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FEATURE

The Tiny Swiss Company That Thinks It Can Help Stop Climate Change

Two European entrepreneurs want to remove carbon from the air at prices cheap enough to matter.

By Jon Gertner

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Just over a century ago in Ludwigshafen, Germany, a scientist named Carl Bosch assembled a team of engineers to exploit a new technique in chemistry. A year earlier, another German chemist, Fritz Haber, hit upon a process to pull nitrogen (N) from the air and combine it with hydrogen (H) to produce tiny amounts of ammonia (NH_3). But Haber's process was delicate, requiring the maintenance of high temperatures and high pressure. Bosch wanted to figure out how to adapt Haber's discovery for commercial purposes — as we would say today, to "scale it up." Anyone looking at the state of manufacturing in Europe around 1910, Bosch observed, could see that the task was daunting: The technology simply didn't exist.

Over the next decade, however, Bosch and his team overcame a multitude of technological and metallurgical challenges. He chronicled them in his 1932 acceptance speech for the Nobel Prize for Chemistry — an honor he won because the Haber-Bosch process, as it came to be known, changed the world. His breakthrough made possible the production of ammonia on an industrial scale, providing the world with cheap and abundant fertilizer. The scientist and historian Vaclav Smil called Haber-Bosch "the most important technical invention of the 20th century." Bosch had effectively removed the historical bounds on crop yields, so much so that he was widely credited with making "bread from air." By some estimates, Bosch's work made possible the lives of more than two billion human beings over the last 100 years.

What the Haber-Bosch method had going for it, from the very start, was a ready market. Fertilizer was already in high demand, but it came primarily from limited natural reserves in far-flung locales — bird droppings scraped from remote islands near Peru, for instance, or mineral stores of nitrogen dug out of the Chilean desert. Because synthetic ammonia competed with existing products, it was able to follow a timeworn pattern of innovation. In much the same way that LEDs have supplanted fluorescent and incandescent bulbs (which in turn had displaced kerosene lamps and wax candles), a novel product or process often replaces something already in demand. If it is better or cheaper — and especially if it is better *and* cheaper — it usually wins in the marketplace. Haber-Bosch did exactly that.

It may now be that another gas — carbon dioxide (CO_2) — can be removed from the air for commercial purposes, and that its removal could have a profound effect on the future of humanity. But it's almost certainly too soon to say for sure. One sunny morning last October, several engineers from a Swiss firm called Climeworks ambled onto the roof of a power-generating waste-incineration plant in Hinwil, a village about 30 minutes outside Zurich. The technicians had in front of them 12 large devices, stacked in two rows of six, that resembled oversize front-loading clothes dryers. These were "direct air capture" machines, which soon would begin collecting carbon dioxide from air drawn in through their central ducts. Once trapped, the CO_2 would then be siphoned into large tanks and trucked to a local Coca-Cola bottler, where it would become the fizz in a soft drink.

[Is It O.K. to Tinker With the Environment to Fight Climate Change?]

The machines themselves require a significant amount of energy. They depend on electric fans to pull air into the ducts and over a special material, known as a sorbent, laced with granules that chemically bind with CO_2; periodic blasts of heat then release the captured gas from the sorbent, with customized software managing the whole catch-and-release cycle. Climeworks had installed the machines on the roof of the power plant to tap into the plant's low-carbon electricity and the heat from its incineration system. A few dozen yards away from the new installation sat an older stack of Climeworks machines, 18 in total, that had been whirring on the same rooftop for more than a year. So far, these machines had captured about 1,000 metric tons (or about 1,100 short tons) of carbon dioxide from the air and fed it, by pipeline, to an enormous greenhouse nearby, where it was plumping up tomatoes, eggplants and mâche. During a tour of the greenhouse, Paul Ruser, the manager, suggested I taste the results. "Here, try one," he said, handing me a crisp, ripe cucumber he plucked from a nearby vine. It was the finest direct-air-capture cucumber I'd ever had.

Climeworks's rooftop plant represents something new in the world: the first direct-air-capture venture in history seeking to sell CO_2 by the ton. When the company's founders, Christoph Gebald and Jan Wurzbacher, began openly discussing their plans to build a business several years ago, they faced a deluge of skepticism. "I would say nine out of 10 people reacted critically," Gebald told me. "The first thing they said was: 'This will never work technically.' And finally in 2017 we convinced them it works technically, since we built the big plant in Hinwil. But once we convinced them that it works technically, they would say, 'Well, it will never work economically.' "

For the moment, skeptics of Climeworks's business plan are correct: The company is not turning a profit. To build and install the 18 units at Hinwil, hand-assembled in a second-floor workshop in Zurich, cost between $3 million and $4 million, which is the primary reason it costs the firm between $500 and $600 to remove a metric ton of CO_2 from the air. Even as the company has attracted about $50 million in private investments and grants, it faces the same daunting task that confronted Carl Bosch a century ago: How much can it bring costs down? And how fast can it scale up?

Gebald and Wurzbacher believe the way to gain a commercial foothold is to sell their expensive CO_2 to agriculture or beverage companies. Not only do these companies require CO_2 anyway, some also seem willing to pay a premium for a vital ingredient they can use to help market their products as eco-friendly.

Still, greenhouses and soda bubbles together represent a small global market — perhaps six million metric tons of CO_2 annually. And Gebald and Wurzbacher did not get into carbon capture to grow mâche or put bubbles in Fanta. They believe that over the next seven years they can bring expenses down to a level that would enable them to sell CO_2 into more lucrative markets. Air-captured CO_2 can be combined with hydrogen and then fashioned into any kind of fossil-fuel substitute you want. Instead of making bread from air, you can make fuels from air. Already, Climeworks and another company, Carbon Engineering, which is based in British Columbia, have moved aggressively on this idea; the Canadians have even lined up investors (including Bill Gates) to produce synthetic fuel at large industrial plants from air-captured CO_2.

The ultimate goal for air capture, however, isn't to turn it into a product — at least not in the traditional sense. What Gebald and Wurzbacher really want to do is to pull vast amounts of CO_2 out of the atmosphere and bury it, forever, deep underground, and sell that service as an offset. Climeworks's captured CO_2 has already been injected deep into rock formations beneath Iceland; by the end of the year, the firm intends to deploy 50 units near Reykjavik to expand the operation. But at that point the company will be moving into uncharted economic territory — purveyors of a service that seems desperately needed to help slow climate change but does not, at present, replace anything on the consumer or industrial landscape. To complicate matters, a ton of buried CO_2 is not something that human beings or governments have shown much demand for. And so companies like Climeworks face a quandary: How do you sell something that never existed before, something that may never be cheap, into a market that is not yet real?

Even the most enthusiastic believers in direct air capture stop short of describing it as a miracle technology. It's more frequently described as an old idea — "scrubbers" that remove CO_2 have been used in submarines since at least the 1950s — that is being radically upgraded for a variety of new applications. It's arguably the case, in fact, that when it comes to reducing our carbon emissions, direct air capture will be seen as an option that's too expensive and too modest in impact. "The only way that direct air capture becomes meaningful is if we do all the other things we need to do promptly," Hal Harvey, a California energy analyst who studies climate-friendly technologies and policies, told me recently. Harvey and others make the case that the biggest, fastest and cheapest gains in addressing atmospheric carbon will come from switching our power grid to renewable energy or low-carbon electricity; from transitioning to electric vehicles and imposing stricter mileage regulations on gas-powered cars and trucks; and from requiring more energy-efficient buildings and appliances. In short, the best way to start making progress toward a decarbonized world is not to rev up millions of air capture machines right now. It's to stop putting CO_2 in the atmosphere in the first place.

The future of carbon mitigation, however, is on a countdown timer, as atmospheric CO_2 concentrations have continued to rise. If the nations of the world were to continue on the current track, it would be impossible to meet the objectives of the 2016 Paris Agreement, which set a goal limiting warming to 2 degrees Celsius or, ideally, 1.5 degrees. And it would usher in a world of misery and economic hardship. Already, temperatures in some regions have climbed more than 1 degree Celsius, as a report by the Intergovernmental Panel on Climate Change noted last October. These temperature increases have led to an increase in droughts, heat waves, floods and biodiversity losses and make the chaos of 2 or 3 degrees' additional warming seem inconceivable. A further problem is that maintaining today's emissions path for too long runs the risk of doing irreparable damage to the earth's ecosystems — causing harm that no amount of technological innovation can make right. "There is no reverse gear for natural systems," Harvey says. "If they go, they go. If we defrost the tundra, it's game over." The same might be said for the Greenland and West Antarctic ice sheets, or our coral reefs. Such resources have an asymmetry in their natural architectures: They can take thousands or millions of years to form, but could reach conditions of catastrophic decline in just a few decades.

At the moment, global CO_2 emissions are about 37 billion metric tons per year, and we're on track to raise temperatures by 3 degrees Celsius by 2100. To have a shot at maintaining a climate suitable for humans, the world's nations most likely have to reduce CO_2 emissions drastically from the current level — to perhaps 15 billion or 20 billion metric tons per year by 2030; then, through some kind of unprecedented political and industrial effort, we need to bring carbon emissions to zero by around 2050. In this context, Climeworks's effort to collect 1,000 metric tons of CO_2 on a rooftop near Zurich might seem like bailing out the ocean one bucket at a time. Conceptually, however, it's important. Last year's I.P.C.C. report noted that it may be impossible to limit warming to 1.5 degrees by 2100 through only a rapid switch to clean energy, electric cars and the like. To preserve a livable environment we may also need to extract CO_2 from the atmosphere. As Wurzbacher put it, "if you take all these numbers from the I.P.C.C., you end up with something like eight to 10 billion tons — gigatons — of CO_2 that need to be removed from the air every year, if we are serious about 1.5 or 2 degrees."

There happens to be a name for things that can do this kind of extraction work: negative-emissions technologies, or NETs. Some NETs, like trees and plants, predate us and probably don't deserve the label. Through photosynthesis, our forests take extraordinary amounts of carbon dioxide from the atmosphere, and if we were to magnify efforts to reforest clear-cut areas — or plant new groves, a process known as afforestation — we could absorb billions more metric tons of carbon in future years. What's more, we could grow crops specifically to absorb CO_2 and then burn them for power generation, with the intention of capturing the power-plant emissions and pumping them underground, a process known as bioenergy with carbon capture and storage, or BECCS. Other negative-emissions technologies include manipulating farmland soil or coastal wetlands so they will trap more atmospheric carbon and grinding up mineral formations so they will absorb CO_2 more readily, a process known as "enhanced weathering."

Negative emissions can be thought of as a form of time travel. Ever since the Industrial Revolution, human societies have produced an excess of CO_2, by taking carbon stores from deep inside the earth — in the form of coal, oil and gas — and from stores aboveground (mostly wood), then putting it into the atmosphere by burning it. It has become imperative to reverse the process — that is, take CO_2 out of the air and either restore it deep inside the earth or contain it within new surface ecosystems. This is certainly easier to prescribe than achieve. “All of negative emission is hard — even afforestation or reforestation,” Sally Benson, a professor of energy-resources engineering at Stanford, explains. “It’s not about saying, ‘I want to plant a tree.’ It’s about saying, ‘We want to plant a billion trees.’ ” Nevertheless, such practices offer a glimmer of hope for meeting future emissions targets. “We have to come to grips with the fact that we waited too long and that we took some options off the table,” Michael Oppenheimer, a Princeton scientist who studies climate and policy, told me. As a result, NETs no longer seem to be just interesting ideas; they look like necessities. And as it happens, the Climeworks machines on the rooftop do the work each year of about 36,000 trees.

Last fall, the National Academies of Sciences, Engineering and Medicine published a lengthy study on carbon removal. Stephen Pacala, a Princeton professor who led the authors, pointed out to me that negative-emissions technologies have various strengths and drawbacks, and that a “portfolio” approach — pursue them all, then see which are the best — may be the shrewdest bet. If costs for direct air capture can be reduced, Pacala says he sees great promise, especially if the machines can offset emissions from economic sectors that for technological reasons will transition to zero carbon much more slowly than others. Commercial aviation, for instance, won’t be converted to running on solar power anytime soon. Jennifer Wilcox, a chemical-engineering professor at Worcester Polytechnic Institute, in Massachusetts, told me that air capture could likewise help counter the impact of several vital industries. “There are process emissions that come from producing iron and steel, cement and glass,” she says, “and any time you make these materials, there’s a chemical reaction that emits CO_2.” Direct air capture could even lessen the impacts of the Haber-Bosch processes for making fertilizer; by some estimates, that industry now accounts for 3 percent of all CO_2 emissions.

Pacala equates the challenges confronting Climeworks and Carbon Engineering to what the wind- and solar-power industries faced in the 1970s and ’80s, when their products were expensive compared with fossil fuels. Those industries couldn’t rely on demand from the private sector alone. But some policymakers perceived tremendous environmental and public benefits if they could surmount that hurdle. Government investments in research, along with state and federal tax credits, helped the young industries expand. “Wind and solar are now the cheapest forms of energy in the right locations,” Pacala says. “The return on those investments, if you calculated it, would blow the doors off anything in your portfolio. It’s like investing in early Apple. So it’s a spectacular story of success. And direct air capture is precisely the same kind of problem, in which the only barrier is that it’s too costly.”

[Thirty years ago, we had a chance to save the planet. Read about the decade we almost stopped climate change.]

Most of Climeworks's 60 employees work in a big industrial space in downtown Zurich, on two floors of a low-slung building that the company sublets from a German aerospace firm. Manufacturing operations are on the ground floor; the research labs are upstairs, along with a small suite of shared offices, a hallway kitchen and a hangout area. The place has the stark, casual feel of a tech start-up, with one exception: The walls are lined with oversize photos of pivotal moments in Climeworks's young history — its ungainly early prototypes; the opening of the first Hinwil plant that collected CO_2 for the greenhouse.

"It's a little bit by accident that we are based in Switzerland," Wurzbacher told me. He and Gebald both grew up in Germany and met as undergraduates at E.T.H. Zurich, the Swiss Federal Institute of Technology. "We met on Day 1, on the 20th of October of 2003," Gebald recalled. "And on Day 1 we decided that we'd have a company." Their aspiration was to be entrepreneurs, not to start a carbon-capture firm, but both men were drawn to research on renewable energy and reducing emissions. After they completed their master's projects, they decided to create a direct-air-capture prototype and go into business. Both took the title of company director. Helped by a number of small grants, Climeworks was incorporated in 2009.

The two men were not alone in trying to chip away at decades of carbon emissions. An American start-up, Global Thermostat, now finishing its first commercial plant in Alabama, began working on air-capture machines in 2010. And almost from the start, Gebald and Wurzbacher found themselves in a friendly competition with David Keith, the Harvard engineering professor who had just started Carbon Engineering in British Columbia. Keith's company settled on a different air-capture technology — employing a higher-heat process, and a liquid solution to capture CO_2 — to brew synthetic fuels. Climeworks's big advantage is that it can make smaller plants early, Keith told me: "I am crazy jealous. It's because they're using a modular design, and we're not." On the other hand, Keith said he believes his firm is closer to building a big plant that could capture carbon at a more reasonable cost and produce substantial amounts of fuel. "I don't see a path for them to match this." Gebald told me he thinks his and Keith's companies will each succeed with differing approaches. For now, what all the founders have in common is a belief that the cost of capturing a ton of carbon will soon drop sharply.

The greenhouse in Hinwil where Climeworks uses carbon dioxide pulled from the air to grow fruits and vegetables. Luca Locatelli for The New York Times

Their view is not always shared by outside observers. M.I.T.'s Howard Herzog, for instance, an engineer who has spent years looking at the potential for these machines, told me that he thinks the costs will remain between $600 and $1,000 per metric ton. Some of Herzog's reasons for skepticism are highly technical and relate to the physics of separating gases. Some are more easily grasped. He points out that because direct-air-capture machines have to move tremendous amounts of air through a filter or solution to glean a ton of CO_2 — the gas, for all its global impact, makes up only about 0.04 percent of our atmosphere — the process necessitates large expenditures for energy and big equipment. What he has likewise observed, in analyzing similar industries that separate gases, suggests that translating spreadsheet projections for capturing CO_2 into real-world applications will reveal hidden costs. "I think there has been a lot of hype about this, and it's not going to revolutionize anything," he told me, adding that he thinks other negative-emissions technologies will prove cheaper. "At best it's going to be a bit player."

Last year, when David Keith and his associates at Carbon Engineering published figures projecting that their carbon-capture technology could bring costs as low as $94 a metric ton, Herzog was not convinced. Keith nevertheless made the case to me that two new investors in Carbon Engineering — Chevron Technology Ventures and a subsidiary of Occidental Petroleum — scrutinized his company's numbers to an exhaustive degree and agreed the economics of the venture were solid enough to merit putting up substantial amounts in a $60 million investment round. Both Climeworks founders told me they agreed with Keith's cost estimates, and saw a similar downward curve for their own technology.

Climeworks's current goal is to remove 1 percent of the world's annual CO_2 emissions by the mid 2020s. Yet meeting such a benchmark, if it's even possible, would require bringing the cost of direct air capture down by nearly an order of magnitude while maintaining and expanding their roster of clients substantially. At the moment, Wurzbacher and Gebald have planned for several generations of Climeworks machines, with each new model promising declining prices. "Basically, we have a road map — $600, down to $400, down to $300 and $200 a ton," Wurzbacher said. "This is over the next five years. Down to $200 we know quite well what we're doing." And beyond $200, Wurzbacher suggested, things get murkier. To move below that price would depend on "new developments" in technology or manufacturing.

Both founders told me they expect to reap enormous cost reductions from expanding production — activities that involve buying materials more cheaply in bulk and assembling units on automated factory lines instead of building them by hand, as is the case now. Design advances could wring out other costs. "Maintenance is very expensive," Wurzbacher said. "Right now, if we exchange the filters in the collectors, we have to rent a crane, and that's a lot of man-hours. In the next-generation units, we have improved that a lot, so relatively small design changes could cut the costs of maintenance by a factor of three." Climeworks also intends to derive savings from improvements to crucial materials, like the sorbent that catches the CO_2. At the moment, the company's technology requires that the temperature inside the units be raised periodically to about 100 degrees Celsius to release CO_2 from the sorbent so it can be drawn off and stored. If the process can be done at a lower temperature, the units will use less energy, and the life of the materials should be extended, further driving down costs.

The company's ambitions for mass production may still seem extreme. To actually capture 1 percent of the world's carbon emissions by 2025 would, by Gebald's calculations, require that Climeworks build 250,000 carbon-capture plants like the ones on the roof at Hinwil. That adds up to about 4.5 million carbon collectors. For a company that has only built 100 collectors (and has 14 small plants around Europe), it's a staggering number. The Climeworks founders therefore try to think of their product as the automotive industry might — a piece of mass-produced technology and metal, not the carbon they hope to sequester. "What we're doing is gas separation," Wurzbacher said, "and that's traditionally a process-industry business, like oil and gas. But we don't really see ourselves there."

The founders note that Toyota makes more than 10 million cars annually. "Every CO_2 collector has about the same weight and dimensions of a car — roughly two tons, and roughly 2 meters by 2 meters by 2 meters," Gebald said. "And all the methods used to produce the CO_2 collectors could be well automated. So we have the automotive industry as a model for how to produce things in large quantities for low cost." The two men have already sought advice from Audi. They are also aware that the automotive industry perfected its methods over the course of 100 years. Climeworks, if it plans to have even a modest impact, doesn't have nearly as much time.

In 1954, the economist Paul Samuelson put forward a theory that made a distinction between "private-consumption goods" — bread, cars, houses and the like — and commodities that existed apart from the usual laws of supply and demand. Modern global markets are obviously quite successful at pricing private goods we need and want. But the other type of commodity Samuelson was describing is something now known as a "public good," which benefits everyone but is not bought, sold or consumed the same way. Definitions of a public good can vary, but the oft-used examples are lighthouses, national defenses and clean air.

Direct air capture can no doubt create private goods, like soft-drink carbonation or fuels. What makes its value so difficult to estimate is that in burying CO_2 for a better atmosphere — and, almost certainly, a better future — its purveyors would also create a public good. "The challenge with just collecting and burying CO_2 is that there isn't a market yet," Julio Friedmann, a former United States Energy Department official who now works at Columbia University, told me. "What it's really about is offering an environmental service for a fee." And what that means, in short, is that direct air capture's success would be limited to the size of the market for private goods — soda fizz, greenhouse gas — unless governments decided to intervene and help fund the equivalent of several million (or more) lighthouses.

An intervention could take a variety of forms. It could be large grants for research to find better sorbent materials, for instance, which would be similar to government investments that long ago helped nurture the solar- and wind-power industries. But help could also come by expanding regulations that already exist. A new and obscure United States tax provision, known as 45Q and signed last year by President Trump, offers a tax credit of up to $50 a ton for companies that bury CO_2 in geologic formations. The credit can benefit oil and gas firms that pump CO_2 underground during drilling work, as well as power plants that capture emissions directly from their smokestacks. Yet it could be used by Climeworks too, should it open plants in the United States — but only if it manages to remove and bury 100,000 tons of CO_2 per year.

Governments can make carbon more expensive too. The Climeworks founders told me they don't believe their company will succeed on what they call "climate impact" scales unless the world puts significant prices on emissions, in the form of a carbon tax or carbon fee. "Our goal is to make it possible to capture CO_2 from the air for below $100 per ton," Wurzbacher says. "No one owns a crystal ball, but we think — and we're quite confident — that by something like 2030 we'll have a global average price on carbon in the range of $100 to $150 a ton." There is optimism in this thinking, he admitted; at the moment, only a few European countries have made progress in assessing a high price on carbon, and in the United States, carbon taxes have been repudiated recently at the polls, most recently in Washington State. Still, if such prices became a reality, they could benefit the carbon extraction market in a variety of ways. A company that sells a product or uses a process that creates high emissions — an airline, for instance, or a steel maker — could be required to pay carbon-removal companies $100 per metric ton or more to offset their CO_2 output. Or a government might use carbon-tax proceeds to directly pay businesses to collect and bury CO_2. In the absence of any meaningful government action, perhaps a crusading billionaire could put all the money in his estate toward capturing CO_2 and stashing it in the earth.

If carbon came to be properly priced, a global ledger would need to be kept by regulators so that air-capture machines could suck in and bury an amount equivalent to the CO_2 that emitters produce. Because CO_2 emissions mix quickly into the atmosphere, location would be mostly irrelevant, except for the need to situate plants near clean energy sources and suitable areas for sequestering the gas underground. A direct-air-capture plant in Iceland, in other words, could take in the same quantity of emissions produced by a Boeing 787 in Australia and thus negate its environmental impact. What's more, there might not be limitations on the burial process. "It doesn't cost too much to pump CO_2 underground," Stanford's Sally Benson says. Companies already sequester about 34 million metric tons of CO_2 in the ground every year, at a number of sites around the world, usually to enhance the oil-drilling process. “The costs range from $2 to $15 per ton. So the bigger cost in all of this is the cost of carbon capture.” Benson told me that various studies suggest that the earth’s capacity for CO_2 sequestration could be in the range of 25 trillion metric tons; burying, say, five billion metric tons of CO_2 a year is therefore within the realm of possibility.

A pilot project at a Swiss university that uses Climeworks equipment to make methane out of airborne CO_2. Luca Locatelli for The New York Times

In an imaginary, zero-carbon future, the revenue prospects for air-capture companies would probably be enormous. “If we get to $100 to $150 a ton,” Wurzbacher told me, “then the market is almost infinite.” It would be so large, he said, that even if his company went through an exponential expansion, he doubted it could serve all the potential clients. At such low prices, companies could potentially fold carbon offsets into their pricing — or be compelled to do so — leading to an explosion in the market. “Christoph and me, we are always saying, we think that if this develops in a direction we think it does, we are not founding a company — we’re really founding a new industry,” Wurzbacher said. He points to the work in Iceland — a collaborative effort, funded partly by the European Union — as the first step toward that industry. At the moment, a single Climeworks collector on a Reykjavik geothermal field takes in air and collects CO_2; after the gas is flushed from the machine's filter, it is mixed with water, essentially forming hot seltzer. Then the liquid is injected into a basalt rock formation deep underground. Over the course of about two years, the CO_2 mineralizes, locking away the gas forever.

At Climeworks's offices in Zurich, I asked Valentin Gutknecht, who was at the time the company's business-development manager, if he could bury in Iceland my emissions from my plane flight from the United States to Zurich. He had a written agreement he could print out and give me, but it wouldn't be cheap, he warned. The price was running about $600 a metric ton, meaning my flight would cost about an extra $700. But I was hardly the first person to ask him. The weekend before, Gutknecht told me, he received 900 unsolicited inquiries by email. Many were from potential customers who wanted to know how soon Climeworks could bury their CO_2 emissions, or how much a machine might cost them. I had the sense I was getting a glimpse of what's to come: A community of people — not large enough to make a difference, but nonetheless motivated — seemed ready to pay a premium to reverse their CO_2 emissions.

Later, Wurzbacher told me he wants to offer a "one click" consumer service, perhaps in a year or two, which would expand what they're doing in Iceland to individual customers and businesses. A Climeworks app could be installed on my smartphone, he explained. It could then be activated by my handset's location services. "You fly over here to Europe," he explained, "and the app tells you that you have just burned 1.7 tons of CO_2. Do you want to remove that? Well, Climeworks can remove it for you. Click here. We'll charge your credit card. And then you'll get a stone made from CO_2 for every ton you sequester." He sat back and sighed. "That would be my dream," he said.

Paradoxical though it may seem, it's probable that synthetic fuels offer a more practical path to creating a viable business for direct air capture. The vast and constant market demand for fuel is why Carbon Engineering has staked its future on synthetics. The world currently burns about 100 million barrels of oil a day. David Keith told me he thinks that by 2050 the demand for transportation fuels will almost certainly be modified by the transition to electric vehicles. "So let's say you'd have to supply something like 50 million barrels a day in 2050 of fuels," he said. "That's still a monster market."

Steve Oldham, Carbon Engineering's chief executive, added that direct-air-capture synthetics have an advantage over traditional fossil fuels: They won't have to spend a dime on exploration. "If you were a brand-new company looking to make fuel, the cost of finding and then extracting fossil fuel is going to be really substantial," he says. "Whereas our plants, you can build it right in the middle of California, wherever you have air and water." He told me that the company's first large-scale facility should be up and running by 2022, and will turn out at least 500 barrels a day of fuel feedstock — the raw material sent to refineries.

Climeworks perceives a large market for fuels, too. In a town near Zurich called Rapperswil-Jona, the firm has installed a collector in a small plant, run by the local technical university, to produce methane. In a room about the size of a shipping container, the Climeworks machine takes in CO_2 through an air duct and sends it through a maze of pipes to combine it with hydrogen, which is derived from water using solar power. When I visited, the plant was a few weeks away from being operational, but the methane coming out of the works could replace gasoline in the engine of just about any car, bus or truck outfitted to run on natural gas. At a larger plant in Italy, Climeworks recently joined a consortium of European countries to produce synthetic methane that will be used by a local trucking fleet. With different tweaks and refinements, the process could be adapted for diesel, gasoline, jet fuel — or it could be piped directly to local neighborhoods as fuel for home furnaces.

From an economic standpoint, synthetic fuels could allow producers to plug into a huge existing infrastructure — refineries, gas stations, cars, planes, trucks, homes, ships — and replace a product already in demand with something arguably better. But the new fuels are not necessarily *cheaper*. Carbon Engineering aspires to deliver its product at an ultimate retail price of about $1 per liter, or $3.75 per gallon. What would make the product competitive are regulations in California that now require fuel sellers to produce fuels of lower "carbon intensity." To date this has meant blending gas and diesel with biofuels like ethanol, but it could soon mean carbon-capture synthetics too.

In an expanding market, synthetic fuels could have curious effects. Since they're made from airborne CO_2 and hydrogen and could be manufactured just about anywhere, they could rearrange the geopolitical order — tempering the power of a handful of countries that now control natural-gas and oil markets. The methane project in Rapperswil-Jona is especially suited for that country's needs, Markus Friedl, a thermodynamics professor overseeing the project, told me, because Switzerland imports almost all of its natural gas, and its ability to generate energy from renewable sources is limited during the colder months. Carbon-capture-derived fuels, if they become cheap enough, could be a form of energy storage — made in summer, with solar or wind power, and used in winter — that carries a lower cost (and longer life) than batteries.

From an environmental standpoint, air-capture fuels are not a utopian solution. Such fuels are carbon neutral, not carbon negative. They can't take CO_2 from our industrial past and put it back into the earth. If all the cars, trucks and planes of the year 2050 run on renewable fuels instead of fossil fuels, their CO_2 emissions would need to be removed from the air, recycled into the same product they originally burned through, and the cycle would need to repeat, ad infinitum, lest emissions increase. Even so, these fuels could present an enormous improvement. Transportation — currently the most significant source of emissions by sector in the United States — could cease to be a net emitter of CO_2. Just as crucial, the technology of direct air capture could scale up to become better and cheaper.

A huge expansion would also involve huge complications. "You start to get into really big challenges when you get to these big, large scales," Glen Peters, a research director at the Cicero Center for International Climate Research in Oslo, told me. "If you can do one carbon-capture facility, where Carbon Engineering or Climeworks can build a big plant, great. You need to do that 5,000 times. And to capture a million tons of CO_2 with direct air capture, you need a small power plant just to run that facility. So if you're going to build one direct-air-capture facility every day for the next 30 years to get to some of these scenarios, then in addition, we have to build a new mini power plant every day as well." It's also the case that you have to address two extraordinary problems at the same time, Peters added. "To reach 1.5 degrees, we need to halve emissions every decade," he said. That would mean persuading entire nations, like China and the United States, to switch from burning coal to using renewables at precisely the same time that we make immense investments in negative-emission technologies. And Peters pointed out that this would need to be done even as governments choose among competing priorities: health care, education and so on.

"The idea of bringing direct air capture up to 10 billion tons by the middle or later part of the century is such a herculean task it would require an industrial scale-up the likes of which the world has never seen," Princeton's Stephen Pacala told me. And yet Pacala wasn't pessimistic about making a start. He seemed to think it was necessary for the federal government to begin with significant research and investments in the technology — to see how far and fast it could move forward, so that it's ready as soon as possible. At Climeworks, Gebald and Wurzbacher spoke in similar terms, asserting that the conversations around climate challenges are moving beyond the choice between clean energy or carbon removal. Both will be necessary.

Gebald and Wurzbacher seem less assured about the future of global policy than on the mechanics of scaling up. Some of that, they made clear, was related to their outlook as engineers, to what they've gathered from observing companies like Audi and Apple. If the last century has proved anything, it's that society is not always intent on acting quickly, at least in the political realm, to clean up our environment. But we've proved very good at building technology in mass quantities and making products and devices better and cheaper — especially when there's money to be made. For now, Gebald and Wurzbacher seemed to regard the climate challenge in mathematical terms. How many gigatons needed to be removed? How much would it cost per ton? How many Climeworks machines were required? Even if the figures were enormous, even if they appeared impossible, to see the future their way was to redefine the problem, to move away from the narrative of loss, to forget the multiplying stories of dying reefs and threatened coastlines — and to begin to imagine other possibilities.

Correction: *Feb. 14, 2019*
An earlier version of this article misstated the abbreviation of the Swiss Federal Institute of Technology. It is E.T.H. Zurich not E.C.H.

Jon Gertner writes frequently for the magazine about science and technology. He last wrote about Tesla's effort to build self-driving cars.

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