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Creating a carbon dioxide removal solution by combining rapid mineralization of CO_2 with direct air capture

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Abstract

As a part of the EU-funded CarbFix2 project, Climeworks and Reykjavik Energy have partnered to combine direct air capture (DAC) technology with the injection of CO_2 into basalts, for permanent storage by mineralization of the injected carbon. This is the world's first DAC installation that is combined with mineral storage of CO_2. There is large potential for further optimization and substantial scale up of this joint operation. The organizations are developing an integrated CO_2 removal solution that may be expanded and applied globally. This type of solution has been recognized as a crucial component in efforts to mitigate global warming.

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1. Introduction

Reducing carbon dioxide (CO_2) emissions will be one of the main challenges in the decades to come. Emission reductions alone will however not be sufficient to reach international climate targets. Almost all of the climate scenarios considered in the 5th IPCC assessment report with >50% chance of limiting global warming to 2 °C involves the large-scale deployment of CO_2 removal [1]. Prominent approaches towards CO_2 removal include afforestation, enhanced weathering, bioenergy and carbon capture and storage (BECCS) and direct air capture of CO_2 (DAC) [2].

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The Swiss clean-tech company Climeworks has designed a plant that captures atmospheric CO_2; air is drawn into the plant and the CO_2 within the air is chemically bound to a filter. Once the filter is saturated, it is heated, and the CO_2 is released and collected as concentrated CO_2 gas. With DAC, such as the technology Climeworks has developed, the CO_2 is isolated but not permanently removed from the atmosphere, and therefore has to be combined with safe storage approaches, such as injection of CO_2 at carefully selected geological sites.

Most of the ongoing carbon storage projects are injecting CO_2 into sedimentary basins where the CO_2 is injected as a separate buoyant phase anticipated to be trapped below an impermeable cap rock [e.g. 3]. In Iceland an alternative method is being developed as a part of the CarbFix project, where the CO_2 is dissolved in water before or during its injection into porous and fractured basaltic rocks [e.g. 4, 5]. Because the CO_2 is dissolved it is not buoyant; in fact the injected fluid is denser than the surrounding reservoir fluid due to the CO_2 and thus has no tendency to rise. Therefore, solubility trapping happens immediately and no cap rock is required [6]. The gas-charged water accelerates the release of metals from the basalts, such as calcium, magnesium, and iron, which combine with the injected CO_2 and form solid carbonate minerals such as calcite, magnesite, and siderite, respectively, resulting in the permanent storage of carbon [e.g. 5, 7, 8]. Climeworks has combined its DAC technology with the CarbFix method, as a part of the EU-funded CarbFix2 project, for permanent geological storage of the air captured CO_2. As a part of CarbFix2, the project partners will demonstrate a safe, economically-viable and highly scalable carbon removal technology.

2. The Climeworks-CarbFix collaboration

2.1. Climeworks

The idea behind Climeworks was sparked in 2007 during research on DAC at the Swiss Federal Institute of Technology, ETH Zürich. The company was founded in 2009, following the development of the first system concepts and working prototypes in the ETH laboratories. In 2011, Climeworks built its first demonstration prototype, scaled-up by a factor of 1,000 compared to previous laboratory-scale prototypes. In 2015, a Climeworks system was commissioned for the world's first synthesis of renewable methane from atmospheric CO_2 [9]. In 2017, Climeworks commissioned the world's first commercial DAC plant in Hinwil, Switzerland (Fig. 1). The plant nominally captures 900 tons of CO_2 per year from the air and delivers the CO_2 to a nearby greenhouse. Later the same year Climeworks joined forces with CarbFix with the world's first combined DAC and mineral storage of CO_2.

Fig. 1. The world's first commercial plant for direct air capture of CO_2 located in Hinwil, Switzerland

Fundamentally, the Climeworks DAC design is based on an adsorption/desorption process on alkaline-functionalized adsorbents. CO_2 adsorption is performed without treating the incoming air stream, and CO_2 desorption is performed through a temperature-vacuum-swing (TVS) process. During this process the pressure in the system is reduced and the temperature is increased from 80 to 120 °C, thereby releasing the captured CO_2. After a cooling phase, the whole process is repeated, as illustrated in Fig. 2.

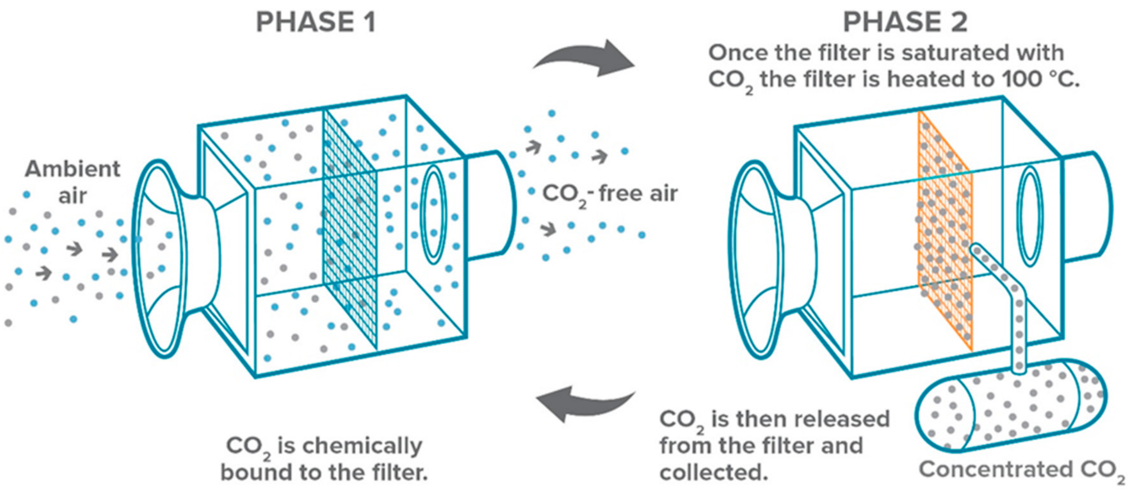

Fig. 2. Schematic illustration of Climeworks direct air capture process

Climeworks adopted a modular design to reduce operating costs, support scalability and diversity in deployment, solve transport issues and enable automated manufacturing. CO_2 adsorption and desorption is performed within the same device, referred to as the "CO_2 Collector" or just "Collector". Collectors are engineered to fit efficiently into a steel frame, with six collectors fitting into a standard 40 foot shipping container. The only moving parts in a CO_2 collector are the fan to draw in air for adsorption, and two lids at the entry and exit of the collector which create an airtight seal for the CO_2 desorption. The present nominal annual CO_2 collector capacity is 50 tons of CO_2, an amount which is anticipated to increase as the technology is optimized. The modular collectors are engineered to operate together as a unit and can easily be scaled with the addition of new modules to expand the capacity. The collectors have been engineered for automated commercial production and use conventional metal fabrication technology.

Another important characteristic of the Climeworks DAC process is that a large share of the energy demand can be met by heat in the range of 80-120°C, which is available from a variety of sources including industrial low-grade waste heat, or as in the case of the CarbFix2 process, geothermal heat.

2.2. CarbFix

The CarbFix project was founded in 2007 by Reykjavik Energy, University of Iceland, CNRS in Toulouse, and Earth Institute at Columbia University in New York. Since then, several universities and research institutes have participated in the project including Amphos21 in Barcelona, Nano Science Center of Copenhagen University, Durham University, Institut de Physique du Globe in Paris, University of Southampton, and University College London. The aim of the project is to develop safe, simple and economical methods and technology for permanent CO_2 mineral storage in basalts.

The first pilot injections took place in 2012 in Hellisheidi in SW-Iceland. In January to March, 175 tons of pure CO_2 were dissolved in water during injection into the basaltic subsurface at depths below 500 m and ~35 °C, and in June-August a gas mixture from the Hellisheidi power plant consisting of 75% CO_2 and 25% hydrogen sulfide (H_2S) was injected under the same conditions. The results were published in 2016 [7] confirming the rapid mineralization of the injected gases.

Following the success of the pilot injections, the project was scaled up to an industrial scale in June 2014, and it is now an integral part of the operations at the Hellisheidi power plant, injecting about one-third of the CO_2 emissions from the plant, or about 10,000 tons annually at current injection rate [10]. The gas mixture consists of 65% CO_2 and 35% H_2S, which are the most abundant geothermal gases in the Hellisheidi field and are of magmatic origin. The gases are dissolved and injected at depths below ~700 m and temperatures about ~250 °C, where the gas charged-fluid reacts with the basaltic bedrock and forms stable carbonate minerals.

Natural analogues have revealed the large storage potential of young basaltic rocks, where normal faults are common and pore space has not been filled with secondary minerals. It is anticipated that >950 Gt of CO_2 could theoretically be stored within the active rift zone in Iceland [11], thereof about 6 Gt in the Hellisheidi field [10] where the CarbFix injections take place. The largest storage potential lies offshore where it is anticipated that CO_2 from burning of all fossil fuel on Earth could theoretically be stored as carbonate minerals within the oceanic ridges [11].

2.3. CarbFix2

In 2017 a new chapter was started with the European Union's Horizon 2020 research and innovation program funding of CarbFix2. The project is as before led by Reykjavik Energy, but further partners to the project are the founding partners at University of Iceland and CNRS in Toulouse (France), along with Amphos21 in Barcelona (Spain), and Climeworks. The CarbFix2 project builds on the success of the CarbFix project, with the goal of moving the CarbFix technology from the demonstration phase to a general and economically viable complete carbon capture and storage chain that can be used in other parts of the world. Towards this goal, CarbFix2 extends the original CarbFix approach in one location to its potential implementation under more diverse conditions. One of the goals of the CarbFix2 project is to combine the storage approach with DAC technology, such as developed by Climeworks, and thus create an integrated CO_2 removal solution with a potential for global application.

As for the current operations of the CarbFix project, the DAC part of CarbFix2 is located at the Hellisheidi power plant. Hellisheidi is a double-flash plant where the geothermal fluid is first separated at 175 °C. The steam and most of non-condensable gases, such as CO_2, are diverted to turbines for power production. The remaining separator water is subjected to secondary flashing stage where additional steam is generated and the remaining fluid at 120 °C is mainly piped to heat exchangers for district heating. A Climeworks DAC module has been installed on-site that utilizes heat from the separator water to capture CO_2 from ambient air for permanent storage underground, thus creating a carbon removal solution (Fig. 3). The module draws in ambient air and captures the CO_2 with a filter, as described above. The filter is then heated with 120 °C separator water from the plant to release the CO_2. The pure CO_2 is then compressed and mixed with condensate from the plant and the resulting mixture is then piped to the injection well. The mixture is maintained under pressure down the injection well and into the reservoir to prevent degassing. There, the CO_2-charged water is released into the basaltic reservoir. A major goal of the trial is to test how Climeworks technology works with the specific weather conditions at the location in SW-Iceland before the DAC operations are substantially scaled up.

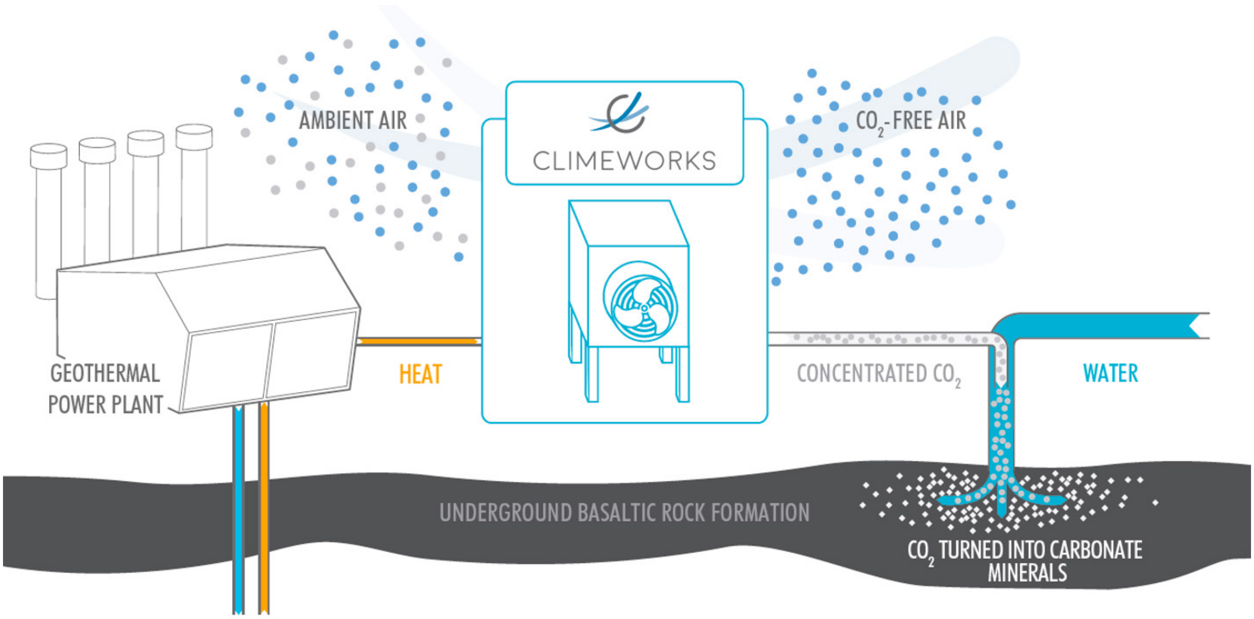

Fig. 3. Schematic illustration of the Climeworks-CarbFix injection at Hellisheidi, Iceland

3. Conclusions and outlook

As described in this paper, an integrated and safe solution towards permanent CO_2 removal has been created through the combination of the CarbFix and Climeworks technologies. Based on the initial trial, the joint operations can be substantially scaled up and further optimized in the coming years. Having such scaled up and optimized operations in place is crucial as deployment of CO_2 removal at gigaton scale will have to start as early as 2030 in order to reach international climate targets by the end of the century [12].

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