exchanger before being fully separated out and removed from the system.
4 The remaining stream of more than 90% CO_2 is repressurized, reheated via the heat exchanger and returned to the combustor. Excess CO_2 generated by the system is directed to a pipeline after repressurization, ready for sequestration.



Basalt cores from the CarbFix–SulFix site in Iceland.

Carbon dioxide injection wells at Hellisheiði geothermal power plant in Iceland.

SIGURDUR GISLASON/CARBFIX

5%. Yet, the atmosphere contains only 400 parts per million of CO_2, on average — although alarming from the point of view of a climate scientist, it presents a tremendous challenge for those who want to capture it.

Climeworks' direct air carbon-capture system, in the town of Hinwil near Zürich, uses its array of fans to draw ambient air over paper filters decorated with the same amines that are found in liquid-based systems such as Petra Nova's. The filters capture CO_2 in much the same way as the liquid system and, similarly, must be heated to release the gas. That heat is provided by the waste-incineration facility above which the Climeworks facility sits.

The customer for this first system is Swiss vegetable producer Gebrüder Meier, which has an almost 40,000-square-metre greenhouse in a field next to the Climeworks site. A pipeline carries the CO_2 across the short distance from plant to greenhouse, where the gas helps the plants to grow faster.

The cost of capturing carbon using the Climeworks system is high: around US$500–600 per tonne. And the system operates on a small scale, netting only about 900 tonnes of CO_2 per year. It also doesn't do much to avert climate change, because the CO_2 produced ends up being re-emitted. But having customers will help the company to bring down the cost of the system and to establish its business. Jan Wurzbacher, co-founder and a director of Climeworks, says that by the end of 2018, it will have seven plants in operation. The company will sell its CO_2 to others that use the gas to make synthetic gas, liquid fuels and other chemicals. After production is scaled up, Wurzbacher expects the costs to fall to $200 per tonne of CO_2, a price that he thinks can be halved in the medium term. Jennifer Wilcox, a chemical engineer at the Colorado School of Mines in Golden, and who is not affiliated with Climeworks, says that a cost of $100 per tonne is reasonable, although capturing carbon at a concentrated source, as happens at Petra Nova, will always be less expensive than filtering it from ambient air. "It's cheaper and easier to avoid emission of this CO_2 in the first place," she says.

Climeworks is one of only a handful of companies worldwide that are working on direct air carbon capture. In the Canadian province of British Columbia, Carbon Engineering operates a demonstration plant that catches 1 tonne of CO_2 a day. At the plant, a strong alkaline solution of potassium hydroxide reacts with the CO_2 in ambient air. The resulting carbonate salts are reacted with lime and precipitate out of solution as pellets of calcium carbonate that resemble chalky couscous. The pellets are then heated to 900 °C, which releases pure CO_2 for storage.

Carbon Engineering plans to use its technology to produce carbon-neutral fuels for heavy transportation and aviation. Passenger vehicles can be electrified, or can run on fuel cells that use renewably sourced hydrogen. But the size of the batteries or fuel cells that would be required to carry a passenger aircraft over long distances make their use in aviation impractical. "There is no practical way in the near or deep future for planes to be powered by hydrogen or batteries," says Adrian Corless, chief executive officer of Carbon Engineering.

The company is working on a process for producing hydrocarbon fuels by combining captured CO_2 with hydrogen produced using renewable energy. Numerous energy inputs are required to produce these starting materials, and then to combine them. Corless says that 50–60% of the energy invested is stored in the chemical bonds of the resulting fuels. Carbon Engineering intends to demonstrate the production of petrol and diesel at commercially relevant scales next year.

The commercialization of carbon capture is a welcome development. But Wilcox and other climate-mitigation scientists have their eyes on the main prize: permanently removing CO_2 from circulation. Carbon used to make fuel will be re-emitted rapidly; at best, says Wilcox, such fuels are carbon neutral.

Wilcox's research suggests that direct air carbon capture can collect 10 billion tonnes of CO_2 a year — and that estimate is conservative. But she hopes that the gas will be sequestered, not used. For climate-change mitigation, she says, "utilization is overrated." If all of the carbon used by the chemical industry were sourced from CO_2, it would only take up 1% of CO_2 emissions worldwide — and the carbon would not be permanently locked up, says Wilcox.

Mac Dowell warns that policy makers should not expect the demand for carbon to pull down the price of its capture and sequestration. He worries there is a misconception that CCS might

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become inexpensive enough to be done without a carbon tax or other form of policy support. “States and governments are waiting for a technology unicorn to help us make money,” he says. “We made money producing carbon, and now we’re going to make money capturing it? I think it’s intellectually disingenuous.”

SOLID AS A ROCK

Whether CO_2 is gathered from ambient air or at a power plant, the best way to mitigate it is to sequester it deep underground, says Herzog. Geologists have been doing so for decades. The first project dedicated to geological carbon storage, the Sleipner CO_2 storage facility, has injected almost 1 million tonnes of CO_2 a year into a formation of the sedimentary rock sandstone under the North Sea since its launch in 1996.

With years of data in hand, says Benson, geologists are confident in the safety of CO_2 sequestration. The basic physics and chemistry are well known, she notes, and sites are selected with great care. Anywhere that is seismically active or close to groundwater deposits is ruled out. Typically, geologists choose deep saline aquifers that are made of sedimentary rock, found kilometres below Earth’s surface. A good site will accommodate the addition of millions of tonnes of CO_2 each year.

After a site has been chosen, a deep well is dug and the CO_2 is injected in under high pressure, pushing it into a supercritical state. Just as water soaks into sand by filling the spaces between grains, supercritical CO_2 moves readily into the pores of sandstone, where it becomes trapped. Surface tension, the immiscibility of supercritical CO_2 with brine and layer on layer of sedimentary rock keep the CO_2 from escaping to the surface.

“All these interactions, between CO_2, water and rock are very well established,” says Benson. Her laboratory is trying to expand that understanding to longer periods of time and larger areas, to help researchers model and plan long-term reservoirs for CO_2. Using computed tomography scanning and samples of rock from deep underground, Benson is studying the geophysical minutiae of how sandstone, brine and CO_2 interact at the high temperatures and pressures found kilometres below Earth’s surface

Known sandstone reservoirs and spent oil and gas wells could sequester up to 11,000 billion tonnes of CO_2, but the gas moves through different rock layers at different rates. Benson wants to model these dynamics across hundreds of square kilometres and thousands of years. She and other researchers are also trying to determine whether CO_2 will, over the millennia, react chemically with the rocks and mineralize, forming a solid that prevents it from escaping.

The answer is a resounding yes when CO_2 is injected into the igneous rock basalt, says Matter.

The main reason that CO_2 is injected into sandstone, he says, is simply that most oil and gas reservoirs comprise sandstone. But the CO_2 that is injected into such reservoirs must be monitored in the long term, requiring several deep wells for monitoring equipment to be drilled in addition to the main one. “That’s why we started to think about unconventional reservoirs,” he says.

In 2012, Matter and colleagues from institutions including Columbia University in New York and the company Reykjavik Energy embarked on a project to inject gases into a basalt reservoir near the Hellisheiði geothermal power plant in Iceland. The plant emits both CO_2 and hydrogen sulfide, the rotten-egg smell of which was an important impetus for the project, called CarbFix–SulFix. CO_2 and hydrogen sulfide were mixed at a ratio of 70:30, and then dissolved in water and injected into the basalt. Although the wells used were much shallower than conventional wells for geological carbon sequestration, both compounds went in without incident. When the researchers took samples from the site less than two years later, 95% of the carbon had been stabilized in carbonate minerals. Following those positive results, and with funding from the European Union, the researchers began to work on CarbFix2 in August. The project aims to scale the original technology, making it practical for use worldwide.

> ***“States and governments are waiting for a technology unicorn to help us make money.”***

If the approach works well at other sites, Matter says, it will not be necessary to perform long-term monitoring of CO_2 in basalt. A choice between basalt and sandstone would also make it easier to find appropriate sequestration sites — both are common, but neither is distributed evenly worldwide. Much of India, for example, lacks the sandstone aquifers used for conventional sequestration but has promising basalt deposits. “This expands the number of places where you can do sequestration,” says Matter. The Pacific Northwest National Laboratory in Richland, Washington, is exploring the potential of a test injection into basalt off the coast of Vancouver, Canada, and Matter says researchers in other countries have contacted him about setting up sites.

Despite the urgent need to slow the build-up of atmospheric carbon, only a few more sequestration projects are at the planning stage. “The pipeline is almost dry,” Herzog says. The lack of opportunities to test CCS systems on a large scale is problematic. “To advance, we need a larger database of real-world injections than we have today,” says Benson.

Such projects are big investments. But instead of receiving political support, industry is getting mixed signals. “The Right underestimates the magnitude of the problem; the Left underestimates the magnitude of the solution,” says Herzog. In the United Kingdom, the Conservative government in 2015 cancelled a £1 billion ($1.5 billion) competition for CCS solutions six months before it was to be awarded. And in the United States, President Donald Trump has withdrawn the Clean Power Plan, an Obama-era policy that would have restricted CO_2 emissions from power plants.

Even if researchers are not optimistic about the national and international politics of climate mitigation, they are excited about progress being made at CCS plants and laboratories — and even in the atmosphere. CO_2 emissions worldwide have been stable over the past few years. Although not enough, it’s something to build on, says Sabine Fuss, who develops models of climate change and natural resources at the Mercator Research Institute on Global Commons and Climate Change in Berlin. Meanwhile, cities such as Pittsburgh and states such as California are adopting local solutions. Strategies to mitigate carbon emissions must be regionally tailored in any case, says Fuss. She’s working on the next Intergovernmental Panel on Climate Change report and says that there’s been an explosion in the literature about the contributions of various CCS technologies to climate-change mitigation. But the task at hand is urgent. “We need to start right now,” says Fuss. “It’s a huge infrastructure to build.”

“It’s not renewable energy or carbon capture — it’s a combination of both,” says Mac Dowell. “It’s everything, all at once, now.” ■

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