Research on Current and Future Aspects of Direct Air Capture of CO_2

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Abstract. Direct Air Capture (DAC) technology is a revolutionary method that employs sorbents and a capturing mechanism to extract carbon dioxide (CO2) from the atmospheric air. This approach presents a highly adaptable and scalable solution for mitigating greenhouse gas emissions. Once the CO2 is captured, its potential uses are virtually limitless, spanning from industrial applications to secure underground storage for long-term sustainability. This research paper delves into the current status and future prospects of DAC technology, which holds immense promise for directly reducing atmospheric CO2 levels. The exploration encompasses the core principles of DAC, its diverse applications, the advantages it offers, the evolving landscape of this transformative technology, and the keen interest of major corporations in expanding the utilization of DAC. With its potential to reshape the way this generation combats climate change, DAC technology emerges as a pivotal tool in our efforts to address the global carbon challenge.

Keywords: DAC, Climate Change, Greenhouse Emission, Sorbent, Scalability.

1. Introduction

In a world engulfed by smog and industrial sprawl, carbon dioxide has morphed into a symphony of despair, orchestrating the planet's downfall. Today, our planet faces a pressing challenge–climate change. By the way the term is used by media today, the words climate change may very much so sound formidable to some; however, like all problems, we need to address the roots of the problem first, and in climate change's case, the centuries' worth accumulation of greenhouse gases (GHG) is to blame.

When examining GHGs holistically, scientists were able to conclude that a major component of GHGs is in fact carbon dioxide (CO_2). CO_2's strong GHG potency is closely tied to its chemical composition and properties. In its linear configuration, a single carbon atom bonded to two oxygen atoms, yet it is this simple structure that jeopardizes Earth's climate system. In fact, recent research concludes that CO_2 accounts for a whopping 76% percentage of all GHGs [1]. CO_2's unique chemical structure gives it immense capabilities of disturbing the cycle absorbing and re-emitting heat in the atmosphere, thereby disturbing the habitable temperature range on our planet. When visualized, this process operates in a similar manner as a traditional greenhouse, hence the name "the greenhouse effect." Dating back to the beginnings of the Industrial Revolution in the early 1800s, the yearly rate of the amount of GHGs released into the atmosphere has generally spiked year after year. This accumulation of GHGs has contributed to the unprecedented escalating significance of causes like global warming and climate change. This research aims to explore the current and future aspects of Direct Air Capture (DAC) technology, which offers a promising avenue by directly removing CO_2 from the atmosphere.

2. Fundamentals of DAC

2.1. Sorbent-Based Capture Process

The heart of Direct Air Capture (DAC) technology lies in its ingenious capture process. As mentioned earlier, DAC employs chemical sorbents to selectively capture carbon dioxide (CO_2) from the atmosphere. This process is founded on the principle of chemical adsorption, wherein a sorbent

material reacts with CO_2, forming stable compounds that can be further processed for storage or utilization.

The choice of sorbent material is critical in determining the efficiency and effectiveness of DAC systems. Various sorbent materials have been explored, with amine-based solvents being a common choice. In a typical DAC reaction, CO_2 gas from the ambient air reacts with the amine-based solvent, resulting in the formation of ammonium carbamate. This stable compound can then undergo further processing during the compression phase of DAC to release pure CO_2.

2.2. The Role of Surface Area Maximization

Invented in 1916 by Irvine Langmuir in New York [2], DAC is a process driven by "[capturing and concentrating] CO2 from atmospheric air" to use in various applications. The main chemical principle behind capturing CO2 in DAC is via a chemical (typically liquid) sorbent. The sorbent reacts with CO_2 to form a stable compound, which can be further processed for storage or utilization purposes, as shown in fig.1.

Efficiency is a primary concern in DAC systems, and to achieve this, the surface area available for sorption reactions is maximized. Within DAC units, structures are composed of special metal sheets arranged in geometric patterns designed to maximize the interaction between the sorbent and incoming air. This ingenious design enhances the overall efficiency of CO_2 capture.

By increasing the surface area available for contact with the sorbent, DAC units can capture more CO_2 from the atmosphere within a given timeframe. This crucial aspect of DAC design ensures that the technology can effectively remove CO_2 on a large scale.

DAC employs an intake system utilizing fans to draw in atmospheric air. Once inside the system, the air is brought into contact with the sorbent [3]. The sorbent exhibits an affinity for CO_2, allowing it to selectively capture the CO_2 molecules from the air. Structures inside DAC systems are typically composed of special metal sheets arranged in ingenious geometric patterns to maximize the surface area available for the solvent to interact with the incoming air, enhancing the overall efficiency of CO_2 capture.

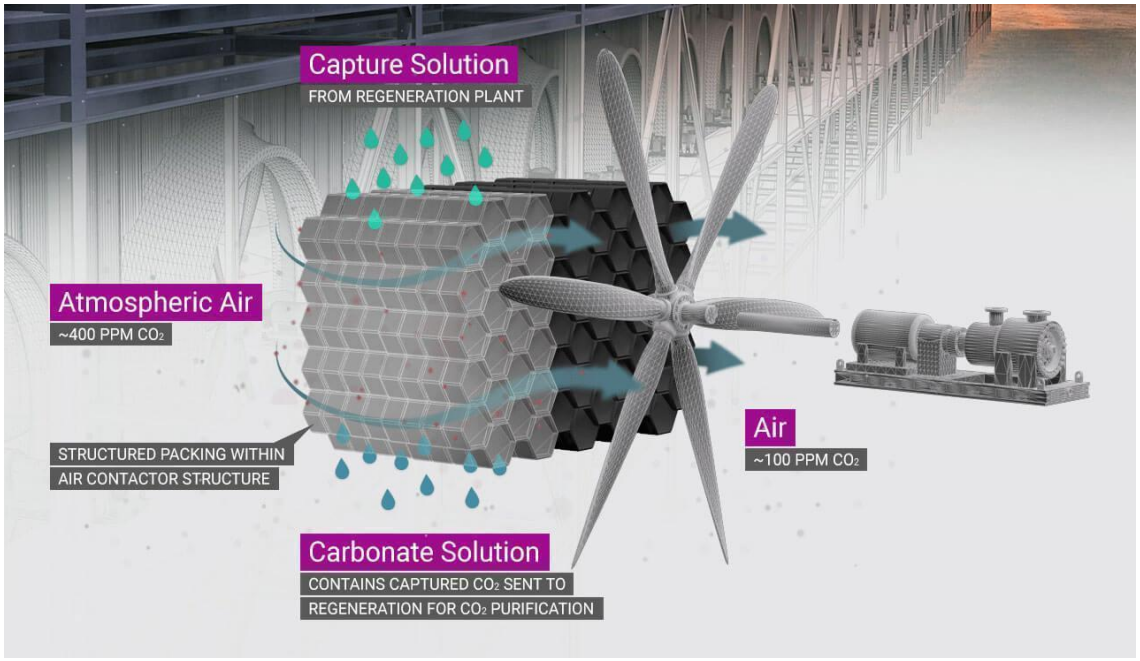


Fig.1 Diagram demonstrating the solvent phase inside of a DAC unit [4]

2.3. Chemical Process

A common reaction seen in DAC is as follows:

$$CO_2\,(g) + 2RNH_2\,(aq) \rightarrow RNH_3{+}\,(aq) + RNCOO{-}\,(aq) \quad (1)$$

In this example, RNH_2 is an amine-based solvent. The reaction results in the formation of the stable ammonium carbamate, which as mentioned previously, is able to be further processed to release pure CO2 through heat and pressure; this happens in the compression phase during DAC. In turn, pure CO2 could be utilized for industrial purposes (eg. to be used for energy) or could alternatively be stored in secure locations deep underground to mitigate emissions, as shown in fig.2 [5].

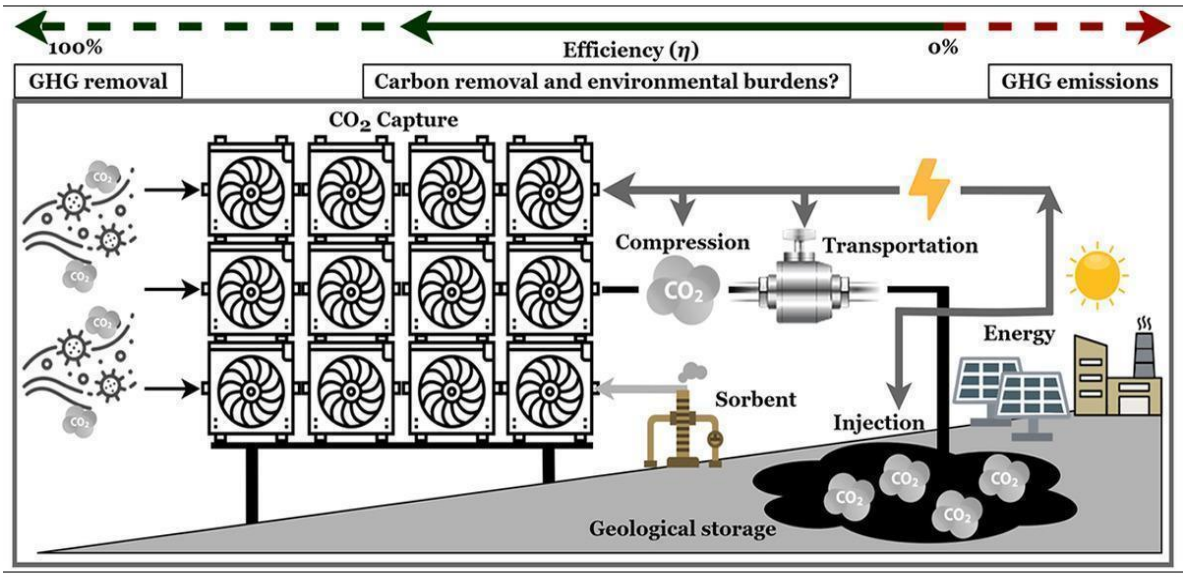


Fig.2 Illustrative diagram of the overall DAC process [5]

3. Applications and Benefits of DAC

3.1. Versatility and Scalability

DAC's real-world applications are not simply limited to industrial facilities: in fact, DAC has already been further employed across diverse fields to extract emissions from various sources, including urban areas, transportation, and agricultural operations, thereby offering a versatile solution for diverse emission challenges. Urban areas plagued by pollution, transportation systems emitting CO_2, and agricultural operations contributing to emissions have all benefited from DAC implementations.

To achieve such feats, DAC's scalability is a key advantage, as it can be implemented in sizes ranging from small urban installations to large industrial setups. While DAC technology may require further cost optimization (current costs are 94-232 \$USD/t-CO_2 as shown in fig.3 [6], it holds the potential to become a cost-effective carbon removal method as it matures and scales up (as per the economies of scale model).

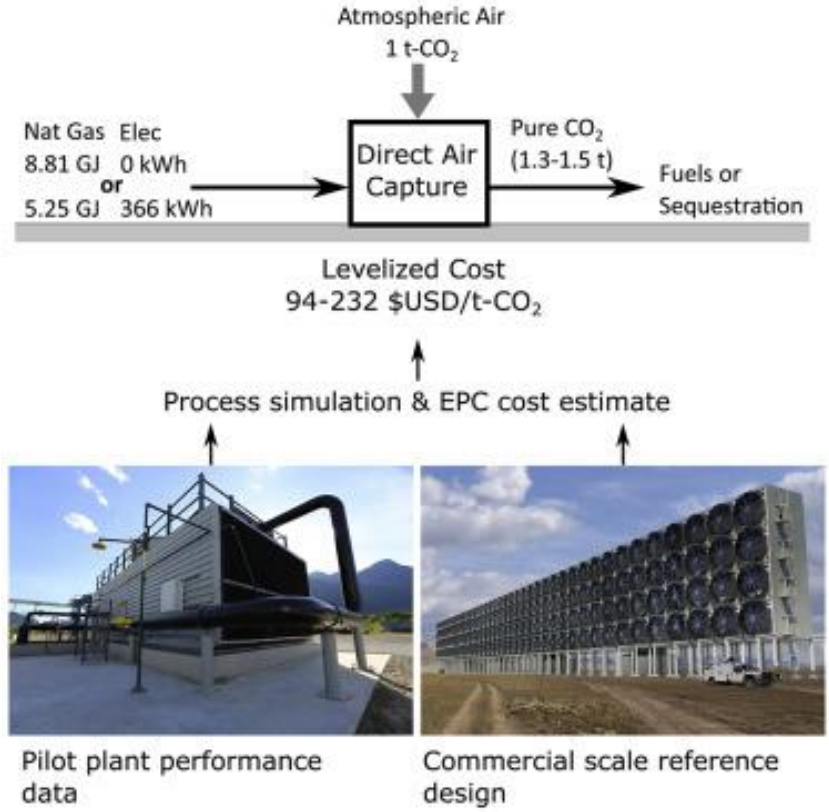


Fig.3 Costs Diagram [6]

Additionally, DAC systems are designed for thermal and chemical stability (which can be modified to suit regional differences such as climate in different places), ensuring their long-term functionality. Overall, DAC represents a promising tool for mitigating climate change all while complementing other greenhouse gas mitigation technologies and promoting carbon capture and utilization efforts.

3.2. Adapting to Challenging Environments and Optimizing Economic Aspects

DAC's adaptability to challenging environments sets it apart as a robust solution for emissions reduction. Unlike some carbon capture technologies that rely on vast tracts of fertile land, DAC systems are not constrained by land requirements. They can be situated in regions with infertile, making them suitable for deployment in a wide range of geographic locations. Because rough terrains are usually also cheaper in price, DACs can be implemented in more areas for less cost.

In addition, DAC systems are designed to function effectively in harsh climates, ensuring their reliability in regions where extreme weather conditions might pose challenges. The systems have simple yet rigid exterior structures, making them able to withstand the natural elements. This adaptability makes DAC a versatile solution for addressing emissions in diverse and demanding settings. This ongoing global expansion of DAC technology holds the promise of creating a network of carbon capture hubs, strategically positioned to combat emissions and combat climate change on a global scale.

4. Current and Future Aspects of DAC

4.1. Climeworks and DAC+S

On DAC’s path in gaining prominence in both current and future climate change mitigation strategies, an exemplary player entering the scene is Climeworks: a pioneering company actively engaged in carbon removal through DAC and its partnership with renowned developers and businesses.

Apart from traditional CO_2 removal from the atmosphere based on the fundamentals of DAC, Climeworks combines DAC with permanent underground, onsite storage in collaboration with their partner, Carbfix. Thus, Climeworks introduces a novel, all-in-one process coined DAC+S (Direct Air Capture and Storage). This underground storage involves the injection of captured CO_2 deep into geological formations, where it reacts with basalt rock, transforming into stone and effectively sequestering carbon for millennia [7]. Climeworks' DAC+S service is unique in its effectiveness and permanence.

4.2. Global Expansion and Collaborations

Climeworks' efforts are not confined to Iceland, where most of their DAC facilities are located. They are actively exploring partnerships and opportunities worldwide, exemplified by their interest in collaborating with 44.01 in Oman [7]. The collaboration with 44.01 in Oman highlights the growing interest in DAC as a viable solution for addressing emissions on a global scale. It also underscores the importance of international cooperation in advancing carbon capture technologies to combat climate change effectively. This global expansion signifies DAC's potential to be deployed in various regions where renewable energy sources and geological storage possibilities exist. The Middle East and North America, in particular, offer promising prospects for DAC technology.

In conclusion, Direct Air Capture technology, with its versatile and scalable applications, presents a promising avenue for mitigating climate change and addressing the challenges posed by greenhouse gas emissions. Innovations like Climeworks' DAC+S offer novel solutions that can help keep global warming below critical thresholds. As DAC evolves and expands its influence, it holds the potential to play a pivotal role in achieving a sustainable and carbon-neutral future for our planet.

5. What Lies Ahead

The Paris Agreement, adopted in 2015 by the United Nations in the COP 21 meeting, is a binding agreement that states participating countries would “pursue efforts to limit the rise in the climatological average global temperature to 1.5ºC above pre-industrial levels” [8]. The central goal of the Paris Agreement is to limit the rise in the average global temperature to 1.5ºC above pre-industrial levels, which remains paramount as we navigate the perilous waters of our changing climate. It was concluded in the COP21 that “global warming of 1.5 degrees Celsius above the preindustrial average, over an extended, decades-long period, would lead to high risks for “some regions and vulnerable ecosystems” [9].

The modular plant design of DAC, coupled with its minimal land footprint, makes it highly adaptable and scalable to diverse geographic regions. As successful DAC installations continue to demonstrate their effectiveness, there is great potential for replication in carbon-critical areas worldwide. In fact, As of July 2023, there are 27 DAC plants recorded by the International Energy Agency (IEA), commissioned worldwide, capturing almost 0.01 Mt CO2/year. Today, the IEA has plans for more than 130 DAC facilities, all at different stages of development. “If all were to advance (even those only at the concept stage), DAC deployment would reach the level required in 2030 under the Net Zero Emissions by 2050 (NZE) Scenario, or around 75 MtCO2/year” [10]. This optimistic statistic underscores the significance of DAC as a crucial component in achieving ambitious climate goals and addressing the mounting pressure to limit global warming to the +1.5°C threshold. It demonstrates that, in the face of this challenging target, modern technology and climate organizations are stepping up to the plate.

6. Conclusion

The continued globalization of DAC and DAC+S represents our commitment to preserving the planet for future generations. With such technologies at the forefront of our battle to reverse the damages to our environment, we have the tools to mitigate the climate crisis, restore balance to our

environment, and safeguard the well-being of all living beings on Earth. In the face of our current climate crisis, the significance of Direct Air Capture (DAC) and DAC+S lies in their ability to address historically unavoidable industrial emissions. By striving for net-negative emissions during an age in which emissions reduction issues remain paramount DAC and DAC+S hold the potential to restore environmental equilibrium and mitigate the devastating impacts of climate change, thereby aiding in keeping global warming below the globally recognized +1.5°C threshold. While DAC+S is one of several carbon removal solutions, its advantages are noteworthy. It is safe, scalable, permanent, measurable, efficient, and a natural process. The carbon dioxide captured is securely stored through natural mineralization processes, and pioneering companies like Climeworks have further simplified this storage step by establishing onsite storage and treatment facilities, paving the way for seamless and efficient carbon capture and storage ecosystems. The modular plant design of DAC, coupled with its minimal land footprint, makes it highly adaptable and scalable to diverse geographic regions. As successful DAC installations continue to demonstrate their effectiveness, there is great potential for replication in carbon-critical areas worldwide.

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