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The use of warehouse automation technology for scalable and low-cost direct air capture

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Direct Air Capture (DAC) offers a promising pathway for combating climate change by removing carbon dioxide (CO_2) directly from the atmosphere. Here, we discuss Heirloom's approach to DAC, which uses naturally occurring minerals, namely, calcium carbonate ($CaCO_3$), in a cyclic process that leverages warehouse automation systems previously developed for large warehouses. The integration of DAC with warehouse automation systems unlocks a degree of manufacturability, scalability, operational efficiency, and financial viability. For successful scaling, DAC technologies and project developers must think through key scalability constraints, including modularity, constructability, supply chains, and leveraging existing infrastructure.

KEYWORDS

direct air capture, carbon dioxide removal, automation, industrial automation, warehouse automation, carbon capture

1 Introduction

It has been well-established that to keep global temperature rise below 2°C we must develop and deploy technologies that not only decarbonize our current infrastructure, but that can remove carbon dioxide (CO_2) directly from the atmosphere (IPCC Special Report, 2018). Here, carbon removal is critical as it aims to address both emissions from hard-to-abate industries, as well as historic (or legacy) emissions (NASEM, 2019; Bergman and Rinberg, 2020).

The UN Intergovernmental Panel on Climate Change (UN IPCC) estimates that up to 1,000 Gt of CO_2\ will need to be removed from the atmosphere by 2,100 to meet climate goals (IPCC Special Report, 2018). There are many paths that can be taken to achieve carbon removal. These include direct air capture (DAC) coupled to CO_2 storage; carbon mineralization; biomass carbon removal and storage (BiCRS), which includes bioenergy with carbon capture and storage (BECCS); soil carbon sequestration; and afforestation and reforestation (NASEM, 2019; Sandalow et al., 2021). Multiple Carbon Dioxide Removal (CDR) approaches will play a crucial role in the integrated portfolio of technologies necessary to achieve gigatonne-scale carbon removal by 2050. Among these approaches, DAC stands out due to several advantages it offers over existing carbon removal technologies – it is additional, permanent (when coupled with permanent storage methods like geological storage), and is capable of clear measurement, reporting and verification (MRV) (Pisciotta et al., 2022; Küng et al., 2023).

DAC describes a suite of engineered technologies that capture CO_2 directly from the air and produce a concentrated stream of CO_2. The concentrated stream of CO_2 can either be utilized, such as to form fuels, construction materials, engineered materials, polymers, or chemicals, or stored geologically (NASEM, 2023). DAC technologies use chemicals to capture and release CO_2, where these chemicals include solid sorbents, liquid solvents, naturally occurring minerals, and industrial byproducts, among others (McQueen et al., 2021).

In recent years, numerous advancements have been made in the development of various materials, approaches, and technologies for DAC. Several iterations of DAC employ engineered solid sorbents. Swiss company Climeworks uses engineered solid sorbents to bind with CO_2 at near-atmospheric conditions, regenerating a concentrated stream of CO_2 at an elevated temperature (80–120°C) and reduced pressure (Beuttler et al., 2019). By contrast, North American-based company, Carbon Engineering, uses liquid alkali metal hydroxides (such as potassium hydroxide, KOH, and sodium hydroxide, NaOH) to capture CO_2 from air at near-atmospheric conditions and a high-temperature calcination process to release that CO_2 in a concentrated form (Holmes and Keith, 2012; Keith et al., 2018).

As of today, there are over 100 companies developing improvements to existing DAC technologies or entirely new DAC technologies (Faber, 2024). A few of these companies are currently operating industrial facilities, including Climeworks, Carbon Engineering, Global Thermostat and Heirloom (International Energy Agency, 2022). However, the total scale of DAC globally is roughly 8,000 tons of CO_2 per year. While these small-scale plants are important to de-risking new technologies and demonstrating the technological, social, and political benefits and challenges to deployment, reaching gigaton scale DAC by 2050 requires annual growth rates of nearly 50% – exponential scaling (McQueen et al., 2021). To achieve this, DAC technologies and project developers must think through key scalability constraints, including modularity, constructability, supply chains, and leveraging existing infrastructure.

This article discusses Heirloom's approach to DAC and how the capture technology can leverage off-the-shelf, industrial automation technologies to accelerate scale. We present an overview of Heirloom's DAC process, detail the integration of the CO_2 capture stage with warehouse automation technologies, and offer a case study on Amazon's warehouse expansion, illustrating the potential scalability of DAC when integrated with these automated warehouse technologies.

2 Process overview

Heirloom's DAC process leverages the properties of natural occurring minerals (McQueen et al., 2022). While the process can theoretically accommodate any alkaline mineral feedstock, Heirloom uses calcium carbonate ($CaCO_3$) which makes up more than 4% of the Earth's crust (Carmeuse, 2024; Dietrich, 2024). The process is divided into two steps, regeneration, and carbonation, as outlined in Figure 1.

Regeneration comprises two stages: calcination and hydration. The $CaCO_3$ feedstock is sent into a high temperature, electrically powered reactor. Inside this reactor the $CaCO_3$ undergoes endothermic decomposition to calcium oxide (CaO) and CO_2 at temperatures near 900°C at atmospheric conditions (Eq. 1). Since the kiln is powered entirely by renewable energy, a pure stream of CO_2 is captured directly from the kiln and is stored permanently via geologic storage.

$$CaCO_3 \rightarrow CaO + CO_2 \tag{1}$$

The resulting CaO is then hydrated to form calcium hydroxide [$Ca(OH)_2$] (Eq. 2). The hydration reaction is exothermic, releasing roughly 30% of the energy required for the calcination process. This reaction thereby presents an ideal opportunity for heat recovery.

$$CaO + H_2O \rightarrow Ca\left(OH\right)_2 \tag{2}$$

Once exposed to air, the $Ca(OH)_2$ will react with the CO_2 to reform $CaCO_3$ via a reaction called carbonation (Eq. 3). When the material is sufficiently recarbonated, it is sent back to the regeneration process to begin the cycle again. The process then continues cyclically with the mineral sorbent being repeatedly carbonated and regenerated.

$$Ca\left(OH\right)_2 + CO_2 \rightarrow CaCO_3 \tag{3}$$

Heirloom built its first operational prototypes in 2021 and first integrated pilot facility in 2022. In collaboration with Canadian company CarbonCure, the integrated pilot facility also highlighted the first time that CO_2 captured from the atmosphere was permanently sequestered in concrete (CarbonCure Technologies, 2023). In November of 2023, Heirloom officially launched the first commercial DAC facility in the United States in Tracy, CA with the capacity to capture up to 1,000 tons of CO_2 from the air per year (Figure 2) (Plumer, 2023).

The rapid scaling of the technology from lab to a commercial facility in less than 3 years was broadly enabled using low-cost materials and technologies with existing supply chains. The three biggest inputs to the process are limestone, plastic, and steel. To achieve the necessary scale required to meet climate goals, DAC companies must persist in utilizing easily manufacturable and constructable systems that offer high scalability, while also drawing upon experiential knowledge from relevant industries.

3 A novel capture system that leverages industrial automation

The removal of vast quantities of CO_2 via Heirloom's cyclic process requires that large amounts of CO_2-capturing materials be exposed to the atmosphere so that they can bind with CO_2. The majority of the research around optimizing the physical infrastructure that holds the sorbent material (designated "contactors") has focused on increasing CO_2 capture while decreasing the pressure drop across the capture medium and the associated energy consumption (Holmes and Keith, 2012; Mazzotti et al., 2013; Gebald et al., 2017; Kasturi et al., 2023). To date, all DAC facilities have leveraged designs similar to traditional chemical processes, including cooling towers and monolith filters (APS, 2011; Holmes and Keith, 2012; Gebald et al., 2017; Beuttler et al., 2019; NASEM, 2019; Spiteri et al., 2021). Heirloom has taken a different approach by leveraging industrial automation for DAC, creating an automated warehouse to remove CO_2 from the atmosphere.

3.1 Warehouse automation technology and DAC

Warehouse automation refers to the integration of various technologies and systems to streamline and optimize the operations within a warehouse. This approach aims to enhance efficiency, accuracy,

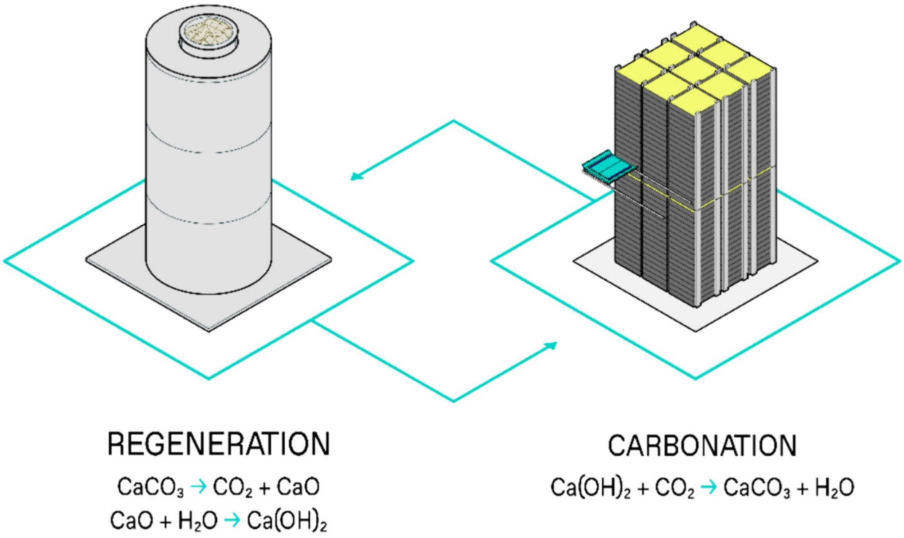

FIGURE 1
Illustration of Heirloom's DAC process.

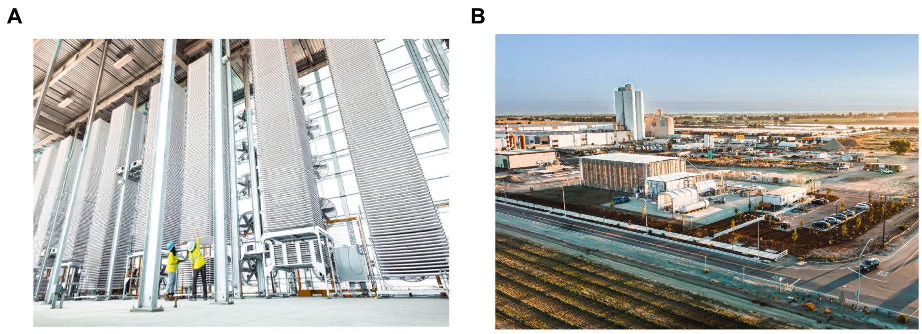

FIGURE 2
The first commercial direct air capture (DAC) facility in the United States in Tracy, California. **(A)** A close up of the contactor system in the first commercial system and **(B)** an aerial view of Heirloom's first commercial deployment.

and speed in tasks such as inventory management, order fulfillment, and material handling. Warehouse automation typically consists of several key components, including automated storage and retrieval systems (AS/RS), which use robotic mechanisms to store and retrieve goods from designated locations within the warehouse. Another component is conveyor systems, which facilitate the movement of materials between different areas of the warehouse. Additionally, robotic picking systems employ robots equipped with sensors and grippers to pick items. High bay racking systems are also essential components, maximizing vertical storage space by storing goods in tall, densely packed racks accessed by AS/RS. Warehouse management software orchestrates and coordinates these various automation components, optimizing workflows, and providing real-time visibility into inventory levels and order status. Other components may include sorting systems, automated guided vehicles for material transportation, and packaging automation systems. Overall, this type of warehouse automation aims to enhance operational efficiency, reduce labor costs, minimize errors, and create faster order processing and fulfillment.

Advancements in automated warehouse systems have steadily increased efficiency and reduced operational costs across a variety of industries, including logistics, distribution centers, and manufacturing facilities (Custodio and Machado, 2020; Funaki, 2023). These systems, exemplified by the AS/RS, offer a mechanized solution for storing and retrieving items within a facility, streamlining tracking and operations and reducing the need for manual labor.

At a high level, these automated warehouse technologies use a combination of vertical lifts, stacker cranes, and shuttles to store modular loads that are several layers deep, across multiple levels of vertical racking. In traditional warehouse storage, these modular loads are typically pallets. As applied to DAC, these modular loads are called caddies, and in Heirloom's DAC facilities, these caddies are a pallet-sized modular carbon capture unit containing the calcium hydroxide sorbent material. This physical infrastructure is complemented by software and controls automation that schedules and tracks the placement and Research Topic of caddies (Figure 3).

In traditional warehouse storage, the AS/RS automation and high bay racking system simplifies and standardizes placement and retrieval of modular units while providing dense and structurally efficient vertical storage, leading to cost savings across the system. The

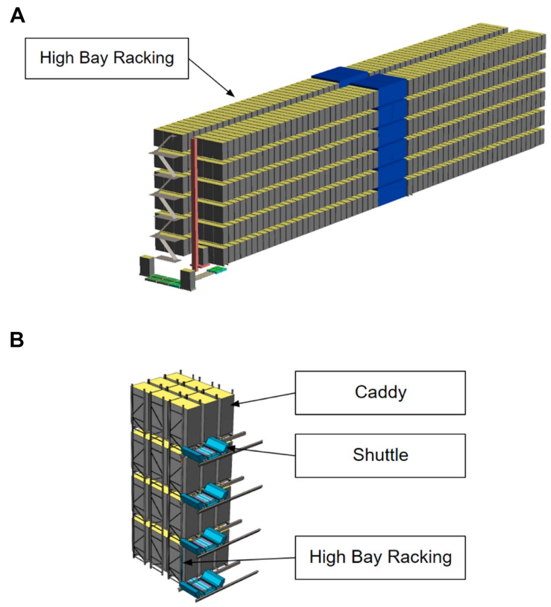

FIGURE 3
(A) A full-building view of warehouse automation infrastructure that can be leveraged for DAC. The yellow layered structure represents the high bay racking. **(B)** An example subsection of the contactor system where the shuttles are shown in light blue and the high bay racking with caddies by the gray and yellow stacked structure. *Both images are representative subsections of the technology but may not be accurate to scale.*

advantages that enable the success of warehouse automation for storage are directly transferable to DAC.

3.2 Advantages of automated warehouse technology for DAC

The benefits of integrating DAC with automated warehouse technologies include increased manufacturability, constructability (ease of onsite assembly), operational efficiency, and financial viability. In this section, each of these categories are explored in more detail and tied back to their potential impact on DAC deployment and the ability to achieve billion-ton scale carbon removal.

3.2.1 Manufacturability

The integration of warehouse automation systems within DAC leads to advantages in manufacturing efficiency and cost reduction – the primary benefit being the facilitation of low-cost, mass manufacturing. The modular design approach enables the repetition of component designs, such as trays, caddies and racking members, thereby reducing capital expenses. For example, the high bay racking design and manufacturing has been optimized and standardized over several decades (Custodio and Machado, 2020; Bedard, 2021). This enables the automated warehouse DAC system to utilize tools and equipment that are already available and widely used in the production of roll-formed steel members. Existing racking design solutions address freight efficiency (effectiveness and optimization of transporting goods or materials), installation time, and interfacing to AS/RS equipment. There already exists tooling to manufacture racking for varying system heights and load sizes, enabling an efficiently scaled system without significant design or infrastructure development.

The caddy, which captures the CO_2, interacts with the AS/RS automation and racking with one standardized physical interface on the bottom, allowing for flexibility, rapid iteration, and parallel manufacturing of the caddies. The trays, which rest inside a caddy and hold $Ca(OH)_2$ in contact with air, serve as the collection beds for CO_2 inside the integrated system. The trays are standardized across the system which lends to the ability to mass manufacture and increases system flexibility.

The entirety of the integrated DAC capture system demonstrates a high degree of modularity. Modularity is the structural property of a system characterized by the degree of compartmentalization and functional independence among its constituent elements, facilitating flexibility, robustness, and efficiency in design, analysis, and adaptation (Ulrich, 1994; Gershenson et al., 2003). This modularity principle, central to reducing manufacturing costs, leverages the uniformity of parts to streamline production processes and diminish design complexity.

The technology learning rate quantifies the percentage decrease in production costs with each doubling of cumulative production experience, indicating efficiency improvements, learning by doing, and economies of scale over time. It serves as a metric for understanding how quickly and consistently the cost of producing a technology declines as experience with that technology accumulates. Differences in learning rates across technologies are influenced by factors such as design complexity and the need for customization (Malhotra and Schmidt, 2020). Technologies with higher degrees of modularity tend to also have higher technology learning rates (Flyvbjerg, 2021). For example, lithium-ion batteries have shown learning rates of 30% (Schmidt et al., 2017), while solar PV panels have demonstrated 23% (Rubin et al., 2015). In contrast, pulverized coal-fired boilers demonstrated learning rates of roughly 6% (Yeh and Rubin, 2007) and natural gas turbines 15% (Rubin et al., 2015). Manufacturing plays a large role in this cost reduction as more modular technologies rely on standardized components and assembly processes, which allow for ease of mass manufacturing as well as replication across different manufacturing facilities, leading to economies of scale and cost reduction (Jacobs et al., 2010). Additionally, modular designs streamline manufacturing by breaking down the system into smaller, more manageable components, leading to increased production efficiency, shorter lead times, and lower costs of manufacturing. This allows for a shorter feedback loop between production improvements and manufacturing, facilitating more rapid iteration and improvement cycles.

3.2.2 Constructability

Leveraging modular, off-the-shelf warehouse automation technologies also presents an opportunity for favorable material lead times, shorter construction timelines, and reduced construction complexity. The warehouse automation technologies leverage two key advantages: global scale and modularity in construction.

These warehouse automation technologies have been widely implemented on a global scale, leading to more efficient design and construction processes, ultimately resulting in shorter development timelines. The high bay racking structure minimizes steel use within the integrated DAC system, leveraging pre-engineered, roll-formed structures. This reduces the capital cost of the storage system as well as the construction complexity. Additionally, the pre-engineered, roll-formed structures enable ease of construction by facilitating straightforward assembly and installation processes (via pieces that 'snap together' in the field) (Meera, 2013). This reduces the installation time compared to conventional construction. Additional benefits include increasing project quality, reducing waste (material waste, defects, waiting times), decreasing greenhouse gas emissions, and improving overall safety (Cassino et al., 2011; Quale et al., 2012).

The modularity of the system, discussed above, also leads to fewer cost overruns during the construction and commissioning of large-scale projects by minimizing on-site work where delays are more likely to occur (Flyvbjerg and Gardner, 2023). A report by McKinsey suggests that modular construction has been shown to reduce construction timelines by 20–50% and those making the shift to modular construction may save 20% in construction costs (Bertram et al., 2019). Modularity in construction also has non-monetary impacts, including ergonomics and work satisfaction (Chauhan et al., 2022). Additionally, modularity can lead to greater benefits when coupled with pre-fabrication, further streamlining the construction process.

A final benefit of the warehouse automation system lies in the installation process. Once the warehouse is built, there is no additional installation required for the CO_2-absorbing caddies. The caddies can be fed into the system and the automation system will install them throughout the facility, decreasing labor requirements and increasing the overall utilization of the installed equipment.

3.2.3 Operating costs

Operational costs are reduced by integrating automated systems into warehouse technologies. Automation technologies reduce labor requirements, enhance reliability, and simplify complex operational procedures, resulting in higher throughput and net productivity of a warehouse. The same operational advantages are expected for the integrated DAC technology.

The impact of automation technology on operating requirements in a warehouse environment is exemplified by the picking system, which refers to the method used to select and retrieve items from an inventory. In traditional warehousing, workers spend roughly 55% of their time traveling between picks, which make up over 50% of overall distribution center costs and drive the majority of labor-related operating costs (Tompkins et al., 2014; Custodio and Machado, 2020). Therefore, automating the picking system results in a roughly 30% decrease in the overall distribution center operational costs. In China, operators spend up to 70% of their time on picking (Xiao-Long et al., 2017). This would accordingly result in a nearly 40% reduction in overall distribution center operational costs. Automation of picking typically involves a system that uses various automation technologies such as robotics, conveyors, and AS/RS to pick items efficiently and accurately from storage locations. By automating routine tasks and facilitating greater vertical stacking of products, the automated picking system minimizes land area requirements, as well as reducing costs, labor hours, and the overall space needed within the warehouse (Custodio and Machado, 2020).

Finally, AS/RS has long-leveraged centralized software-based controls and management systems, which further contribute to maximizing efficiency, accuracy, and productivity while reducing disruptions and ensuring the safety and security of both equipment and personnel. Such software solutions are also highly scalable, flexible, and easily extendable to multiple warehouses. Additionally, as discussed, the components of warehouse automation are modular, enabling flexible maintenance and / or upgrades to each piece of equipment.

4 Scaling up: a scenario analysis

Amazon's warehouse expansion serves as a compelling case study for scalable warehouse technology. Amazon, a global e-commerce leader, has significantly grown their warehouse capabilities over the past decade from a land area of roughly 6 km^2 in 2012 to roughly 53 km^2 in 2022 (Figure 4).

The rack system is foundational to the warehouse infrastructure as well as to the integration of DAC with automated warehouse technology. While not all Amazon warehouses are automated, the foundational warehouse infrastructure buildout is represented in Figure 4. Additionally, in 2012 Amazon bought Kiva Systems, a company that specializes in automation technology for warehouses (Rao, 2012). Their systems utilize mobile robots to move goods around warehouses.

This case study speaks to a singular application of warehouse automation technology, and it is limited in breadth as it only considers application via Amazon technologies. The same supplier could engineer and design for several different applications and companies, which would be a truer representation of the technology buildout. In the absence of this detailed information, a singular company provides a suitable proxy.

Using the warehouse land area estimates, the rough equivalent DAC capacity can be calculated. A DAC facility requires roughly 0.4 km^2 per million metric tons of removal capacity per year including both direct and indirect land use (Lebling et al., 2022). Direct land use refers to the physical space occupied by the DAC facility itself, including the land required for equipment, operations, and maintenance activities. Indirect land area encompasses spatial requirements beyond the immediate footprint of the DAC facility, such as the space needed between contactors for mixing CO_2 or other ancillary processes associated with DAC technology. We anticipate that the direct land area usage for DAC contactors will be somewhere between solar and wind generation at ~70% and ~2% direct land area, respectively (Ong et al., 2013; Harrison-Atlas et al., 2022). The assumption here is that the direct land use of the contactors is roughly 25% of overall land area requirements, or

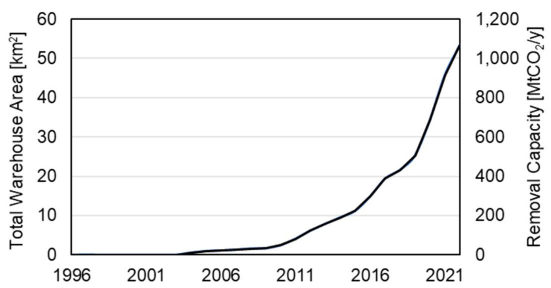

FIGURE 4
Growth in Amazon warehouse square footage from 1996 through 2022 used to estimate the rough equivalent amount of DAC that could be done on that same land area. The land area for warehouses are estimated from Amazon's Annual Reports from 2004 through 2022 (Amazon.com, 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017; Amazon, 2018, 2019, 2020, 2021, 2022, 2023) less estimated land area usage for Data Centers using the available information on data center buildout (Amazon, 2024) and an average data center size of roughly 100,000 square feet (Zhang, 2023). Data is unavailable for the years 1998 through 2003.

0.1 km^2 per million metric tons of removal capacity per year. Using this estimate, the current capacity of Amazon warehouses could equivalently capture over 1 billion tons of CO_2 from the atmosphere per year. This growth included an expansion in the warehouse area by roughly 12 km^2 in one year, which could be equivalent to roughly 230 $MtCO_2$ per year in DAC capacity. To reach 1 $GtCO_2$ / year by 2035 would require scaling DAC at an average rate of ~91 $MtCO_2$ / year. Achieving 5 Gt of removal by 2050 will require 192 $MtCO_2$ / year on average.

5 Conclusion

DAC is a promising technology to remove CO_2 from the atmosphere at scale in accordance with global climate goals. Rapid deployment of these technologies is imperative, necessitating close attention to supply chain scalability and the ability to manufacture DAC systems at a massive scale. The integration of DAC with warehouse automation presents clear advantages with respect to manufacturing, construction, operational efficiency, and financing, which offer cost-effectiveness and enhance scalability. However, it's essential to recognize that a diverse portfolio of solutions will be required to effectively reach our global climate goals and attain net-zero emissions.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

NM: Writing – review & editing, Writing – original draft. DD: Writing – review & editing.

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Conflict of interest

NM and DD were employed by the Heirloom Carbon Technologies, Inc.

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