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News & Highlights

Direct Air Carbon Capture Takes Baby Steps—Giant Strides Are Needed

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In September 2021, the world's largest industrial plant to pull carbon dioxide (CO_2) directly out of the atmosphere officially became operational in Iceland. Designed and built by the Zurich, Switzerland-based company Climeworks, its "Orca" facility—the company claims—can remove and permanently store 4000 t of CO_2 per year (Fig. 1) [1].

Around the world, a growing number of commercial entities like Climeworks have ramped up efforts to deliver direct air capture (DAC) of carbon at an industrial scale. According to the International Energy Agency (IEA), in 2020 there were 15 DAC plants operating worldwide, which captured about 10 000 t of CO_2 per year [2]. Today, that annual figure is closer to 14 000 t, but the IEA suggests that this capacity must reach 1×10^7 t by 2030 if the international community is to meet the climate goals of the Paris Agreement [2].

Currently, human activity is estimated to add approximately 4×10^{10} t of CO_2 to the atmosphere every year, of which the planet's natural systems can absorb about half [3]. And there appears to be little political will for supporting the rapid reductions—by all possible means—required to achieve the net-zero emissions by 2050 that the Intergovernmental Panel on Climate Change (IPCC) projects could limit global warming to 1.5 °C, or net-zero by 2070 to limit warming to 2 °C [4–6]. Indeed, the latest IPCC report, released 9 August 2021, finds that "unless there are immediate, rapid and large-scale reductions in greenhouse gas emissions, limiting warming to close to 1.5 °C or even 2 °C will be beyond reach" [7].

"We are bound to overshoot our climate targets," said Klaus Lackner, DAC pioneer and professor of sustainable engineering and director of the Center for Negative Carbon Emissions at Arizona State University in Tempe, AZ, USA. "As a consequence, we will need the large-scale ability to remove carbon directly from the environment—without also creating a horrible environmental footprint."

Besides the enormous cuts in emissions required, there is a growing consensus that mitigating climate change will ultimately also require a portfolio of negative emissions technologies, including DAC [8]. But the scale of the challenge facing the fledgling DAC industry was recently summed up by lead scientist Robert Rhode at the independent non-profit environmental science organization Berkeley Earth in Berkeley, CA, USA [9]: "Right now, DAC is like trying to bail out the Titanic using an eyedropper."

Besides Climeworks, another emerging player in the industry is Carbon Engineering, based in Squamish, BC, Canada. They have partnered with development company 1PointFive, based in Houston, TX, USA, on the engineering of what they anticipate will be the world's biggest DAC facility, at a site yet to be announced in the Permian basin area of West Texas. If all goes to plan, when it is operational—estimated by 2024—the plant is expected to capture 1×10^6 t of CO_2 per year. Carbon Engineering says the CO_2 will be "used in lower-carbon oil production, which permanently stores CO_2 as part of the process, and for geologic sequestration to deliver permanent carbon removal." Carbon Engineering also has plans for a similar facility in Scotland in the United Kingdom, to be developed in partnership with Storegga Geotechnologies, based in Aberdeenshire.

Fig. 1. Located next to the Hellisheiði Power Station in Hengill, Iceland, Climeworks' "Orca," a direct air capture of carbon plant, became fully operational in September 2021. Credit: Climeworks, with permission.

The most pressing need from the climate perspective is that global emissions must fall rapidly through, among other things, an urgent transition to renewable forms of energy [8,10]. One may also prevent CO_2 emissions by capturing it where it is created—at fossil-fuel-based power plants, for example—and sequestering or using it before it can enter the atmosphere. But in the decades to come, DAC advocates hope to make a difference by taking CO_2 out of the atmosphere in great quantities. To do that, its application needs to grow fast.

"I believe that DAC wants to be a mass-produced technology—it does not want to scale up, it wants to number up," said Lackner. "It is like photovoltaic (PV) technology, in the sense that there is nothing to be gained by being particularly large in an individual unit." Lackner is scientific advisor to Dublin, Ireland-headquartered start-up Carbon Collect, which has designed what it calls

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Mechanical Trees (Fig. 2). These 10 m tall units consist of stacked horizonal discs of a sorbent material. Ambient wind blows air across the discs, and the CO_2 binds with the sorbent. When the sorbent—in this case a resin—is saturated with CO_2, the tower concertinas down and seals into its base unit, where a change in the moisture levels or temperature causes the CO_2 to be released, allowing its capture [11]. Each Mechanical Tree will capture 1000 times more CO_2 than its natural namesake, Lackner claims. A full-size prototype of the latest version is due to be installed at the Arizona State University campus around the end of 2021.

Climeworks also takes a modular approach. Its units are stackable, like shipping containers (Fig. 1). The units pull in ambient air using fans, passing it through what the company calls "a highly selective filter material." When the filter material has taken in sufficient CO_2, the unit is closed, and the filter heated to about 100 °C, causing the release of the gas, which is then collected (Fig. 3). A key benefit of modularity, according to the company, is that units in production will always contain the very latest and most efficient technology. "The Orca plant is the second generation of the firm's technology," said Jan Wurzbacher, Climeworks co-founder and co-chief executive officer, at the Direct Air Capture Summit, an event organized by the company on 14 September 2021 [12]. "The third generation will lead us towards multi-megaton scale by the end of this decade. That is

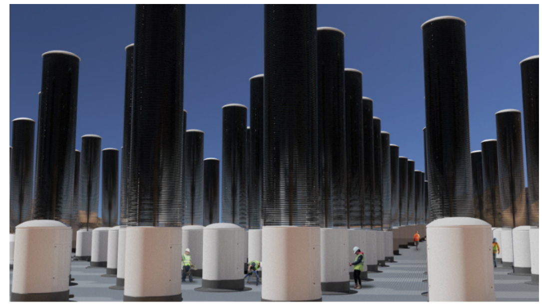

Fig. 2. An artist's visualization of Carbon Capture's Mechanical Trees. Each tree will contain an array of horizonal discs made of a sorbent resin which binds CO_2. When the disks have captured sufficient CO_2, the disks collapse down into the base, where they are induced to release the CO_2 for capture. Credit: Carbon Capture, with permission.

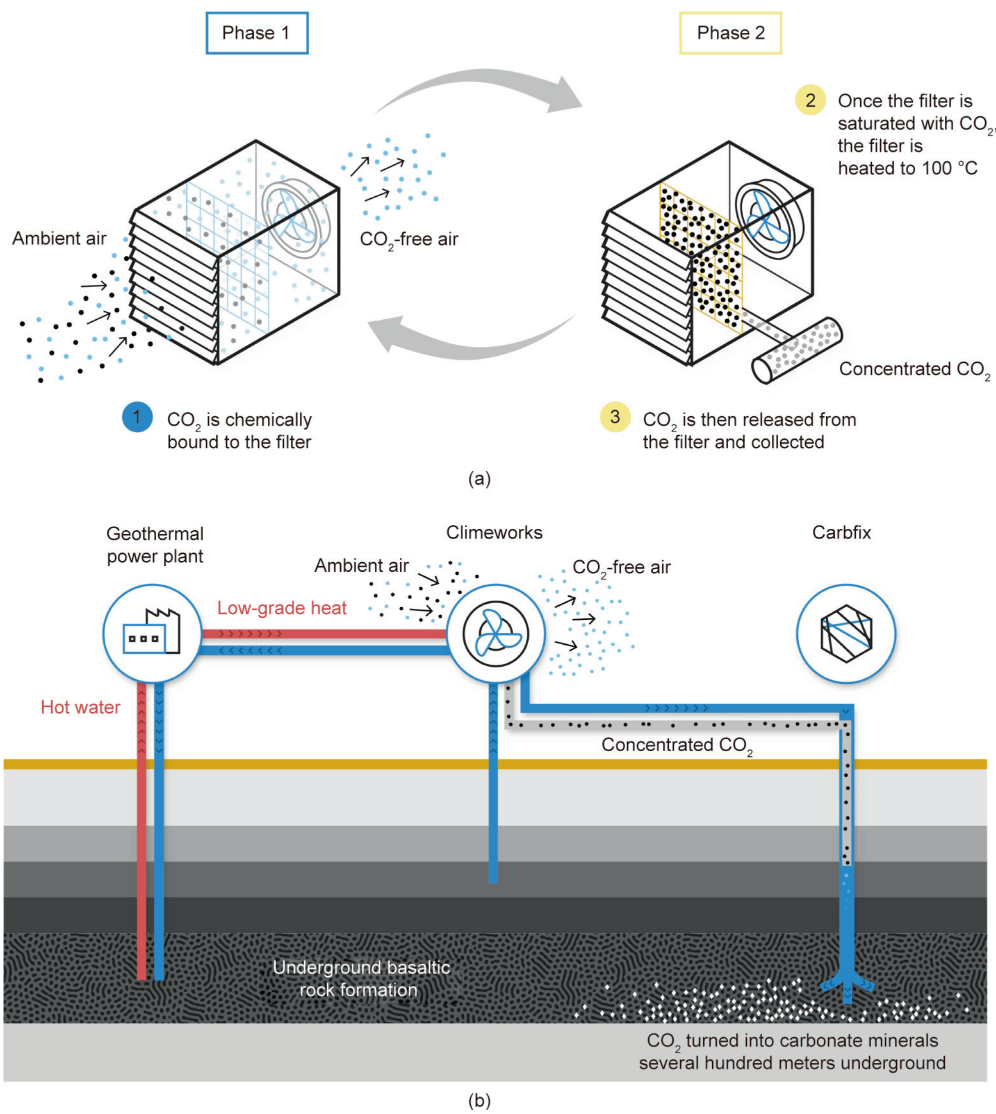

Fig. 3. (a) How direct air capture of CO_2 in the Climeworks Orca plant works in combination with permanent geological storage through mineralization. (b) The Climeworks process is powered by heat from a neighbouring geothermal power plant, and the concentrated CO_2 produced by Climeworks' Orca plant is pumped underground by partner firm, Carbfix. Credit: Climeworks, with permission.

the pace that will lead us, eventually, to gigaton scale by the middle of the century."

A key factor that will define the future of DAC is cost. Right now, DAC is expensive—prohibitively for most organizations. Climeworks is not saying how much its process costs, but its prices go as high as 1150 USD·t^{-1} of CO_2 permanently removed. The company has deals with some high-profile firms, such as Microsoft, which has announced plans to reach negative carbon emissions by 2030 and even remove its historic emissions from the atmosphere by 2050 [13]. And San Francisco, CA, USA-based Stripe, a payment platform, is paying Climeworks 854 USD·t^{-1} [14].

"At the moment we are seeing vanity purchasing by very cash-rich companies with relatively low CO_2 signatures. I welcome that, but it is not a replicable model," said Stuart Haszeldine, professor of geosciences and director of the Scottish Carbon Capture and Storage research group at the University of Edinburgh, UK. "If the price can be reduced down to $200 to $100 per ton, then you are within the price range of acceptability that will make it a very big business."

Lackner agrees: "When dealing with gigatons, nobody would be able to afford 800 USD per ton of CO_2. But if the cost of DAC technology follows the path of many other mass-produced technologies, such as PV, the cost should come down by about 20% for every doubling of production." His calculations suggest it would take investment of a few hundred million USD to "buy down" the price of carbon capture to the region of 100 USD per ton [15]. "But if it turns out that DAC does not follow that cost curve, and you spend 200 million USD to figure that out, that is still a very worthwhile lesson," Lackner said.

Some commentators worry that the energy requirements of proliferating DAC plants could end up being enormous [16]. Increasing the efficiency of the carbon capture process is paramount, said Lackner. "When you burn gasoline, you get 700 kJ of energy for every mole of CO_2 you produce. To extract CO_2 from the air you only need 22 kJ per mole, so the thermodynamic requirements are quite small. But nobody is close to that now because we are all beginners."

Another key element that will be required before DAC can scale to impactful levels will be the establishment of a regulated market for CO_2 disposal. What needs to be addressed urgently, said Haszeldine, is proof of capture and storage. "What is missing in all of the carbon markets around the world is the certification of long-duration storage of captured CO_2. Valid certification creates the value of the end point. Right now, we have a lot of voluntary carbon markets, where companies are saying 'If you give us money, we promise to find some way to avoid emitting a ton of CO_2.' But nobody knows how valid those promised outcomes are. Carbon offsetting is currently the Wild West, with virtually no regulation."

It will be impossible to become a net-zero world without a mature portfolio of negative emissions technologies, because even in the most optimistic climate scenarios, there are unavoidable carbon emissions, such as those from the aviation industry [8]. But climate optimism is in short supply, said Haszeldine. "By the time of the next review of the Paris climate agreement, in 2025, it will be too late."

"We are in a car going way too fast, and there is a bend coming," said Lackner. "At this point there is no question that we will hit the guard rail. The question is whether we will roll the car. We will have damage when this is done, so we need to start acting now to minimize that damage."

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