Technologies for Direct Air Capture of CO2

Direct Air Capture (DAC) offers a way to mitigate CO2 emissions already in the atmosphere, with the carbon dioxide stored either underground or converted into useful chemicals or materials. Stephen B. Harrison, sbh4 consulting, reviews some of the companies developing commercial DAC solutions.

The worldwide dependency on fossil fuel energy has led to a steady increase in the carbon dioxide (CO2) concentration in the atmosphere in the past 250 years from about 250 ppm to more than 400 ppm. This increase in anthropogenic CO2 concentration is the root cause of the global warming mean temperature increase, which our planet is experiencing. To limit this temperature increase, fossil CO2 emissions into the atmosphere must be reduced to the point of 'net-zero'. Direct air Capture of CO2 can help to accelerate this transition.

Carbon dioxide itself is not harmful to humans, up to a certain concentration. But the steady increase in atmospheric CO2 concentration harms our environment. CO2 removal from the atmosphere is mainly through natural biological processes, in particular photosynthesis in plants where the CO2 is converted to starchy hydrocarbons. Given sufficient time, this process can bind atmospheric CO2 to form other gaseous, liquid, or solid forms of hydrocarbons – most of our fossil resources like oil, gas, and coal were plants million years ago.

Various mechanical direct air capture (DAC) processes have been developed to simulate the action of plants and capture CO2 directly from the air. In the past decade tremendous amount of research has been undertaken to scale up and commercialise these technologies. Each emerging technology has its own advantages, and they are currently at different levels of maturity.

The theoretical minimum specific energy demand for DAC is 150 kWh/Tonne of CO2, but all real-world process operate at a multiple of several times this value. The development challenge is to come as close to this theoretical minimum as possible. The updates presented here highlight several companies and technologies that have made progress in this direction.

Climeworks

Climeworks was founded in 2009 as a Spin-Off from the ETH Zürich. In 2019 they acquired their Dutch competitor Antecy and incorporated their know-how on adsorption. The Climeworks DAC equipment operates a cyclical batch process.

In the first step air is blown through a collector with the help of a fan. Much of the CO2 from the air is captured on the amine-based solid adsorbent in the collector. The CO2 concentration in the exhaust is significantly reduced, but CO2 is not fully captured. Once the adsorbent material is saturated, the collector is heated up to 80°C to 100°C. This releases the CO2 from the solid sorbent. The high purity carbon dioxide is collected and can be processed or sequestered.

Each Climeworks collector can capture up to 50 Tonnes of carbon dioxide per year, assuming a capacity factor of close to 100%. The actual performance is impacted by several parameters, including the ambient conditions and weather at the installation site.

The specific energy demand is 2,000 kWh/Tonne CO2 of low-grade heat and 650 kWh/Tonne of CO2 for electricity, which is mainly required to operate the fan that draws air across the sorbent material. Despite the heat demand being quite large, an advantage of the process is that it only needs heat at low temperature. If this can be recovered as waste-heat from an adjacent chemical or thermal process, the total primary heat demand can be significantly reduced.

Climeworks has sold or operates more than 14 DAC systems of various sizes worldwide. The largest project, with an annual capture capacity of 4,000 Tonnes of CO2, is under construction in Iceland. The captured CO2 will be permanently stored underground when the gas is mineralised to carbonates using the innovative Carbfix process. Heat and power for the system will be supplied from a geothermal power plant to ensure a negative carbon footprint to the overall scheme.

CarbonEngineering

The Canadian-based company, Carbon Engineering was also founded in 2009. Their four-step process starts with a contactor where air is continuously pulled through a large tower and chemically reacts with a potassium hydroxide solution to yield potassium carbonate ($CO_2 + 2KOH \rightarrow K_2CO_3 + H_2O$). In the second step the aqueous potassium carbonate is mixed with calcium hydroxide in a pellet reactor at ambient temperature. This regenerates the potassium hydroxide solution and creates calcium carbonate pellets ($K_2CO_3 + Ca(OH)_2 \rightarrow 2KOH + CaCO_3$).

In the next step the calcium carbonate is thermally decomposed in a classical Calciner at 900°C. This is like the production of lime or cement and releases carbon dioxide

($CaCO_3 \rightarrow CaO + CO_2$).

Unlike classical calciners, the carbon dioxide is not released into the atmosphere, but separated and the resultant high purity carbon dioxide is available for utilisation or sequestration.

The remaining calcium oxide is hydrated in a steam slaker at 300°C ($CaO + H_2O \rightarrow Ca(OH)_2$), and the regenerated calcium hydroxide is fed back into the pellet reactor in step two above.

The specific energy demand varies, depending on the Calciner operating temperature. The total specific energy is around 1,850 kWh/Tonne of CO2 if operated with natural gas heating, or approximately 1,500 kWh/Tonnes CO2 if renewable electricity is used instead of natural gas.

This is a comparatively low specific energy

Geothermal power is ideal to be combined with some DAC technologies

consumption, but the operating temperature is high and the potential to use of waste heat is therefore low. Furthermore, water evaporation within the large air contactor can be very high in dry climate zones. This continuous loss of water must be considered in a full lifecycle analysis.

Carbon Engineering operates a demonstration plant in Canada. A large demonstration plant in the Permian Basin, Texas has been announced, where the captured CO2 will be used for enhanced oil recovery of depleted crude oil fields.

Verdox

A completely different approach to DAC has been implemented by Verdox. The underlying technology developed by Dr. Sahag Voskian at MIT utilises electrochemical cells to capture CO2 from the atmosphere during charging, and releases CO2 when the cells discharge.

The symmetric cells consist of a quinone–carbon nanotube composite. Quinones change their characteristics when an external voltage is applied. This feature is utilised to adsorb CO2 onto the cells in the charging phase.

Several different types of cell have been tested under lab scale conditions to determine their long-term efficacy. The best performing cells have shown a degradation of 30% over 7,000 cycles, which corresponds to just less than 6 months of operation when using a cycle time of 30 minutes.

From a technology maturity perspective, the challenge for this process is to reduce the degradation rate. But the benefits may justify the efforts because the specific energy demand at the cell level is just 568 kWh/Tonne of CO2. If the degradation rate can be reduced by an order of magnitude and thereby extending the cell lifetime to several years, this technology will have great potential.

Verdox has received US$500,000 of funding within the ARPA-E scheme to build a prototype which will be operational in 2022.

Carbyon

Carbyon from the Netherlands, a Spin-Off from TNO, is taking yet another path to innovate an efficient DAC technology. The proposed process is derived from photovoltaic research. It is based on a porous thin-film which is coated with amine- and/or bicarbonate-based adsorbents.

The combination of this thin-film, which is only a few microns thick, and a porous medium could prove to be very energy efficient. The pressure-drop for air to cross the thin, porous medium is very small and the thermal mass of the thin film is low. These factors result in a very low heat demand for the process to capture CO2. The CO2 will be released at a temperature in the range of 65°C to 85°C from the solid-state sorbent.

The company was founded in 2019 and a first demonstration unit is expected to run this year, in 2021. The features of this new approach are very promising, but they must be confirmed at scale.

More information

www.iea.org/reports/direct-air-capture
sbh4.de