DIRECT AIR CAPTURE: RECENT DEVELOPMENTS AND FUTURE PLANS

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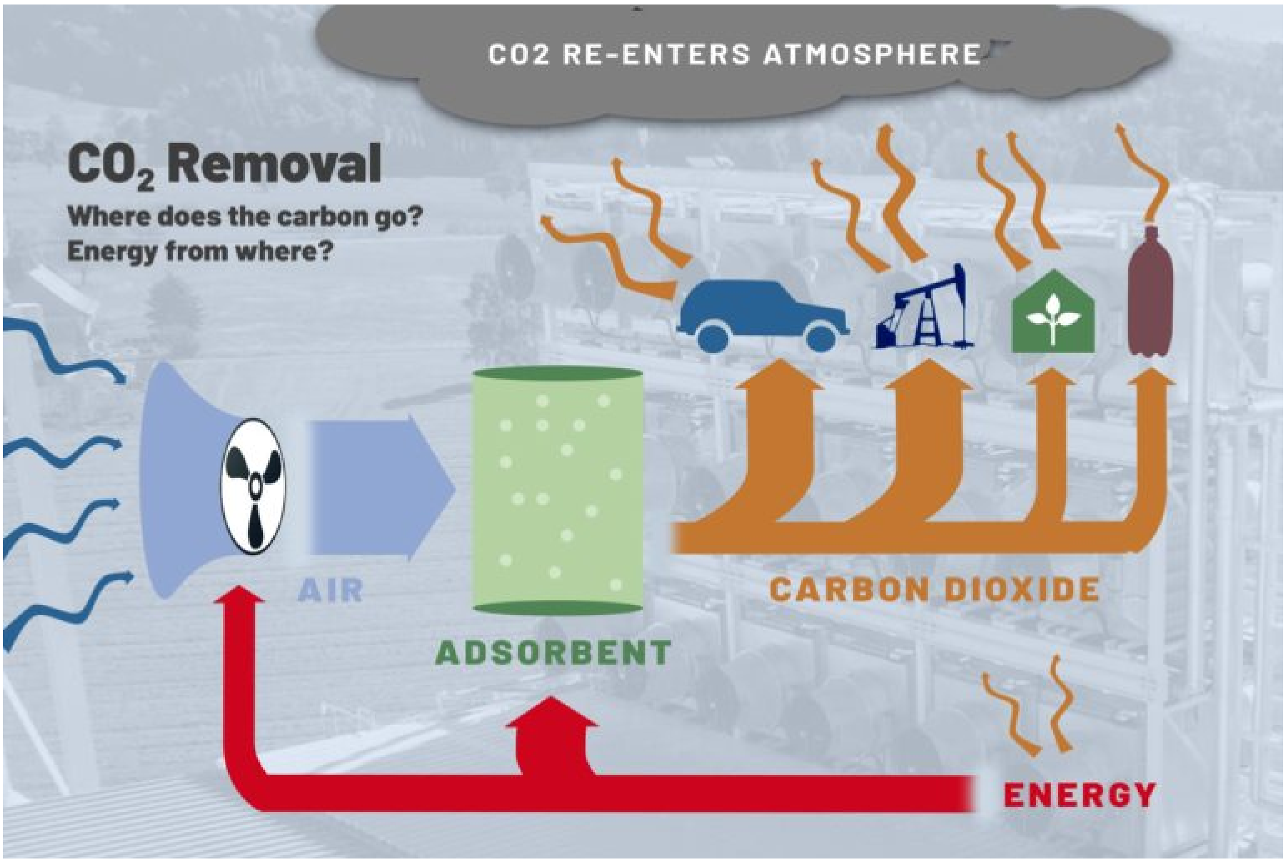

by Anja Chalmin

In the early 1990s, the European Space Agency launched a technology to extend space missions by filtering exhaled CO_2 out of the air on board of shuttles and space stations. During the past two decades, the technology – known as Direct Air Capture (DAC) – has been further developed, but in a different context: researchers are considering the technology as a means to remove CO_2 or other greenhouse gases from the earth's atmosphere.

Although little is known about the technology's efficiency, safety, economic impacts or the likelihood that it will actually reduce overall carbon emissions, several companies have already started marketing DAC as a climate solution, and propose capturing CO_2 as a feedstock for industrial uses. Among the marketing concepts: synthetic fuels, enhanced oil recovery, mechanical trees, and a sponge mountain.

INTRODUCTION TO DAC TECHNOLOGY

The technical approaches to capture CO_2 from ambient air involve a filter or absorbent. The Canadian startup **Carbon Engineering Ltd.** is using a strong hydroxide solution as a chemical absorbent. Amsterdam-based **Skytree** uses a plastic resin able to act as a CO_2 filter. Finland’s **Soletair Power** has developed a solid amine sorbent. Multiple uses of the filter or absorbent are possible in most cases. Once the filter is saturated, CO_2 can be isolated by applying heat. Swiss **Climeworks AG** has a filter that releases the captured CO_2 at 100°C. The Tennessee-based **Oak Ridge National Laboratory** has a method of bubbling air through a liquid sorbent; the CO_2 is subsequently released at 120°C.

Moving the air through the filter requires energy as well. Several firms capture CO_2 from ambient air by using large fans to push air through the filters, among them California-based **Global Thermostat**.

The **Center for Negative Carbon Emissions** (CNCE) in Arizona developed a synthetic membrane that absorbs CO_2 from dry ambient air. The membrane releases the CO_2 if exposed to high humidity or if wetted directly. Further technical approaches are under development, e.g. the Pennsylvania-based **National Energy Technology Laboratory** (NETL) investigates the electrochemical reduction of CO_2 with nanostructured metals.

PRICE DEVELOPMENTS AND ENVIRONMENTAL COSTS

Despite varied technical approaches, the providers of DAC technology are all racing to lower production costs. In 2018, **Carbon Engineering** published a research paper, calculating that DAC is possible for US$100 per tonne. It remains to be seen how the theory will be put into practice, as Carbon Engineering's chemical absorbent needs to be heated to ~900°C to release captured CO2. **Climeworks** is presently producing at ~ US$ 600 per tonne and plans to bring costs down to US$ 100 by the end of the decade. **Global Thermostat** explains that bringing down costs to US$ 100 per tonne is possible, if a cheap or free source of heat or energy is available, and adds that federal subsidies are just as important to lower costs of DAC.

Another point in common is that precise studies of present and future environmental costs of the technologies are not available. Every DAC process is energy-intensive. The **Climeworks** plant in Hinwil, Switzerland, needs 1.800 – 2.500 KWh of thermal energy and ~600 KWh of electricity to capture 1t of CO_2. One Climeworks collector can capture 50 tonnes of CO_2 per year, six collectors fit into one shipping container. More than 1.23 million shipping containers with six collectors each would be needed to capture 1 % of global annual emissions[1], as well as ~800 billion KWh of thermal energy and ~220 billion KWh of electricity (sufficient kWh to supply Canada with electric energy for a period of two years). This calculation does not yet cover the resources and energy input needed to produce, install and maintain the capture plants. , Details on the toxicity production and disposal of the CO2 filters or absorbents in use are not available.

ONGOING RESEARCH AND MARKET TRENDS

DAC actors are researching strategies for processing and marketing the captured CO_2. Most of the companies aim to produce synthetic fuels (which would in most cases produce new emissions, which would in turn need to be captured) and valuable chemicals.

Soletair

Power commissioned a demonstration facility in 2018. The facility combines DAC, an electrolyser for hydrogen production, and a synthesis reactor for hydrocarbon production. In 2018, the pilot plant operated 300 hours, producing 6.2 kg of oil and wax per day. Soletair's technology was developed by the VTT Technical Research Centre of Finland.

In 2019, the Swiss **Synhelion** started testing a small refinery in Zürich. The demonstration project uses solar energy to extract CO_2 and water from ambient air and to split them into hydrogen and carbon monoxide at 1,500°C. The syngas mixture can afterwards be processed into hydrocarbons such as kerosene or methanol. According to Synhelion, a photovoltaic system with an area of 1 km^2 could produce 20,000 litres of kerosene a day.

The German **Sunfire GmbH** opened a Power-to-Liquid plant and developed an electrolysis system for the production of syngas, in 2014. The process needs electricity for high-temperature electrolysis of water and CO_2. To convert syngas to so-called "Blue Crude" fuel, Sunfire uses the Fischer-Tropsch process. Blue Crude can be further processed to produce fuels as methane or diesel. In 2015, the first batch of diesel fuel was produced. The CO_2 – DAC capture technology used by **Synhelion** and **Sunfire** was provided by **Climeworks**.

The European Union's Horizon 2020 research and innovation programme is investigating the potential for producing synthetic gas and fuels from captured CO_2 with renewable energy as well as energy storage options. The currently running **SUN-to-LIQUID** research project established a demonstration plant at the IMDEA Energy Institute, near Madrid, to enhance and validate the production of kerosene from captured CO_2 with solar energy. The project **STORE&GO** is carried out by 27 European project partners and involves three pilot sites, where different power-to-gas technologies are tested and developed. The pilot plant in Troia, Italy, captures up to 150 tonnes of CO_2 per year and generates up to 240 m³ of hydrogen per hour. A power-to-gas methanization unit turns hydrogen into methane, afterwards the methane is liquefied at -162°C. The objective of the project is producing liquefied fuel for natural gas tanks, e.g. for trucks or ships, without depending on pipeline access.

Another approach being explored and commercialized, e.g. by **Climeworks**, **Skytree** and **Infinitree**, is the use of captured CO_2 as a fertilizer in greenhouses. The American company **Infinitree LLC**, founded by its parent company Carbon Sink (former Kilimanjaro Energy, former Global Research Technology), is commercializing a CO_2 capture system for use in greenhouses: CO_2 is captured from ambient dry air and released inside greenhouses with high humidity.

Global Thermostat aims at selling captured CO_2 to soda companies. **Climeworks** recently started exploring this marketing channel in the framework of two collaborations in Switzerland: Climeworks CO_2 – DAC technology will be used for the **Coca-Cola** brand “Valser”, and for filling gas bottles for sparkling water dispensers manufactured by the company **Carbagas**.

In addition, **Climeworks** is offering travel emissions offsets with its DAC technology storing the captured CO_2 underground in Iceland at the **CarbFix** project site. The CarbFix project is a combination of DAC with Carbon Capture and Storage (CCS). The approach involves capturing CO_2 and H_2S at the Hellisheidi Geothermal Power Plant, nearby Reykjavik. The CO_2 is dissolved in water under pressure, and the solution is injected into basaltic formations nearby the plant, at 400 m to 800 m depth, with the aim of storing the gas in mineral form in the bedrock.

SOURCES OF FUNDING

The DAC sector receives funding from private investors and public sources. In most cases, the list of private sponsors is not fully disclosed, or not disclosed at all. For this reason, the below Table 1 can only offer a brief insight, but not a comprehensive overview on private investments. The influence of public funding and research on the DAC sector is displayed in Table 2.

Table 1: Information on private investment

Company	Links to research programs and institutions
Carbon Engineering	During the foundation years, the company received funding through public projects and CAD$ 30 million from private sources, among them Bill Gates and Alberta-based tar sands mega-investor Murray Edwards. Since 2018, Carbon Engineering has raised more than CAD$ 80 million from multiples investors, among them Occidental Petroleum, Chevron Technology Ventures and the Australian mining company BHP (US$ 6 million).
Climeworks	In 2018, the start-up secured € 30.5 million from old and new investors during its fourth round of funding. Since its foundation, Climeworks received over € 50 million in total from investors to commercialize the DAC system.

Global Thermostat – Pilot project	Among the private funding sources are: Corning Technology, Edgar Bronfman Jr., Georgia Tech, NRG, SRI International, US Energy Company, and Vice Media. Public funding was provided by the US Department of Energy (US$ 2 million) and the New York State Energy Research and Development Authority (US$ 0.25 million). In 2010, Global Thermostat raised US$ 29.5 million for its pilot plant. According to press reports the company raised more than US$ 70 million in total.
Global Thermostat – Commercial project	In 2017, Global Thermostat raised US$ 42 million for the construction work.
PrometheusFuels	The company was founded in 2018 and aims to produce fuels based on CO_2 – DAC. PrometheusFuels demonstrated its technology at the **Y Combinator** demonstration day. Shortly thereafter, the company had raised sufficient funds to hire staff and start building a single prototype machine.
Skytree	The company received funding from various sources, including Jaguar Land Rover. Skytree raised € 0.16 million, after participating in a startup-bootcamp in Amsterdam, in 2014.
Soletair Power	The company is supported by several Finnish and German industrial partners. In 2019, Soletair Power received € 0.5 million of funding from the energy technology group Wärtsilä.

Sunfire	The company received funding from various sources, including Audi, and in various funding rounds. Sunfire secured € 25 million during its first funding round in 2019.

Table 2:
Links between publicly funded DAC research and commercialization

Company	**Links to research programs and institutions**
Carbagas	Spin-off of the ETH Zürich.
Carbon Engineering	Founded by David Keith (Harvard University).
Climeworks	Spin-off of the ETH Zürich. Participant in the European **CarbFix** (2011-14, ~€ 2.2 million) and **CarbFix2** (2017-21, ~€ 2.2 million) projects. Participant in the European **CELBICON** project (2016-19, ~€ 6.2 million). Participant in the German research project **Kopernikus** (2016 – 19, € 30 million). Participant in the Swiss **Power-to-Methane** project (2015-17). Participant in the European **STORE&GO** project (2016-19, ~€ 28 million). Participant in the European **SUN-to-LIQUID** (2016-19, ~€ 6 million) and the preceding **EU-SOLAR-JET** (2011-15, ~€ 3 million) project.
Coca-Cola & Climeworks	The collaboration was prepared by the EU-funded research project “CAPDrinks” (2016-17, ~€ 1.07 million).

Silicon Kingdom Holdings	Obtained the right to commercialize DAC technology developed at the **Centre for Negative Carbon Emissions**, Arizona State University.
Skytree	Spin-off of the European Space Agency.
Soletair Power	R&D activities at the Finish Lappeenranta University of Technology; DAC method developed by the public VTT Technical Research Centre of Finland.
Sunfire	Participant in the German research project **Kopernikus**.
Synhelion	Spin-off of the ETH Zürich. Participates in the European **SUN-to-LIQUID** project.

NEW PLANS AND PROJECTS IN PREPARATION

In recent weeks, several new projects have been announced.

In Reykjavík a Letter of Intent was signed for thoroughly investigating the technical and financial suitability of the **CarbFix** method for large emitters in Iceland. The signatories aim to design and construct experimental equipment for CO_2 capture from flue gas (DAC) and for CO_2 injection underground (CCS), followed by the construction of larger-scale technology. The letter was signed by the Prime Minister of Iceland, Reykjavík Energy, the Aluminium and Silicon Industry in Iceland (Elkem, Fjardarál, PCC and Rio Tinto), and the Ministries for Environment and Natural Resources, for Industries and Innovation, and for Education, Science and Culture.

Carbon Engineering & Oxy Low Carbon Ventures LLC announced their joint plan to design and construct the world's largest DAC and CO_2 sequestration facility in the Permian Basin (Texas, New Mexico). Oxy Low Carbon Ventures is a subsidiary of the international gas and oil company Occidental, the largest oil producer in the Permian Basin. The plant will be located at an Occidental oil field; the exact location has not yet been decided. The captured CO_2 will be used for Enhanced Oil Recovery (EOR). Occidental employs EOR since 2010, but up to now, the captured CO_2 needed transport, e.g. via pipelines. Presently, the partners are evaluating a DAC plant with a capture capacity of 0.5 million tonnes of CO_2 per year. Future plans include multiple DAC plants with twice the capacity.

The **Rotterdam Jet Fuel** cooperation was signed by the Rotterdam The Hague Airport and an European consortium. The partners aim to develop a demonstration plant with solar energy supply and an annual production of ~0.36 million litres of jet fuel. **Climworks** will provide the CO_2 capture technology, **Sunfire** an electrolyser to transform the captured CO_2 into syngas, and the German Ineratec GmbH the technology to turn syngas into synfuel by Fischer-Tropsch synthesis. The German "EDL Anlagenbau Gesellschaft mbH" will be responsible to convert synfuel to jet fuel, and the Dutch SkyNRG for the commercialization.

The Norwegian **Nordic Blue Crude AS** released its plan to produce synthetic fuels and other fossil replacement products already in 2017. The company plans the development of ten commercial production sites in Norway, starting with the "E-Fuel 1" – site in Heroya industrial park, Porsgrunn, to be commissioned in 2020. **Climworks** will provide the CO_2 capture technology, **Sunfire** the technology to produce Blue Crude fuel.

Rob McGinnis, the founder of **PrometheusFuels**, announced a partnership with Boom Supersonic. The aircraft company plans using the Prometheus fuel for its airline.

Synhelion & ENI, an Italian oil group, announced their first joint commercial plant for 2025. The partners plan to produce methanol from captured CO_2 and water. The plant will be supplied with solar energy; a solar reflector with a surface of 0.16 km^2 has been announced.

Silicon Kingdom Holdings (SKH) aims to commercialize and "plant" 1,200 mechanical trees for carbon capture. In May 2019, the company obtained the rights to commercialize the DAC technology developed by **CNCE**. SKH has started designing its pilot plant and is presently looking at possible project sites in Arizona and California. At pilot-scale, 1 "trees", is expected to capture ~2.5 tonnes of CO_2 per year. The DAC devices will be up to 10 m high and expose ~150 sorbent-filled discs, each with a diameter of ~1.5 m. After 20 minutes of exposure to ambient air, the discs are saturated with CO_2. Discs return into the base of the column, where CO_2 is released, either by heat or humidity.

The architect Angelo Renno proposed a 90-metre-high "**sponge mountain**" for CO_2 capture in Turin, Italy. The mountain could be formed out of 6 million tonnes of soil excavated during the construction of the 170-km railway tunnel planned between Turin and Lyon (France).

Engineered soil, a mix of sand and concrete, would be added to absorb CO_2. The artificial mountain would cover an area of 11 ha and could, according to proponents, be used as a recreation park at the same time.

By 2025, **Climeworks** aims to capture 1 % of the annual global CO_2 emissions and states that 0.75 million shipping containers with six DAC collectors each would be needed to fulfil this goal. According to figures from the European Commission[1] for 2017, this number of shipping containers would only be sufficient to capture 0.6 % of global annual anthropogenic fossil CO_2 emissions. The annual amount of energy required (618.8 billion KWh), to run 0.75 million shipping containers with DAC collectors would supply more than 75 % of EU-28 citizens with electricity for a period of one year (average consumption 1.584 KWh/capita).

OUTLOOK

Companies, involved in Direct Air Capture (DAC), have to face several challenges:

- **Production costs:** With costs at US$ 600 per tonne of captured CO_2 or even more, the technology is not economically viable. Lower costs for DAC were only proven theoretically and theory was not yet put into practice. The theoretical proof was published in a research paper compiled by Carbon Engineering in 2018. The main evidence supporting lower costs was, in other words, published by researchers with a financial interest in commercializing their DAC technology and receiving funding to do so.
- **Commercialization:** Already-existing markets for CO_2 – among them the beverage industry (sparkling water), food industry (inert gas for food packaging), and some greenhouse producers (fertilization) – are rather small. These markets can be easily saturated with CO_2 originating from far cheaper sources. Among other examples, CO_2 is a decomposition product from lime burning. Enhanced Oil Recovery is not economically feasible at costs of US$ 600 per tonne of captured CO_2. This means the DAC sector has to develop new and financially attractive markets, to ensure its survival. In the last years there has been increasing research into replacing crude oil. DAC promoters argue that this market is huge (fuels, plastics, further materials) and would allow DAC on large scale. This line of argument attracted large amounts of funding during the past months.
- **Fundamental environmental concerns:** DAC technology captures CO_2 at high costs. The technology itself needs various inputs to be

produced, sufficient space and maintenance, and the CO_2 capture process itself is very energy intensive. In the end, the final product of the DAC process, the CO_2, is used for various consumer products and the captured CO_2 usually re-enters into the atmosphere. The very likely overall result is that more CO_2 has entered the atmosphere due to the large amounts of energy used for the DAC process.

RESOURCES FOR FURTHER INFORMATION:

Geoengineering Monitor: http://www.geoengineeringmonitor.org/2018/05/direct-air-capture/ – further information and background on Direct Air Capture and further climate geoengineering technologies, research, experimentation and implications

Interactive Geoengineering Map: https://map.geoengineeringmonitor.org/ – contains details and references for the above mentioned (highlighted in bold characters) and further climate geoengineering projects

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Based on 37.1 Gt of global annual anthropogenic fossil CO_2 emissions in 2017. Source: European Commission (M. Muntean, et al.: Fossil CO_2 emissions of all world countries. 2018 report.). 37.1 Gt are excluding further CO_2 emissions, such as land-use change emissions and further greenhouse gas emissions, such as N_2O or CH_4.