QUARTERLY REVIEW #2: DIRECT AIR CAPTURE

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By Anja Chalmin

Current developments on geoengineering technologies across six continents

Part 3 of this quarterly review on geoengineering presents new technical developments and funding programmes and reports on a number of long-standing projects.

DIRECT AIR CAPTURE (DAC): NEW PUBLIC FUNDING PROGRAMS TRY TO MAKE DAC TECHNOLOGY MORE EFFECTIVE AT CAPTURING CARBON, LESS POLLUTING, AND LESS ENERGY INTENSIVE

The British Greenhouse Gas Removal Programme was launched in 2017 and aims to increase knowledge of the means to remove greenhouse gases from the atmosphere at a climate-relevant scale. In May 2021, 24 new projects were selected to participate in the programme, among them the following DAC projects:

- The programme granted £ 0.25 million in funding for R&D to Carbon Engineering and Pale Blue Dot Energy. In June, the partners started the engineering and design works, aiming to make Carbon Engineering's DAC technology more energy-efficient. Carbon

Engineering, a company founded by David Keith (Harvard University), developed a method to absorb CO_2 directly from air: A strong hydroxide solution acts as chemical absorbent. The liquid solution captures CO_2 and converts it into carbonate. In the following step, the carbonate solution is dried and transformed into small pellets of calcium carbonate. When heated to more than 900°C the pellets release the CO_2 and leave calcium oxide (CaO) behind. The entire CO_2 capture process requires more than 1.300 kWh to capture one tonne of CO_2. This is equivalent to a quarter of the average annual per capita consumption of electricity in the UK.

- The programme also granted support to a project that aims to develop a cost-effective, membrane-based DAC approach. The project is led by the Dutch CO2CirculAir and conducted in cooperation with the London-based Oil and Gas Technology Centre and the Research Centre for Carbon Solutions at Heriot-Watt University. The project partners plan to design a pilot plant with the capacity to capture 100 tonnes of CO_2 annually. The technical approach is not new, DAC with membranes was already researched in the 90s, e.g., by the pan-European project "Membrane technology for low CO_2 power generation".
- The UK-based Rolls-Royce and the Australian CSIRO (Commonwealth Scientific and Industrial Research Organisation) were granted support to develop an efficient and cost-effective DAC approach. The project aims to design a pilot plant in the U.K., with the capacity to capture 100 tonnes of CO_2 annually. There is no reference to the envisioned DAC concept in the funding announcement. However, Rolls-Royce describes the possibility of performing DAC with nuclear energy and hopes to use captured CO_2 for synthetic fuel production.
- The British Carbon Neutral Petrol Ltd. was granted support to complete a business plan and a feasibility study to scale a modular DAC approach. Information on the envisioned DAC concept is not yet available. However, the company plans to use the captured CO_2 as a feedstock for plastics, building products and fuels.

In June 2021, the U.S. Department of Energy announced six grant projects to be funded with a total of US$ 12 million. The associated call for proposals, number DE-FOA-0002481, *"Materials and Chemical Sciences Research For Direct Air Capture Of Carbon Dioxide"* was published in March. The selected projects are expected to increase the amount of CO_2 captured by DAC and to decrease the energy consumption and costs of DAC:

- Cormetech Inc., North Carolina, developed CO_2 capture technology with an amine-based sorbent. The grant will be used to further develop and improve the approach, aiming to maximize the amount of CO_2 captured from the atmosphere, while reducing the amount of energy needed to operate this DAC system.
- The Research Triangle Institute, North Carolina, was awarded funding to design and test more cost-effective CO_2 capture solutions for the cement industry.
- Susteon Inc., North Carolina, aims to develop more cost-effective and longer-lasting solid sorbent materials for DAC. The company was already awarded funding for DAC research in the 2020 funding round under the funding opportunity announcement "*Novel Research and Development for the Direct Capture of Carbon Dioxide from the Atmosphere*".
- The University of Illinois aims to develop three preliminary designs for large-scale DAC operations "*and work with partners to perfect the designs to permanently store CO_2 at underground facilities in Wyoming, Louisiana and California*". The partners and exact locations for the three DAC and CO_2 injection sites have not yet been declared.
- The Black & Veatch Corporation, a global engineering, consulting and construction company, aims to develop initial engineering designs for three large-scale DAC operations, placed in Odessa, Texas; Bucks, Alabama; and Goose Creek, Illinois. The exact locations for the three DAC sites have not yet been disclosed. Global Thermostat's DAC technology will be employed at all sites. The DAC technology developed by the American company Global Thermostat is based on a chemical sorbent.
- The Carbon Collect Ltd., Ireland, aims to develop initial designs for three commercial-scale DAC operations, aiming to capture 0.3 million tonnes of CO_2 annually. Details on the project partners and the exact locations of the three DAC projects have not yet been disclosed. Carbon Collect Ltd., former Silicon Kingdom Holdings Ltd., aims to commercialize and "plant" mechanical trees for CO_2 capture. The DAC technology, a synthetic membrane that absorbs CO_2 from passing air when dry and releases CO_2 if immersed in water, has been developed at the Arizona State University. Carbon Collect Ltd. obtained the rights to commercialize the technology and started designing a pilot plant – a metal column with discs made of sorbent material. The device is up to 10 meters high and contains ~150 sorbent-filled discs, each with a diameter of ~1.5 meters. After 20 minutes of exposure to (moving) air, the discs are saturated with CO_2 and return into the base of the column, where CO_2 is released either by exposure to heat or humidity. Carbon Collect Ltd. plans to

deploy MechanicalTrees™ farms, e.g., capturing ~3.65 million tonnes of CO_2 per year. Such a farm would consist of 120,000 metal columns, requiring 2 to 3 km² of land area. This DAC approach has been researched since the 1990s and the inventors have been trying to commercialise the technology since 2004. Several companies have already been founded for this purpose, which have disappeared or have been renamed.

FURTHER CURRENT DEVELOPMENTS FROM VARIOUS FIELDS OF GEOENGINEERING

- **Australia:** The commissioning of the Australian Gorgon CCS project, operated by Chevron, was subject to the condition, that Chevron must capture and inject at least 80 % of the CO_2 emissions released at the plant over a five-year period starting in July 2016. Gas production began in 2016 and CCS activities began only three years later due to extensive technical problems. In January 2021, it became known that the CO_2 injection system was clogged with sand. The Conservation Council of Western Australia demanded that the government "*shut the [LNG] plant until [Chevron] can demonstrate its CCS was working*". Whether and what consequences non-compliance with the condition will have for Chevron is still unclear. So far, the CCS project received at least AU$ 60 million in public funding.
- **USA:** In June 2021, the California-based Holy Grail Inc. raised US$ 2.7 million to advance its DAC concept. The company aims to develop a cost-effective and electricity-based DAC system. The approach involves air flowing through a positively charged cathode, where CO_2 molecules are ionized and transported from the cathode to the anode. No information is yet available on the energy consumption of this technical approach. A similar approach has already been developed at the Massachusetts Institute of Technology, with an energy input of about one gigajoule per tonne of CO_2 captured – that's about 20 % of the amount of energy required by the Carbon Engineering process. So far, the MIT approach has not been successfully commercialised.
- **Israel/Germany/sub-Saharan Africa:** In April 2021, the Israeli High Hopes Labs Ltd., with a subsidiary in Stuttgart, Germany, tested a new DAC approach. The company's goal is to attach DAC technology to high-altitude balloons and send them to altitudes of 10 to 15 km. There, the CO_2 is first to be separated and then – at a freezing point of -80°C – frozen as dry ice. The dry ice is to be collected in a tank and enclosed. The company explains, that back on earth, the CO_2 becomes gaseous again, but because of the closed container it cannot expand, so it is compressed and thus

ready to be pumped underground for storage. The balloon is supposed to use hydrogen as its energy source. The High Hopes Lab estimates that a balloon needs to remain in the air for 12 to 24 hours to collect one tonne of CO_2. The full tank is then exchanged for an empty one and the process starts anew. The company has built and tested various small-scale balloons. In April 2021, a DAC-test was conducted in Germany, during which the balloon flew about 16 km high. In 2022, the company plans to increase the size of the experimental setup and capture 50 to 100 kg of CO_2 per day. By 2024, each balloon is expected to capture one tonne of CO_2 per day. For a large-scale implementation, the company is looking for suitable locations – with optimal air conditions and minimal air traffic – in sub-Saharan Africa.

- **Chile:** The Haru Oni project, Chile, aims to produce synthetic fuel from captured CO_2 and water. According to this press statement the DAC technology will be provided by Global Thermostat.
- **Oman:** The Omani company 44.01, the company name derives from CO_2's molecular mass (44.01 g/mol), aims to permanently mineralize captured CO_2 in peridotite rocks in Oman. Peridotite reacts with CO_2 and water and forms the mineral calcite. To accelerate this years-long process, highly carbonated water is to be injected through targeted boreholes into the rock. 44.01 plans to mineralise one billion tonnes of CO_2 per year by 2030 and hopes to finance the project through carbon credits. To obtain captured CO_2, the company sought cooperation with DAC technology companies. Since 2021, Climeworks and 44.01 are jointly testing the combination of Climeworks' direct air capture technology with geological storage of CO_2 in Oman. The Swiss company Climeworks AG, founded in 2009, develops and markets DAC technology.
- **UK:** A biochar research project, led by the University of Nottingham and financed by the UK Research and Innovation fund, aims to demonstrate and trial biochar at scale. The four-year project plans to produce 200 tonnes of biochar from wood and/or organic wastes and to distribute this amount of biochar on 12 hectares of arable fields, grasslands and forests in the UK Midlands and Wales. Ten one-hectare plots will be established on ten farms, and biochar will be applied to 50 % of the land per farm to study any notable variations. The researchers also aim to investigate how much carbon remains in the soil or returns to the atmosphere.
- **USA:** The company Heirloom Carbon Technologies, California, aims to develop an enhanced weathering approach based on mineral carbonates, such as magnesite ($MgCO_3$): At high temperatures, up

to 1,200 °C, the carbonate is heated (= calcined), causing it to break down into oxides (MgO) and release CO_2. The CO_2 thus separated is captured. The oxides are again brought into contact with air to carbonate them again. Afterwards, they can again be calcined. For the carbonation process, the oxides are spread on land, in layers ~10 cm thick. According to the company, this layer needs to be stirred daily and remains on the land for about one year, in order to react with atmospheric CO_2. Afterwards, the carbonates are collected, calcined, and the cycle is repeated. Heirloom Carbon Technologies suggests to store the captured CO_2 in geological reservoirs or in mineralized form. If this approach were to be implemented on a large scale, it would consume large land areas and huge amounts of energy.

- **USA:** In 2021, a research team at Purdue University revealed an "*ultrawhite*" paint which reflects more than 98 % of the sunlight. The high solar reflectance of the paint is achieved by adding the pigment barium sulphate ($BaSO_4$), a pigment that even reflects ultraviolet light. The researcher states that the new paint "*offers great promises to […] alleviate the global warming*", adding that the paint has the potential to "*reduce the global warming by reducing the CO_2 emission for cooling applications*". Due to the high $BaSO_4$ content in the paint, large-scale application of the paint would require large amounts of $BaSO_4$. These would have to be obtained by mining the mineral barite. No information is yet available on the ecological footprint of the paint or its durability, but scientists at Stanford University suggested "*roofs covered in photovoltaic panels would do a better job, by producing electricity that then obviates the need for more fossil fuel–burning power plants*". The idea of whitening roofs is not entirely new. As part of the CoolRoofs initiative, the city of New York has covered 50 hectares of its roofs with a bright, reflective coating, aiming to increase albedo, create a cooling effect and combat global warming. However, studies have shown that even if applied on a large scale, the efficiency would be low and the overall costs very high.
- **USA:** Stripe, a San Francisco based e-commerce platform and software company, announced its Stripe Climate program in 2020. The program aims to offset greenhouse gas emissions by purchasing carbon offsets and investing in so-called carbon storage projects. In May 2021, Stripe decided to support CarbonBuilt (please see chapter 2) with US$ 0.25 million for carbon removal. In 2020, Stripe paid Charm Industrial to store 416 tonnes of CO_2 at US$ 600 per tonne. In April 2021, Charm Industrial announced that these 416 tonnes of CO_2 were pumped underground in the Permian Basin – the exact place has not yet been disclosed. Charm Industrial aims

to capture and store CO_2 by transforming biomass in a pyrolysis process (500°C, no oxygen present) into biochar and oil and by injecting the pyrolysis oil into geological storage sites. The company is looking for further wells, e.g., in Kansas and Oklahoma – with suitable geology for injections and large quantities of farm waste for biochar production. There are no studies on the environmental footprint of the entire process, including pyrolysis, the origin, growth and handling of biomass, as well as the handling of the pyrolysis oil such as transportation and injection into geological storage sites. There are also no studies on the long-term behaviour of the pyrolysis oil after injection into geological sites.