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Driving CO_2 emissions to zero (and beyond) with carbon capture, use, and storage

Any pathway to mitigate climate change requires the rapid reduction of CO_2 emissions and negative-emissions technologies to cut atmospheric concentrations. Technology and regulation will be the key.

by Krysta Biniek, Kimberly Henderson, Matt Rogers, and Gregory Santoni

Growing concerns about climate change are intensifying interest in advanced technologies to reduce emissions in hard-to-abate sectors, such as cement, and also to draw down CO_2 levels in the atmosphere. High on the list is carbon capture, use, and storage (CCUS), the term for a family of technologies and techniques that do exactly what they say: they capture CO_2 and use or store it to prevent its release into the atmosphere. Through direct air capture (DAC) or bioenergy with carbon capture and storage (BECCS), CCUS can actually draw down CO_2 concentrations in the atmosphere—"negative emissions," as this is called. In some cases, that CO_2 can be used to create products ranging from cement to synthetic fuels.

To better understand the possible role of CCUS, we looked at current technologies, reviewed current developments that could accelerate CCUS adoption, and assessed the economics of a range of use and storage scenarios. The short- to medium-term technical potential for CCUS is significant (Exhibit 1). CCUS doesn't diminish the need to continue reducing CO_2 emissions in other ways—for instance, by using more renewable energy, such as wind and solar power. But it offers considerable potential for reducing emissions in particularly hard-to-abate sectors, such as cement and steel production. What's more, CCUS, along with natural carbon capture achieved through reforestation, would be a necessary step on the pathway to limiting warming to 1.5 degrees Celsius above preindustrial levels.[1]

However, to reach CCUS's potential, commercial-scale[2] projects must become economically viable. In the short to medium term, CCUS could continue to struggle unless three important conditions are met: (1) capture costs fall, (2) regulatory frameworks provide incentives to account for CCUS costs, and (3) technology and

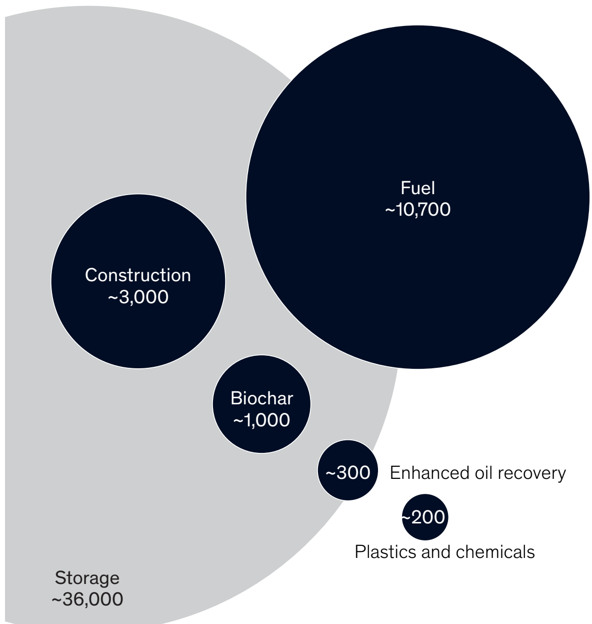
[1] See "Climate math: What a 1.5-degree pathway would take," *McKinsey Quarterly*, April 2020, McKinsey.com.
[2] Commercial scale projects are those with at least 0.5 Mtpa of capacity.

Exhibit 1

Applications for captured CO_2 cover a wide range of materials.

Technical potential of CCUS in 2030, metric megatons of CO_2 per year[1]

■ Carbon capture and use ■ Carbon capture and storage



Selected examples

Fuel

Synfuel and macro- or microalgae fuel

Enhanced oil recovery (EOR)

Conventional or unconventional CO_2 EOR and CO_2 EOR in residual oil zones

Construction materials

Cement and aggregates

Plastics and chemicals

Polyethylene, polypropylene, carbon fiber, and methanol

Biochar

A charcoal derived from burning organic agriculture- and forestry -waste products

Storage

Saline aquifers and depleted oil and gas reservoirs

[1] CCUS = carbon capture, use, and storage. Excludes small amounts of CO_2 used for other applications, such as decaffeination, dry ice, food and beverages, fire extinguishers, and greenhouses.

innovation make CO_2 a valuable feedstock for existing or new products. This article surveys the state of a portfolio of CCUS technologies, the underlying economics, and the changes needed to accelerate progress.

The value chain of carbon capture, use, and storage

The potential of CCUS can be tracked along an intuitive value chain. Many industrial processes generate CO_2, most prominently when hydrocarbons are burned to generate power, but also less obviously—for example, when limestone is heated to produce cement. Driving your car or heating your home also releases CO_2. Carbon dioxide can be captured at the source of the emissions, such as power plants or refineries, or even from the air itself.

A range of technologies—some using membranes, others using solvents—can perform the capture step of the process. Once captured, concentrated CO_2 can be transported (most economically by pipeline) to places where it can be used as an input—for example, cured in concrete or as a feedstock to make synthetic jet fuel—or simply stored underground.

While these options all help stabilize levels of CO_2 in the atmosphere, the challenge is economics. Storage would seem the obvious choice, as the geologic-storage-reservoir potential is vast, and the technology involved is mature. But storing CO_2 at scale is a pure cost, and related investments have (understandably) been limited, given the absence of regulatory incentives to defray the installation of capture technology and a storage infrastructure. There are also tricky legal issues, such as liability for potential leaks and the jurisdictional complexities associated with underground property use.

The economics of CCUS

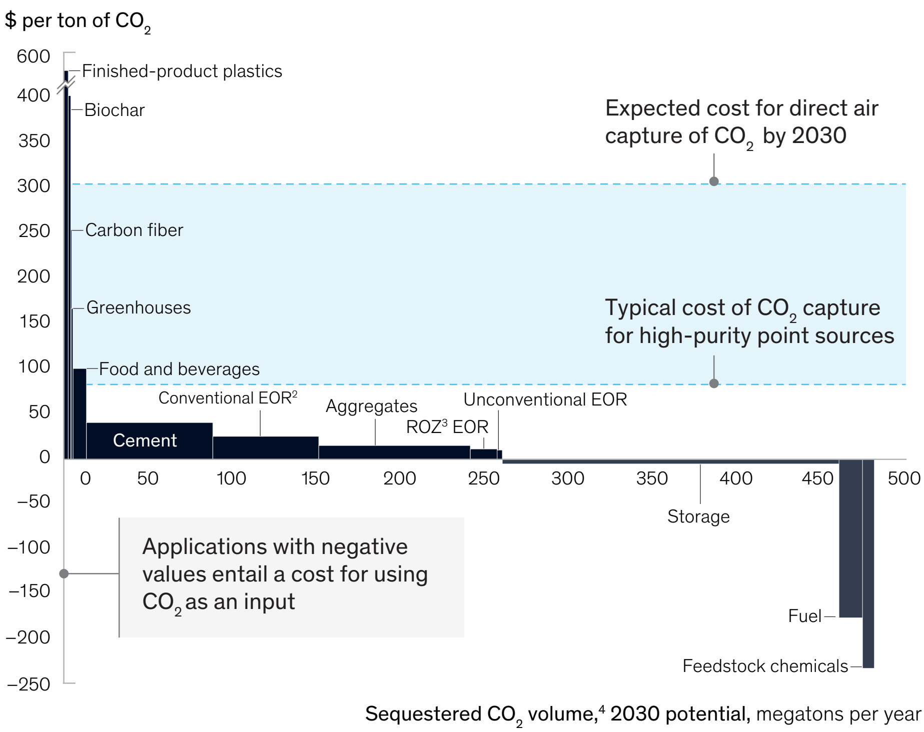
To clarify these dynamics, we modeled the expected alternative CO_2 uses in 2030—from the already proven technologies, such as enhanced oil recovery (EOR), to more speculative ones, such as CO_2-derived substitutes for carbon fiber. We also included an estimate for CO_2 storage.

From now to 2030, our research and modeling suggest, CCUS *could* expand from 50 million tons of CO_2 abatement per year (Mtpa) today, mostly for enhanced oil

Exhibit 2

The demand for CO_2 varies across applications, depending on cost and value.

Manufacturers' maximum willingness to pay for CO_2 as an input in 2030[1]



[1]While keeping their CO_2-based products cost competitive with traditional products.
[2]EOR = enhanced oil recovery.
[3]ROZ = residual oil zone.
[4]Amount stored in product through manufacture; excludes avoided emissions or those created through use of product.

For further reading

There is ongoing discussion about the level of abatement through carbon capture, use, and storage (CCUS) needed to avoid catastrophic climate change. Some key sources for insights and estimates include the following:

- *Meeting the dual challenge: A roadmap to at-scale deployment of carbon capture, use, and storage*, National Petroleum Council, 2019, dualchallenge.npc.org

- *Global status of CCS 2019: Targeting climate change*, Global CCS Institute, globalccsinstitute.com

- "Climate math: What a 1.5-degree pathway would take," *McKinsey Quarterly*, April 2020, McKinsey.com

recovery and beverage carbonation,[3] to at least 500 Mtpa (0.5 gigatons a year, or Gtpa)—just over 1 percent of today's annual emissions (41 Gtpa). Such an expansion would be possible only with a supportive regulatory environment. Exhibit 2 offers a view of where the economic payoff is close and where more incentives would be needed to enable CCUS technologies to scale and reach their full potential. (For additional background on the relationship between CCUS and climate-abatement potential, see sidebar, "For further reading.")

High potential

Despite the challenging economics, there is a wave of creative energy gathering around a number of CCUS bets.

Today's leader: Enhanced oil recovery

Among CO_2 uses by industry, enhanced oil recovery leads the field. It accounts for around 90 percent of all CO_2 usage today (mostly in the United States)[4] and benefits from a clear business case with associated revenues. Typical recovery processes leave anywhere from 40 to more than 80 percent of oil unrecovered, depending on factors such as reservoir depth, porosity, and type of oil. In some cases, the additional oil recovered is substantial (5 to more than 15 percent), and, if a nearby industrial source of CO_2 can be found (say, a power plant or refinery), the use of emitted CO_2 could be economically attractive. Our model estimates that by 2030, CO_2 usage for EOR could account for more than 80 Mtp[5] of CO_2 annually across conventional reservoirs, residual oil zones (ROZ), and unconventional oil fields[6]—an enabling step along the journey to reduced emissions through CCUS.

Cementing in CO_2 for the ages

New processes could lock up CO_2 permanently in concrete, "storing" CO_2 in buildings, sidewalks, or anywhere else concrete is used. This could represent a significant decarbonization opportunity (see "Laying the foundation for zero-carbon cement,"

[3] National Energy Technology Laboratory, US Department of Energy, netl.doe.gov.

[4] Ibid.

[5] CO_2-abatement estimates for CO_2 uses in this section are based on McKinsey demand-curve modeling.

[6] Around three million barrels of daily oil production use enhanced-oil-recovery techniques with approximately 30 percent of that oil produced using injected CO_2.

on McKinsey.com). For example, consider precast structural concrete slabs and blocks. They could potentially be made with new types of cement that, when cured in a CO_2-rich environment, produce concrete that is around 25 percent CO_2 by weight. There's a CO_2 bonus available here as well: cement used in this curing process has a lower limestone content. That's significant, since baking limestone (calcination) to make conventional Portland cement releases around 7 percent of all industrial CO_2 emissions globally. A second concrete process involves combining the aggregates with cement to make concrete (think cement mixers). Synthetic CO_2-absorbing aggregates (combining industrial waste and carbon curing) can be formed to produce this type of concrete, which is 44 percent CO_2 by weight. We estimate that by 2030, new concrete formulations could use at least 150 Mtpa of CO_2.

Carbon-neutral fuels for jets and more

Technically, CO_2 could be used to create virtually any type of fuel. Through a chemical reaction, CO_2 captured from industry can be combined with hydrogen to create synthetic gasoline, jet fuel, and diesel. The key would be to produce ample amounts of hydrogen sustainably. One segment keen on seeing synthetics take off is the aviation industry, which consumes a lot of fuel and whose airborne emissions are otherwise hard to abate. By 2030, we estimate, this technology could abate roughly 15 Mtpa of CO_2.

Turning the dial negative?

Other interesting applications seem further out. While several are novel enough to be worth keeping an eye on, their abatement potential is often uncertain. Estimating their cost and scalability is also difficult.

Capturing CO_2 from ambient air—anywhere

Direct air capture (DAC) could push CO_2 emissions into negative territory in a big way. DAC does exactly what it suggests—capture CO_2 directly from the atmosphere, where it exists in very small ambient concentrations (400 parts per million, or 0.04 percent by volume). It has been put there in a variety of ways, including both industrial point sources and more diffuse emissions, such as those from vehicles, airplanes, ships, buildings, and agriculture. DAC facilities could be located at storage or industrial-use locations, bypassing the need for an expensive CO_2-pipeline infrastructure. The challenge is that it takes a lot of energy—and money—to capture CO_2 at very low atmospheric concentrations. Costs are high, running more than $500 per ton of CO_2 captured—five to ten times the cost of capturing CO_2 from industrial or power-plant sources. There are plans to scale this technology and reduce unit costs substantially, but the pathway to competitive economics remains unclear.

The biomass-energy cycle: CO_2 neutral or even negative

Bioenergy with carbon capture and storage relies on nature to remove CO_2 from the atmosphere for use elsewhere. Using sustainably harvested wood as a fuel renders the combustion process carbon *neutral.* (Other CO_2-rich biomass sources, such as algae, could be harvested, as well.) Biomass fuel combustion could become carbon negative if the resulting CO_2 emissions were then stored underground or used as inputs for industrial products, such as concrete and synthetic fuel. The degree to which BECCS can yield negative emissions, however, depends on a number of intermediate factors across the life cycle. These factors include how the biomass is grown, transported, and processed—all of which may “leak” CO_2. (For more on the role of forests in sequestering CO_2, see “Climate math: What a 1.5-degree pathway would take,” on McKinsey.com.)

Next horizons

Three other opportunities to capture and use carbon—in carbon fiber, plastics, and agricultural “biochar”—are also worth watching.

Carbon fiber

Superstrong, superlight carbon fiber is used to make products from airplane wings to wind-turbine blades, and its market is booming. The price of the component carbon is high ($20,000 a ton), so manufacturers would love to have a cheaper, CO_2-derived substitute. Moreover, the volume of CO_2 used could become significant if cost-effective carbon fiber could be used widely to reinforce building materials. A number of pilot projects in the works focus on cracking the tough chemistry involved, but a commercially viable process appears to be perhaps a decade or more away. By 2030, we believe, the contribution to CO_2 abatement would be 0.1 Mtpa of CO_2.

Storing carbon in your mattress?

CO_2 could substitute for fossil fuel–based inputs in plastics production. The combination of technical feasibility and high interest from environmentally aware consumers has attracted the attention of major chemical companies, which are testing a range of CO_2-based plastics for widespread use. Green polyurethane—used in products such as textiles, flooring for sports centers, and, yes, mattresses—is in the early stages of commercial rollout. Storing carbon in green plastics would sequester it indefinitely. By 2030, we estimate, plastics could abate a modest but growing 10 Mtpa of CO_2.

Biochar, anyone?

Farms produce enormous amounts of biomass waste. When this is heated in an oxygen-poor environment, it creates what’s called “biochar”—a charcoal-like soil amendment that today is used by a modest number of small farmers and gardeners, mostly in the United States. Producing biochar captures 50 percent of the CO_2 that would otherwise escape during waste decomposition—and retains most of it for up to 100 years. We estimate that biochar technology is more than a decade away from the point when it could start having a real impact: by 2030, it could sequester roughly 2 Mtpa of CO_2.

The road ahead: Obstacles and enablers

Moving toward an economy where CCUS plays a meaningful role would require overcoming challenges across three areas of the value chain, as well as changes in the regulatory environment to expand incentives.

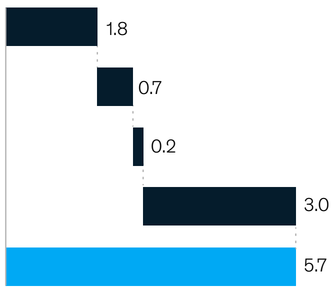
Capture

About half of CO_2 emissions are generated by factories, refineries, power plants, and the like. Some emissions, such as those from ethanol plants, are purer than others and can be captured relatively cheaply, for around $25 to $30 a ton. For less pure sources

Exhibit 3

In the United States alone, potential industrial sources for carbon capture, use, and storage are plentiful, though they vary in terms of CO_2 concentration.

Total CO_2 emissions in United States, 2018, metric gigatons of CO_2



	Total CO_2 emissions, metric gigatons of CO_2	Number of sites	Average emissions per site, megatons of CO_2
Power[1]	1.8	~1,400	1.3
Heavy industries[2]	0.7	~5,300	0.1
High-purity industrial point sources[3]	0.2	~1,000	0.2
Diffuse/mobile[4] emissions	3.0		
Total	5.7		

[1]Includes gas and coal.
[2]Includes oil and gas production, storage and distribution, refining, cement, iron/steel, and chemical production (except as noted in high-purity sources).
[3]Includes natural-gas processing, ethanol, ammonia, hydrogen, and pulp and paper production.
[4]Diffuse/mobile sites number in the millions, with average emissions per site of ~0.001 megatons of CO_2; includes transportation (eg, cars, trucks, aircraft, ships), residential/commercial use, and agriculture.

Source: "Greenhouse Gas Reporting Program (GHGRP)," US Environmental Protection Agency, epa.gov

(such as emissions from cement and steel-making facilities or coal and natural-gas power plants), the costs get steeper, ranging from $60 to more than $150 a ton.[7] What remains, of course, is the other half of CO_2 emissions—widely dispersed or mobile. A look at four tiers of CO_2 sources in the United States offers a perspective on the challenges of scaling CO_2 capture (Exhibit 3).

CO_2 transportation

Today, CO_2 transportation—a necessity for CCUS to scale—is a weak link in the value chain. In the United States, some 5,000 miles of pipeline transport CO_2, compared with 300,000 miles of natural-gas pipelines. Outside the United States, pipelines for moving CO_2 are rare.

Storage

The challenges for CO_2 storage are primarily nontechnical—a function of economic, legal, and regulatory challenges. By some estimates, the United States could geologically store 500 years of its current rate of CO_2 emissions; globally, the number is around 300 years. This potential is constrained by the fact that carbon storage (without use) is largely a cost, as we have noted, and thus attracts relatively little project investment and innovation, particularly in the absence of regulatory support or incentives. Moreover, there are also complex legal issues that must be resolved, such as liability for potential leaks, as well as the jurisdictional complexities associated with underground property ownership and use. Still, by 2030 we estimate that storage could account for 200 Mtpa of CO_2 abatement—a small but meaningful slice of the full potential for storage.

[7] For data used in this section, see "CCUS supply chains and economics," in *Meeting the dual challenge: A roadmap to at-scale deployment of carbon capture, use, and storage*, National Petroleum Council, December 2019, dualchallengenpc.org.

Regulation
Anywhere you look in the CCUS value chain, projects to jump-start progress are costly. One avenue of government support is tax credits. In the United States, a tax credit (Internal Revenue Code, Section 45Q) offers \$35 a ton for CO_2 use and \$50 a ton for geologic storage (the higher incentive accounts for the lack of revenue potential). An alternative would be a market price for carbon.

In some sense, the CCUS opportunity is a natural extension of something that occurs every day in the global economy: the collection and disposal of waste and the transformation of some of it into higher-value products and materials. For a wide variety of players in the oil, gas, and chemical industries, this also represents a natural extension of core capabilities—such as operating pipelines, managing reservoirs, and synthesizing new materials—and could therefore be a major opportunity. To make the economics work and to encourage further technological innovation, incentives and supportive regulatory frameworks will be necessary. If they come, CCUS can help support the transition to a low-carbon economy. Without CCUS, the transition would become much more challenging—because every scenario to stabilize the climate depends on investment in negative-emissions technologies. Q

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