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How to Make Recyclable Plastics Out of CO2 to Slow Climate Change

Teaser: Chemists are manipulating carbon dioxide to make clothing, mattresses, shoes, and more.

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[Article Body:]

It's morning, and you wake up on a comfortable foam mattress made partly from greenhouse gas. You pull on a T-shirt and sneakers manufactured using carbon dioxide pulled from factory emissions. After a good run, you stop for a cup of joe and guiltlessly toss the plastic cup in the trash, confident it will fully biodegrade into harmless organic materials. At home, you squeeze shampoo from a bottle that has lived many lifetimes, then slip into a dress fashioned from smokestack emissions. You head to work with a smile,

knowing your morning routine has made Earth's atmosphere a teeny bit cleaner. Sound like a dream? Hardly. These products are [already on the market](#) around the world. And others are in the process of being developed. They're part of a growing effort by academia and industry to reduce the damage caused by [centuries of human activity that has sent CO2](#) and other heat-trapping gases into the atmosphere.

The need for action is urgent. In its 2022 report, the United Nations Intergovernmental Panel on Climate Change, or IPCC, stated that [rising temperatures have already caused irreversible damage to the planet](#) and [increased human death and disease](#).

Meanwhile, the amount of CO2 emitted continues to grow. In 2023, the U.S. Energy Information Administration [predicted](#) that if current policy and growth trends continue, annual global CO2 emissions could increase from more than 35 billion metric tons in 2022 to 41 billion metric tons by 2050.

Capturing—and Using—Carbon

Carbon capture and storage, or CCS, is a climate mitigation strategy with “considerable” potential, according to the IPCC, [which released its first report on the technology in 2005](#). CCS traps CO2 from smokestacks or ambient air and pumps it underground for permanent sequestration; controversially, the fossil fuel industry has also used this technology to pump more oil out of reservoirs.

As of 2023, almost 40 CCS facilities operate worldwide, with about 225 more in development, [according](#) to Statista. The [Global CCS Institute](#) reports that, in 2022, the total annual capacity of all current and planned projects was estimated at 244 million metric tons. The 2021 Infrastructure Investment and Jobs Act includes [\\$3.5 billion](#) in funding for four U.S. direct air capture facilities.

But rather than just storing it, the captured carbon could be used to make things. In 2022, for the [first time, the IPCC added carbon capture and utilization](#), or CCU, to its list of options for drawing down atmospheric carbon. CCU captures CO2 and incorporates it into carbon-containing products like cement, jet fuel, and the raw materials used for making plastics.

CCU could reduce annual greenhouse gas emissions by [20 billion metric tons in 2050](#)—more than half of the world's global emissions today, the IPCC estimates.

Such recognition was a significant victory for a movement that has struggled to emerge from the shadow of its more established cousin, CCS, says [chemist and global CCU expert Peter Styring of the University of Sheffield in England](#), during a 2022 interview. He adds that many CCU-related companies are springing up, collaborating with each other and

with more established companies, and working across borders. London-based consumer goods giant Unilever, for example, [partnered](#) with companies from the United States and India to create the first laundry detergent made from industrial emissions.

The potential of CCU is “enormous,” both in terms of its volume and monetary prospects, [said mechanical engineer Volker Sick](#) at an April 2022 conference in Brussels following the IPCC report that first included CCU as a climate change strategy. Sick, of the University of Michigan in Ann Arbor, [directs](#) the Global CO2 Initiative, which promotes CCU as a mainstream climate solution. “We’re not talking about something that’s nice to do but doesn’t move the needle,” he [added](#). “It moves the needle in many, many aspects.”

The Plastics Paradox

The use of carbon dioxide in products is not new. CO2 makes soda fizzy, keeps foods frozen (as dry ice), and converts ammonia to urea for fertilizer. What’s new is the focus on creating products with CO2 as a strategy to slow climate change. According to Lux Research, a Boston-based research and advisory firm, the CCU market, estimated at [nearly \\$2 billion in 2020](#), could mushroom to [\\$550 billion by 2040](#).

Much of this market is driven by [adding](#) CO2 to cement (which can improve its strength and elasticity) and to [jet fuel](#)—two moves that can lower both industries’ large carbon footprints. CO2-to-plastics is a niche market today, but the field aims to battle two crises: climate change and plastic pollution.

Plastics are made from fossil fuels, a mix of hydrocarbons formed by the remains of ancient organisms. Most plastics are produced by refining crude oil, which is then broken down into smaller molecules through a process called cracking. These smaller molecules, known as monomers, are the building blocks of polymers. Monomers such as ethylene, propylene, styrene, and others are linked together to form plastics such as polyethylene (detergent bottles, toys, rigid pipes), polypropylene (water bottles, luggage, car parts), and polystyrene (plastic cutlery, CD cases, Styrofoam).

But making plastics from fossil fuels is a carbon catastrophe. Each step in the life cycle of plastics—extraction, transport, manufacture, and disposal—emits massive amounts of greenhouse gases, mainly CO2, according to the Center for International Environmental Law, a nonprofit law firm with offices in Geneva and Washington, D.C. These emissions alone—more than 850 million metric tons of greenhouse gases in 2019—[are enough to threaten global climate targets](#).

And the numbers are about to get much worse. A 2018 report by the Paris-based intergovernmental International Energy Agency projected that global demand for plastics

will [increase](#) from about 400 million metric tons in 2020 to nearly 600 million by 2050. Future demand is expected to be concentrated in developing countries and vastly outstrip global recycling efforts.

Plastics [are a severe](#) environmental crisis, from fossil fuel use to their buildup in landfills and oceans. But we're a society addicted to plastic and all it gives us—cell phones, computers, comfy Crocs. Is there a way to have our (plastic-wrapped) cake and eat it too? Yes, Sick. First, cap the oil wells. Next, make plastics from aboveground carbon. Today, there are [products made of](#) between 20 and 40 percent CO₂. Finally, he says, build a circular economy that reduces resource use, reuses products, and then recycles them into other new products.

“Not only can we eliminate the fossil carbon as a source so that we don't add to the aboveground carbon budget, but in the process, we can also rethink *how* we make plastics,” Sick says. He suggests that plastics be specifically designed “to live very, very long so that they don't have to be replaced... or that they decompose in a benign manner.” However, creating plastics from thin air is not easy. CO₂ needs to be extracted from the atmosphere or smokestacks, for example, using specialized equipment. It must often be compressed into liquid form and transported, generally through pipelines. Finally, to meet the overall goal of reducing the amount of carbon in the air, the chemical reaction that turns CO₂ into the building blocks of plastics must be run with as little extra energy as possible. Keeping energy use low is a unique challenge when dealing with the carbon dioxide molecule.

A Bond That's Hard to Break

There's a reason that carbon dioxide is such a potent greenhouse gas. It is incredibly stable and can [linger](#) in the atmosphere for 300 to 1,000 years. That stability makes CO₂ hard to break apart and add to other chemicals. Lots of energy is typically needed to ensure that chemical reaction.

“This is the fundamental energy problem of CO₂,” says chemist Ian Tonks of the University of Minnesota in Minneapolis in a July 2022 interview. “Energy is necessary to fix CO₂ to plastics. We're trying to find that energy in creative ways.”

Catalysts offer a possible answer. These substances can increase the rate of a chemical reaction and thus reduce the need for energy. Scientists in the CO₂-to-plastics field have spent more than a decade [searching](#) for catalysts that can work at close to room temperature and pressure and coax CO₂ to form a new chemical identity. These efforts fall into two broad categories: chemical and biological conversion.

First Attempts

Early experiments focused on adding CO₂ to [highly reactive monomers](#) like epoxides to facilitate the necessary chemical reaction. Epoxides are three-membered rings composed of one oxygen atom and two carbon atoms. Like a spring under tension, they can easily pop open.

In the early 2000s, industrial chemist Christoph Gürtler and chemist Walter Leitner of RWTH Aachen University in Germany [found](#) a zinc catalyst that allowed them to break open the epoxide ring of polypropylene oxide and combine it with CO₂. Following the reaction, the CO₂ was joined permanently to the polypropylene molecule and was no longer in gas form—something that is true of all CO₂-to-plastic reactions.

Their work resulted in one of the first commercial CO₂ products—a polyurethane foam [containing](#) 20 percent captured CO₂. As of 2022, the German company Covestro, where Gürtler now works, [sells 5,000 metric tons of CO₂-based polyol annually](#) in the form of mattresses, car interiors, building insulation, and sports flooring.

Other research has focused on other monomers to expand the variety of CO₂-based plastics. Butadiene is a hydrocarbon monomer that can be used to make polyester for clothing, carpets, adhesives, and other products.

In 2020, chemist James Eagan at the University of Akron in Ohio mixed butadiene and CO₂ with a series of catalysts developed at Stanford University. Eagan hoped to create a carbon-negative polyester, meaning it has a net effect of removing CO₂ from the atmosphere rather than adding it. When he analyzed the contents of one vial, he discovered he had created something even better: a [polyester made with 29 percent CO₂](#) that degrades in high-pH water into organic materials.

“Chemistry is like cooking,” Eagan says during an interview. “We took chocolate chips, flour, eggs, butter, mixed them up, and instead of getting cookies, we opened the oven and found a chicken potpie.”

Eagan’s invention has immediate applications in the recycling industry, where machines can often get gummed up from the nondegradable adhesives used in packaging, soda bottle labels, and other products. An adhesive that easily breaks down may improve the efficiency of recycling facilities.

Tonks, described by Eagan as a friendly competitor, took Eagan’s patented process a step further. By putting Eagan’s product through one more reaction, Tonks [made the polymer fully degradable back to reusable CO₂](#)—a circular carbon economy goal. Tonks created a startup in 2022 called [LoopCO₂](#) to produce a variety of biodegradable plastics.

Microbial Help

Researchers have also harnessed microbes to help turn carbon dioxide into useful materials, including dress fabric. Some of the planet's oldest living microbes emerged at a time when Earth's atmosphere was rich in carbon dioxide. Known as [acetogens](#) and methanogens, the microbes developed simple metabolic pathways that use enzyme catalysts to convert CO₂ and carbon monoxide into organic molecules. In the last decade, researchers have studied the microbes' potential to remove CO₂ and CO from the atmosphere or industrial emissions and turn them into valuable products.

[LanzaTech](#), based in Skokie, Illinois, partners with steel plants in China, India, and Belgium to turn industrial emissions into ethanol using [the acetogenic bacterium *Clostridium autoethanogenum*](#). The first company to achieve the conversion of waste gases to ethanol on an industrial scale, LanzaTech designed bacteria-filled bioreactors to fit onto existing plant facilities. Ethanol, a valuable plastic precursor, goes through two more steps to become polyester. In 2021, the [clothing company Zara announced a new line of dresses made from LanzaTech's CO₂-based fabrics](#).

In 2020, steel production emitted [almost 2 metric tons of CO₂](#) for every 1 metric ton of steel produced. By contrast, a life cycle assessment study found that LanzaTech's ethanol production process lowered greenhouse gas emissions by more than 80 percent [compared](#) with ethanol made from fossil fuels.

In February 2022, researchers from LanzaTech, Northwestern University in Evanston, Illinois, and other institutions reported in *Nature Biotechnology* that they had [genetically modified the *Clostridium* bacterium to produce acetone and isopropanol](#), two other fossil fuel-based industrial chemicals. The spent bacteria is used as animal feed or biochar, a carbon dioxide removal method that stores carbon in the soil for centuries.

Other researchers are skipping living microbes and just using their catalysts. More than a decade ago, chemist Charles Dismukes of Rutgers University began looking at acetogens and methanogens to capture and use atmospheric carbon. He was intrigued by their ability to release energy when making carbon building blocks from CO₂, a reaction that usually requires energy. He and his team focused on the bacteria's nickel phosphide catalysts, which are responsible for the energy-releasing carbon reaction.

Dismukes and colleagues [developed six electrocatalysts](#) to make monomers at room temperature and pressure using only CO₂, water, and electricity. The energy--releasing pathway of the nickel phosphide catalysts "lowers the required voltage to run the reaction, which lowers the energy consumption of the process and improves the carbon footprint,"

says Karin Calvinho, a former student of Dismukes. Calvinho is now the chief technical officer at [RenewCO2](#), a startup that began to commercialize Dismukes' innovations in 2018. RenewCO2 plans to obtain CO2 from biomass, industrial emissions, or direct air capture, then sell its monomers to companies wanting to reduce their carbon footprint, Calvinho says during an interview.

Barriers to Change

Yet researchers and companies face challenges in scaling up carbon capture and reuse. Some barriers lurk in the language of regulations written before CCU existed. An example is the U.S. Environmental Protection Agency's program to [provide tax credits and other incentives](#) to biofuel companies. The program is geared toward plant-based fuels like corn and sugar-cane. LanzaTech's approach for producing jet fuel doesn't qualify for credits because bacteria are not plants.

Other barriers are more fundamental. Styring points to the long-standing practice of fossil fuel subsidies, which in 2021 topped [\\$440 billion](#) worldwide. According to the International Energy Agency, global government subsidies to the oil and gas industry [keep fossil fuel prices artificially low](#), making it hard for renewables to compete. Styring advocates shifting those subsidies toward renewables.

"We try to work on the principle that we recycle carbon and create a circular economy," he says. "But current legislation is set up to perpetuate a linear economy."

The happy morning routine that makes the world carbon-cleaner is theoretically possible. It's just not the way the world works yet. Getting to that circular economy, where the amount of carbon aboveground is finite and controlled in a never-ending loop of use and reuse, will require change on multiple fronts. Government policy and investment, corporate practices, technological development, and human behavior would need to align effectively and quickly in the interests of the planet.

In the meantime, researchers continue their work on the carbon dioxide molecule.

"I try to plan for the worst-case scenario," Eagan [said](#) during an interview. "If legislation is never in place to curb emissions, how do we operate within our capitalist system to generate value in a renewable and responsible way? At the end of the day, we will need new chemistry."