A scalable direct air capture process based on accelerated weathering of calcium hydroxide

March 29, 2022
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Summary

The removal of CO_2 from air has become critical to achieving net zero emissions by mid-century and minimizing the dangerous effects of climate change. Scalable direct air capture (DAC) technology, paired with geological carbon storage, can offer a path to removing ambient CO_2 at the gigatonne scale. Here, we provide insight into Heirloom's DAC process that uses Earth-abundant minerals, namely calcium carbonate ($CaCO_3$), and renewable energy to capture carbon dioxide (CO_2) directly from air. We also discuss the need for supporting systems, such as renewable electricity generation and geologic storage, to scale DAC.

Introduction

Atmospheric concentrations of CO_2 have exceeded 410 parts per million by volume (ppm), while yearly emission levels exceed 35 billion metric tonnes of CO_2 per year ($GtCO_2$/year) [1]–[3]. To meet climate goals and avoid the catastrophic effects of climate change, we must not only develop technologies that mitigate CO_2 emissions, but also technologies that can remove CO_2 directly from the atmosphere [4], [5]. Carbon removal technologies will not only play a supporting role in the transition from fossil to renewable energy (via carbon utilization) but can also help to offset emissions from hard-to-abate sectors, such as steel and cement industries, and provide a means to remove legacy CO_2 emissions, or those that were previously emitted into the atmosphere [5], [6]. Additionally, carbon removal may offer a path towards climate justice as it could enable countries, corporations, and entities that have contributed the most to climate change to repay their climate "debt" [7].

There are several approaches to carbon removal, including afforestation and reforestation, bioenergy with carbon capture and storage (BECCS), soil carbon sequestration, carbon mineralization, and direct air capture (DAC). The success of any carbon removal strategy relies on the evaluation of a combination of metrics - durability, safety, cost, resource usage, and environmental impact - using tools, such life cycle assessments (LCAs), techno economic analysis (TEAs), and environmental impact assessments (EIAs).

DAC describes a suite of engineered technologies that remove CO_2 directly from the atmosphere using either a solid sorbent or liquid solvent that selectively binds to CO_2. The captured CO_2 can then be released during a regeneration process by leveraging a swing in temperature, pressure, or electrochemical potential, where specific conditions are dependent on the properties of the sorbent or solvent material. The regeneration process results in a high purity stream of CO_2 suitable for storage or utilization, and a sorbent or solvent material that can be reused.

Most DAC technologies uptake CO_2 near atmospheric conditions and require electricity for fans to move CO_2 through engineered structures called contactors. Additionally, the sorbent regeneration process is energy intensive as the system must overcome the energy of desorption of CO_2 (and sometimes H_2O) from the sorbent [8]–[11]. Furthermore, the efficiency of capture from dilute sources, such as air, is inherently limited by thermodynamics, resulting in either additional energy or contact area being required to achieve the performance of point-source capture [12], [13]. Any emissions associated with energy production for DAC offset the benefit of the captured CO_2. Therefore, the development and expansion of low-carbon energy infrastructure is crucial to realizing DAC processes that are net negative.

Several iterations of DAC employ engineered solid sorbents. The Swiss company Climeworks uses engineered solid sorbents that bind with CO_2 near atmospheric conditions and are regenerated at an elevated temperature (80 - 120 ºC [10]) and reduced pressure. By contrast, Canada-based Carbon Engineering uses liquid alkali metal hydroxides (such as potassium hydroxide, KOH, and sodium hydroxide, NaOH) to capture CO_2 from air [8], [14]. Both processes rely on the use of forced air by continuously running fans to overcome the thermodynamic limits of dilute source capture.

Heirloom's Direct Air Capture Process

Heirloom Carbon Technologies (or Heirloom, for short) takes a different approach to DAC by leveraging energetically favorable carbon mineralization reactions that occur in nature. In this process, naturally occurring minerals are used instead of synthetic sorbents, and capture efficiency is achieved by maximizing air-sorbent contact area rather than by relying on forced air, also known as passive DAC. In passive DAC, the energy burden is also decreased by eliminating the need for fans. Although the approach can theoretically accommodate any mineral carbonate feedstock, Heirloom uses calcium carbonate, $CaCO_3$, which is earth abundant and makes up roughly 4% of the Earth's crust. The process is divided into two steps, regeneration and carbonation, as outlined in **Figure 1**.
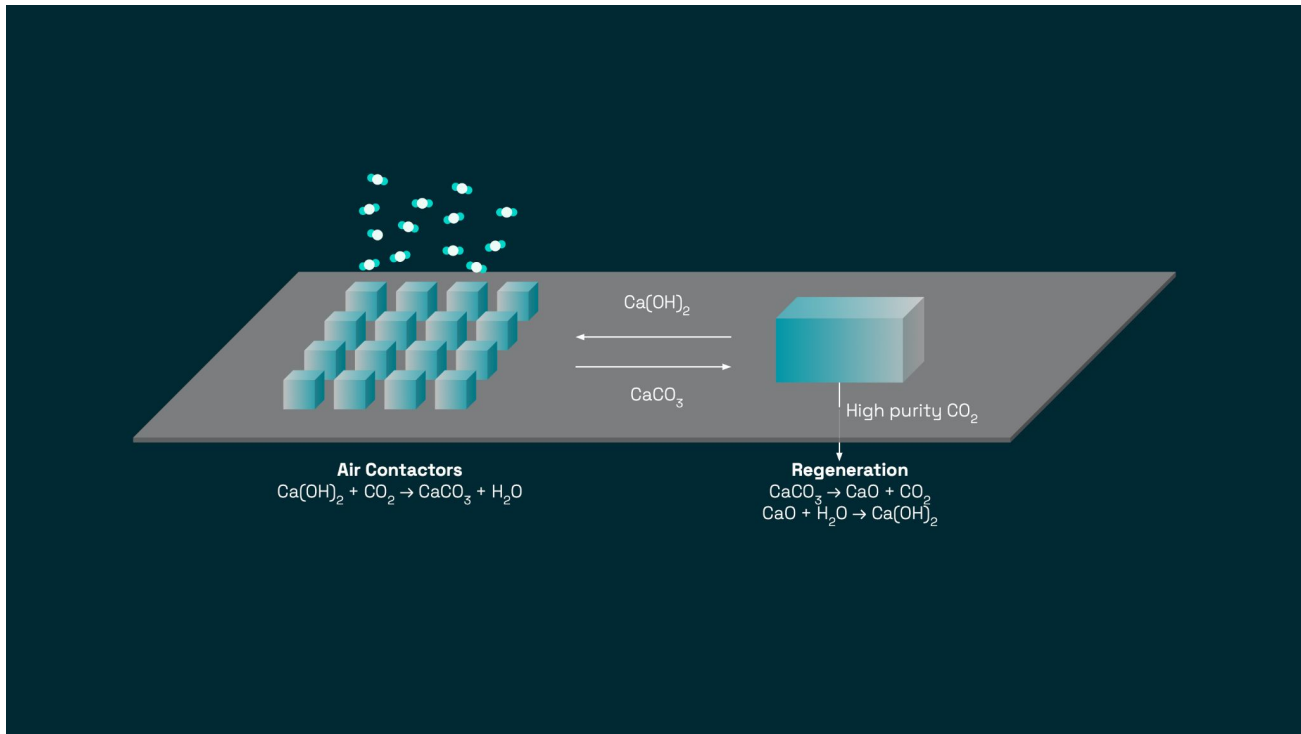
Figure 1: Heirloom DAC process utilizing calcium carbonate in a cyclic process.

Regeneration comprises two stages: calcination and hydration. In the initial step, $CaCO_3$ is sent into a high temperature reactor. Inside this reactor the $CaCO_3$ decomposes into calcium oxide (CaO) and CO_2 at temperatures near 900 °C at atmospheric conditions. This reaction is shown in Eq. 1.

Eq. 1
$$CaCO_3 + Heat \rightarrow CaO + CO_2$$
$$\Delta Hrxn = 178 \text{ kJ/mol}$$

The high temperature reactor is powered by renewable electricity which, unlike fossil fuel-powered kilns, allows for the capture of a high-purity stream of CO_2 directly from the reactor. The CO_2 produced through calcination can be stored either in geological reservoirs or by mineralization. In the second stage, the calcium oxide is then hydrated to form $Ca(OH)_2$ (Eq. 2) or exposed directly to air where it will naturally hydrate. The hydration reaction is exothermic and, therefore, presents a suitable opportunity for heat recovery.

Eq. 2
$$CaO + H_2O \rightarrow Ca(OH)_2$$
$$\Delta Hrxn = -65 \text{ kJ/mol}$$

The resulting $Ca(OH)_2$ is used as the sorbent material in the capture step of the system. Upon exposure to ambient air the material reacts with CO_2 to reform the $CaCO_3$ species (Eq. 3).

Eq. 3
$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3$$
$$\Delta Hrxn = -113 \text{ kJ/mol}$$

To carbonate the material, Heirloom lays out thin layers of $Ca(OH)_2$ powder onto large area trays. The trays are then stacked into vertical, tiered contactor structures to minimize land area requirements, all whilst enabling maximum air-to-sorbent contact. The use of tiered structures also renders the process highly modular by allowing for the carbonation capacity to be increased incrementally rather than being fixed at the initial time of deployment.

Once the material is sufficiently recarbonated (i.e., saturated with captured CO_2), it is sent back to the regeneration unit where it is once again decomposed to form CaO and CO_2 (see Figure 1). The process continues cyclically with the mineral sorbent (CaO) being repeatedly carbonated and regenerated. The cyclic nature of the process not only lowers operating costs but also reduces the extractivity of the process (i.e., how much mineral must be mined).

Controlled Carbonation

Heirloom's DAC process is facilitated by a material handling system that can move the sorbent between the regeneration and carbonation units. The rate of transfer of $CaCO_3$ from the carbonation to the regeneration unit is dictated by the rate at which the $Ca(OH)_2$ reacts with ambient CO_2 to form $CaCO_3$. By employing proprietary methods, Heirloom is able to maintain a minimum baseline rate of carbonation independent of changes to environmental conditions, such as temperature, relative humidity, precipitation, and airflow.

In the initial TEA for passive mineralization as a direct air capture technique, it was assumed that carbonation of a 10 cm layer would occur over 1 year [15]. The current literature benchmark for the carbonation of thin layers of $Ca(OH)_2$ is two weeks, reported by Erans et al. (2020) for 5mm layers exposed to ambient indoor conditions [16].

Heirloom has accelerated that rate to under 3 days for 85% carbonation. The fastest rate consistently achieved by our process is equivalent to 630g CO_2 removed per $1m^2$ of exposed contactor area every 2.5 days, reaching 85% carbonation of the $Ca(OH)_2$ utilized. Here, the exposed contactor area refers to the area of material exposed to air, not the land area on account of Heirloom's stacked contactor configuration. The vertically stacked contactor configuration vastly increases the exposed contactor area per unit of land area.

Process Design Philosophy: Developing DAC 2.0

Heirloom's process was designed with several key properties that may drive low-cost DAC in the long term. First, the capture process in the air contactors requires very little energy input (< 0.05 GJ/tCO_2 removed from air, where other approaches require on the order of 0.5 - 1 GJ/tCO_2 [5], [11], [17]). The CO_2 concentration in the system can be maintained by natural transport of CO_2, even at low wind speeds. This precludes the need for continuously running fans, as is required by other DAC techniques. The calcium material absorbs CO_2 from the atmosphere on longer timescales than those associated with other DAC approaches, such as the solvent or amine-based sorbent DAC. Heirloom leverages longer absorption timescales to circumvent the use of expensive materials and forced airflow through the system, which results in overall lower capture costs.

Second, Heirloom leverages low-cost, Earth-abundant minerals. MOFs (metal organic frameworks), a class of synthetic compounds offering highly tunable topologies and a wide range of porosities, are one of the primary sorbents of interest for carbon capture. However, the chemical complexity of such sorbents results in high material and processing costs. MIL-101(Cr)-PEI-800 and mmen-Mg2(dobpdc) cost between $7,000 - $30,000 per metric ton and $25,000 - $100,000 per metric ton, respectively [18], [19]. By contrast, Heirloom uses $CaCO_3$, where costs are roughly $10 - 50 per metric ton, which is orders of magnitude lower than other types of engineered sorbents. Recycling the $CaCO_3$ also makes the process less-extractive by reducing our process demand for carbonate and further decreases both the cost and the carbon intensity of the $CaCO_3$ per ton of CO_2 removed from air.

Finally, Heirloom's system employs a modular approach. Modularity refers to the ability of a system to be partitioned into smaller, repeated systems. As such a modular unit can be repeatedly produced and rapidly implement improvements to designs, manufacturing, or efficiency [20], [21]. Specifically, Heirloom's carbonation system has several degrees of modularity, ranging from a single tray to a complete contactor unit. An array of contactors is additionally paired to one regeneration system to form a DAC module. This allows for system modularity and increased iterations over system designs and subsequent improvements.

Each of these key design properties, especially modularity, put Heirloom in a position for rapid deployment and a steep learning curve. Systems that exhibit modularity commonly demonstrate higher learning rates. Technologies such as solar photovoltaics (PV) and lithium ion batteries demonstrate learning rates as high as 23% and 30%, respectively [22], [23]. Whereas, more monolithic and site-built systems, such as natural gas turbines and onshore wind, demonstrate lower learning rates (15% and 12%, respectively) [22]. Leveraging modularity and design iteration cycles encourages learning and corresponding cost reductions.

Deploying and Scaling DAC Systems

While modularity and cost are important factors when developing DAC technologies with high potential to scale, achieving gigaton scale carbon removal requires parallel, supporting infrastructure (Figure 2). Specifically, access to firm renewable electricity, on-site or proximate geological storage (paired with affordable CO_2 transport), onsite shared utilities, and sufficient land are all essential to achieving gigaton scale at low cost.
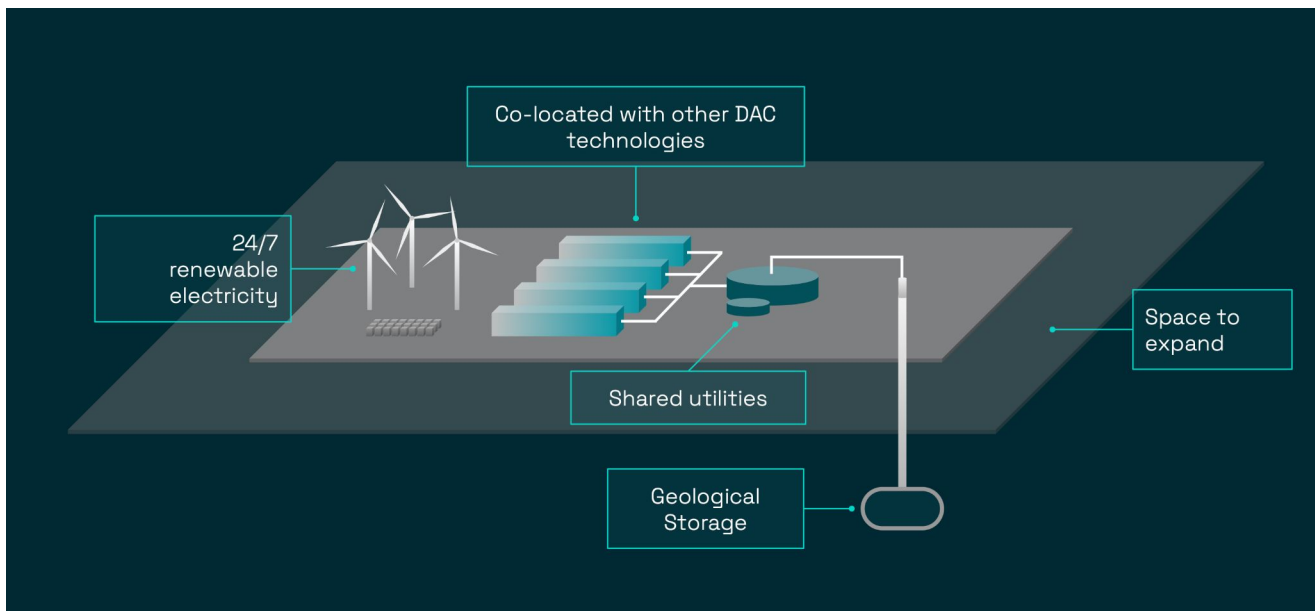

Figure 2: Schematic illustration of key components of an integrated DAC facility to achieve negative carbon emissions. This includes renewable electricity and CO_2 storage opportunities.

Direct air capture is inherently energy intensive, requiring between 150-500MW per million tons of CO_2 removed [5], [8], [10], [21]. The decomposition of $CaCO_3$ alone requires 1.78 GJ per metric ton of $CaCO_3$ decomposed, or roughly 4 GJ per metric ton of CO_2 captured. Since the reaction occurs at 900 ºC, there is also energy associated with elevating the material to temperature. Heirloom targets a total energy requirement of less than 1,500 kWh/tCO_2, or 5.4 GJ/tCO_2. Approaches like Heirloom's, which is powered nearly 100% by low-carbon electricity, will require electricity on the scale of 100's of MW per million metric tons removed. This is a net-new power requirement that will need to be developed if we hope to achieve our climate targets. Developing DAC facilities in geographies with high wind, solar, or other renewable potential enables lower cost electricity and therefore lower cost direct air capture deployments.

Similarly, the cost of DAC paired with geologic injection can be greatly reduced if CO_2 injection is co-located with the DAC system, eliminating transportation requirements. CO_2 transport costs are especially sensitive to the distance from an injection site and the chosen method of transport (by truck, rail, or pipeline), and are modeled to increase overall costs by as much as $50 per metric ton [24]. Close proximity or co-location of a DAC deployment to geologic storage is a major opportunity to limit the overall cost of DAC. Fortunately, there are many opportunities around the world to co-locate DAC, geologic storage, and renewable power [25].

DAC facilities would also benefit from co-location with one another, enabling shared access to onsite utilities and common storage and transportation infrastructure. These utilities may include power infrastructure, water, centralized CO_2 compression, and more. Each of these utilities benefit greatly from economies of scale, making a larger system more economically viable, lowering the leveled capital cost relative to multiple, separate, vertically integrated systems.

Finally, while DAC facilities are less land-intensive than many alternative forms of carbon dioxide removal, they will require noteworthy land for deployment and expansion. Publicly available estimates suggest that DAC facilities will require roughly 0.4 km^2 per million metric tons of removal [5], [10], [20], [26]. Additional land requirements are also necessary for co-developing renewable energy infrastructure. Identifying sites with sufficient land for initial deployments as well as incremental expansion and additional land for renewable electricity production will enable the modular deployment of DAC technologies.

Developing Markets

To scale DAC and achieve costs near or below $100/$tCO_2$ [27] by the end of the next decade, we need to deploy DAC technologies at a rapid pace. To do that, we need incentives that meet DAC where it is, not where it will be. Currently, voluntary carbon markets dictate the demand for carbon removal and by proxy, DAC. Companies like Microsoft, Stripe, and Shopify are injecting catalytic capital to help create a marketplace for carbon removal, above and beyond the pricing of current policy incentives (i.e., California's Low Carbon Fuel Standard (LCFS) a compliance credit trading at approximately $200/$tCO_2$ [28][citation], the European Union Emissions Trading Scheme (ETS) $90/$tCO_2$ [29], or the United States 45Q tax credit $50/$tCO_2$ by 2026 [30]). The voluntary carbon markets exhibit a willingness to pay from some customers beyond the regulatory price of carbon [31], [32], which is crucial as we begin to scale DAC. In particular, voluntary offtake agreements on the scale of low $100M's per year by the mid-2020's would be sufficient to push DAC down in cost to meet markets like LCFS and the EU ETS.

Voluntary markets alone cannot scale DAC to the gigatonne scale required to combat the most devastating effects of climate change. Gigatonne scale carbon removal requires global carbon markets, government procurement and incentives, and publicly financed investment in crucial project infrastructure, such as renewable electricity and CO_2 injection wells.

Conclusion

As the deadline to achieve net zero emissions approaches, DAC has become an increasingly important complementary strategy to tackle the climate crisis. Heirloom's approach to DAC leverages the naturally occurring carbon mineralization reactions to capture CO_2 directly from air. To date, Heirloom has achieved the fastest reported carbonation rates under representative outdoor conditions. The process uses cheap, abundant calcium carbonate feedstock and avoids the need for forced air by maximizing the air-sorbent interface in the contactor design to provide a cost-effective and modular DAC system. Accelerating DAC deployments such as Heirloom's will ultimately rely on the development and expansion of new renewable energy infrastructure and CO_2 storage infrastructure, incentivization to participate in voluntary carbon markets, and government policy to support all types of CDR projects, including DAC.

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