JANUARY 2018

Sustainability & Resource Productivity

Why commercial use could be the future of carbon capture

Emerging technologies point toward a variety of practical—and profitable—industrial applications for carbon dioxide. That could also be good for the planet.

Krysta Biniek, Ryan Davies, and Kimberly Henderson

Nearly two years after the signing of the Paris Agreement to prevent average global temperatures from rising by more than two degrees Celsius, the world continues its urgent search for cost-effective methods of reducing greenhouse-gas (GHG) emissions. Even the surprising growth of renewable energy probably won't make up for the expected increases in emissions from other sources. In all likelihood, staying under the two-degree limit will require the development and rapid adoption of advanced technologies.

Carbon capture and storage (CCS) has long been seen as one technology with the potential to reduce GHG emissions significantly. The basic idea is to collect carbon dioxide gas and confine it underground. CCS hasn't caught on, however, because it is expensive. But a new twist on the concept might change its cost profile. If carbon dioxide could be put to industrial use, the resulting revenues could make carbon capture financially viable.

A few industrial applications for captured carbon dioxide are already in play. One involves using the gas to make chemicals and plastics, such as polyurethane foams for seat cushions. Covestro, formerly Bayer MaterialScience, recently opened a plant that makes these foams from carbon dioxide. Research also suggests that making carbon fiber out of carbon dioxide gas would cost less than the typical production process, which uses polymers. However, the quantity of carbon dioxide that might eventually go into chemicals, plastics, and carbon fiber would be too small—between 40 million and 90 million metric tons per year—to make an appreciable dent in global GHG emissions. Methods of carbon capture and use (CCU) that take up much larger amounts of carbon dioxide gas will therefore be needed to help reduce overall GHG emissions.

A look at new uses for captured carbon

Creating large-scale CCU technologies won't be easy. One big challenge is that carbon dioxide is a highly inert molecule. Because of this, transforming the captured gas into industrial products typically requires a lot of energy. Another challenge is that oil remains a highly cost-effective industrial feedstock, both as a fuel and as a precursor in the synthesis of other substances, such as plastics.

These factors mean that clever solutions to the energy-balance challenge are required, and it could be years before CCU is a big business with major environmental benefits. Nonetheless, CCU should have a future in an emissions-constrained world. That creates intriguing medium-term prospects for investors, companies, and governments.

Some new applications for captured carbon dioxide are being piloted; others are in the developmental stage. Three of these applications stand out for their potential to reduce emissions and generate revenue: fuel production, concrete enrichment, and power generation. We estimate that carbon usage, driven largely by this trio of applications, could reduce annual GHG emissions by as much as one billion metric tons in 2030, compared with a scenario in which these applications do not develop quickly.

Fuel made from captured carbon

Captured carbon dioxide can technically be converted into virtually any type of fuel or chemical that is otherwise derived from petroleum. The question is how to do this economically enough so that the resulting fuels and chemicals are cost-competitive with those derived from oil.

One method involves causing a chemical reaction between hydrogen and carbon monoxide molecules to create the hydrocarbon chains that make up liquid fuels. Getting the chemistry right is difficult. Producing the chemical reaction is energy-intensive, roughly equivalent to combustion in reverse. And if hydrogen fuel cells are ever adopted more widely, demand for hydrogen could reach the point where it is more economical to use as an energy source than to make liquid fuel. Recently, however, several cheaper, more efficient catalysts to break down carbon dioxide into carbon monoxide have been discovered, a critical first step.

If a goal of synthesizing fuels from carbon dioxide is to reduce GHG emissions, then using energy to power the synthesis makes sense only if the energy is both cheap and low or zero carbon. A way to make this work would be to produce fuel from captured carbon dioxide only when renewable power plants, such as solar or wind farms, are generating excess electricity. This would also provide a means of storing energy from renewable sources in a form that is portable and easy to use in existing industrial equipment.

Another method of turning captured carbon dioxide into fuel depends on using microorganisms to power the necessary chemical reactions. Microorganisms naturally consume carbon dioxide during photosynthesis, which produces simple sugars such as glucose. Some of the microorganisms can then ferment the resulting sugars into ethanol. Other microorganisms produce lipids (along with proteins and starches), which contain hydrocarbon components that can be refined into liquid fuel. Since microorganisms are inefficient at converting solar energy into chemical energy, the trick is to genetically modify them to make ethanol or lipids more efficiently and quickly, or even to excrete liquid fuels directly. Once that is done, one more issue remains: providing the microorganisms with enough space and the right conditions to live. We estimate that microorganisms producing enough liquid fuel to meet the annual needs of the United States would require a lake one-third the size of California.

More research and investment will be needed to scale these biological methods of making fuel from carbon dioxide up to commercial size. Even so, the long-term potential of these techniques to turn waste gases into valuable products has attracted interest from large industrial firms.

Concrete enriched with captured carbon

The manufacture of cement, which serves as the binding agent in concrete, accounts for roughly 8 percent of global carbon dioxide emissions, a significant share of the total. This is because making cement involves using immense amounts of mechanical and heat energy to quarry rock for limestone and extract the lime by way of a high-temperature treatment process. Cement is then combined with aggregates and water to make concrete.

Captured carbon dioxide can't readily lessen the amount of energy that goes into this process. But using captured carbon dioxide during the making of concrete would sequester the gas in buildings, walls, bridges, sidewalks, and other concrete structures, allowing the material to serve as a major carbon sink.

Carbon dioxide can be added to concrete in two ways. The first is to make the gas into a carbonate mineral aggregate that goes into concrete and construction fill. This is not practical now, because natural aggregate is inexpensive. A more promising approach is to infuse wet concrete with carbon dioxide. This technique, known as "carbon curing," involves curing concrete in a carbon dioxide–rich environment, causing the carbon dioxide to react with water to form carbonate ions, which then react with calcium ions in the concrete to form solid calcium carbonates. This is an exothermic and spontaneous chemical reaction that releases rather than consumes energy.

Carbon curing can produce concrete that is 4 percent carbon dioxide, by mass. Carbon curing can also shorten curing times, increase concrete's water resistance, and strengthen it—improvements that should make it more appealing to concrete makers and construction companies, regardless of the environmental benefits.

Power generation using supercritical carbon dioxide

Repurposing captured carbon dioxide as an ingredient in products such as fuel and concrete represents one means of lowering emissions of the gas. A different approach is cutting GHG emissions from power generation by using carbon dioxide to make turbines run more efficiently. Although this would not repurpose carbon dioxide as a product, it could prevent a significant amount of emissions.

Steam cycles powered by fossil fuels have been used to generate electricity for more than a century. But carbon dioxide–based cycles, in which carbon dioxide is heated and pressurized into a supercritical fluid, transfer heat more readily and take less energy to compress than steam, which can make power generation more efficient. A conventional cycle using steam converts roughly 33 percent of the energy in fuel to electricity. Using supercritical carbon dioxide instead can boost the energy-conversion rate to 49 percent.

Increasing the efficiency of power-generation cycles is important because fossil fuels are expected to be important sources of power for decades to come. In principle, supercritical carbon dioxide can replace steam in any power-generation process that relies on turbines. Whether it will be economical to do so on a large scale is another matter. One question is how much it will cost to retrofit or replace equipment in steam-based power plants. Another is whether utilities will see large enough benefits from switching to power generation that is more energy efficient and less emissions intensive.

These uncertainties make it difficult to predict how supercritical carbon dioxide technology for turbines might affect the power sector or overall GHG emissions trends. But the potential of the technology, reinforced by research investments by industrial heavyweights, means it is worth watching. Early indications of its viability should emerge after Sandia National Laboratories launches its demonstration plant, which is scheduled for 2019.

Scaling up the use of captured carbon

Most efforts to commercialize these three uses for captured carbon dioxide are still in their early stages. All three have the potential to become profitable in the medium to long term as the technologies advance and countries pursue their plans to reduce GHG emissions.

Two major sets of costs need to be addressed. First, the technology used to collect carbon dioxide from the flue gases of power plants and industrial facilities would have to become more cost-effective. Capturing and transporting the gas can cost as much as $80 per metric ton. Firms working in this area expect to halve that cost in the coming years. Second, as noted earlier, the technologies for using captured carbon dioxide need to become more efficient and cost-effective.

CCU technologies also have to win support in industry, which has proven alternatives to fall back on: fossil fuels instead of synthetic ones; ordinary concrete instead of carbon-cured concrete; steam turbines instead of carbon dioxide turbines. Conventional practices can be difficult to overcome, even when better ones come along. Policy makers can play a role in accelerating the development and adoption of CCU technologies. Just as regulatory support helped ensure steady demand for renewable energy in some countries, the right policy environment will encourage companies and investors to get behind CCU.

■ ■ ■

Reducing and eventually stopping increases in the atmosphere's GHG concentration will require multiple methods of cutting emissions to be used widely. Since existing methods are being adopted slowly, relative to the GHG challenge, new methods may be needed. This is one reason why carbon capture features prominently in some emissions-reduction scenarios: the International Energy Agency, for example, expects carbon storage to account for 14 percent of GHG-emissions reductions from 2015 to 2050. While carbon capture and storage has been slow to catch on, CCU seems to have more promise, partly because of its revenue-generating potential. Making CCU work at scale in the long term will depend on technology investment decisions made today. Companies and governments that provide the right support now may position themselves to reap the benefits from CCU in the years to come. ■

Krysta Biniek is a consultant in McKinsey's London office, **Ryan Davies** is a partner in the Washington, DC, office, and **Kimberly Henderson** is an associate partner in the Chicago office.