The Role of Direct Air Capture in the Sequestration of Anthropogenic Carbon Dioxide Emissions

Shaan Janardhan

Received June 16, 2023
Accepted September 14, 2023
Electronic access October 31, 2023

In the wake of climate change, increasing global carbon emissions threaten the welfare and livelihoods of humankind. A suite of climate mitigation strategies exists (e.g., Direct Air Capture, Afforestation, Biochar, etc.) to try to lower total carbon emissions and, subsequently, lessen climate impacts on humans and the environment. Yet, the cumulative impact that each climate mitigation strategy encompasses addresses only a fraction of the total carbon emitted into the environment. However, there is now a promising option to significantly offset carbon flux and emissions - the sequestration of carbon through the use of carbon capture and storage technologies (CCS). Specifically, one of the newest and most promising CCS technologies is direct air capture (DAC). DAC employs sorbents that absorb carbon directly from the atmosphere which are then heated to extreme temperatures, releasing the stored CO_2 into deep underground reserves. This paper explores current trends in DAC usage and compares DAC to other technological options for carbon sequestration. The goal of the paper is to not only provide a helpful, centralized report on the current status of DAC technology but to also assess the future promises, and potential pitfalls, of DAC technologies in the effort to strive for net zero global carbon emissions.

Introduction

Anthropogenic climate change presents a monumental threat to humanity. With over 34 billion tonnes[1] of carbon dioxide (CO_2) being emitted into the atmosphere every year, a number of irreversible environmental changes have already occurred, are currently ongoing, or are an imminent risk[2]. This includes sea level rise, historically extreme weather events, and the release of additional greenhouse gasses through the melting of arctic ice. A seemingly obvious solution to combat climate change would be to halt carbon dioxide emissions. However, this is proving to be a daunting task because 84% of world energy[3] is derived from fossil fuels. In addition, some industrial sectors that are logistically difficult to decarbonize—from the steel and cement industry to cattle farming to transportation—also contribute to global carbon emissions.

In order to meet the goal of limiting the global temperature rise to +1.5°C, as set by the Paris Agreement, the IPCC has estimated 1GT of net negative emissions is required by 2025[4]. This margin of +1.5°C was established in an attempt to avoid the most extreme anticipated impacts of climate change, but a global average temperature rise within these bounds would still contribute to irreversible changes. In order to avoid, or mitigate, such environmental change, net zero carbon emissions are necessary. Net zero carbon emissions (i.e., “net zero”) describe the sequestration of the same amount of CO_2 emitted. In order to achieve this ambitious goal, the IPCC has estimated that more than 85 Mt CO_2/year sequestration by 2030 and 980 Mt CO_2/year sequestration by 2050 is required (IPCC 2022)[5]. Figure 1 illustrates a path to the 1.5°C goal through a hybrid approach of reducing emissions and capturing CO_2. A hybrid approach presents the most feasible way to net zero global emissions.

Stemming from the above challenges to optimize negative carbon emissions, a promising frontier of carbon capture and storage (CCS) technologies have emerged in order to combat the climate crisis: direct air capture (DAC). With a multitude of CCS technologies already in use, DAC particularly stands out due to its ability to capture carbon dioxide emissions directly from the atmosphere and store unadulterated CO_2 gas. By comparison, other CCS technologies either sequester CO_2 from flue gas from fossil fuel power plants (much higher concentration of CO_2) or through entirely or enhanced natural processes, even with similar technologies. Despite this major difference, DAC and other CCS technologies use similar equipment and processes but employ them in different ways.

DAC can be divided into two major approaches: first, ‘Solid sorbent DAC’ and, second, ‘Liquid solvent DAC’. Here, ‘sorbent’ refers to the medium through which the CO_2 is absorbed. Both types of DAC require high amounts of energy and resources to absorb CO_2. Typically, solid sorbent DAC follows a simpler but slightly more energy-intensive process, as shown in Figure 2. It uses solid sorbents[6] that absorb CO_2 through chemical bonds (“chemisorbents”), van der Waals forces (“physisorbents”), or most commonly through amine-based chemisorbents[7]. Following CO_2 absorption, the sor-

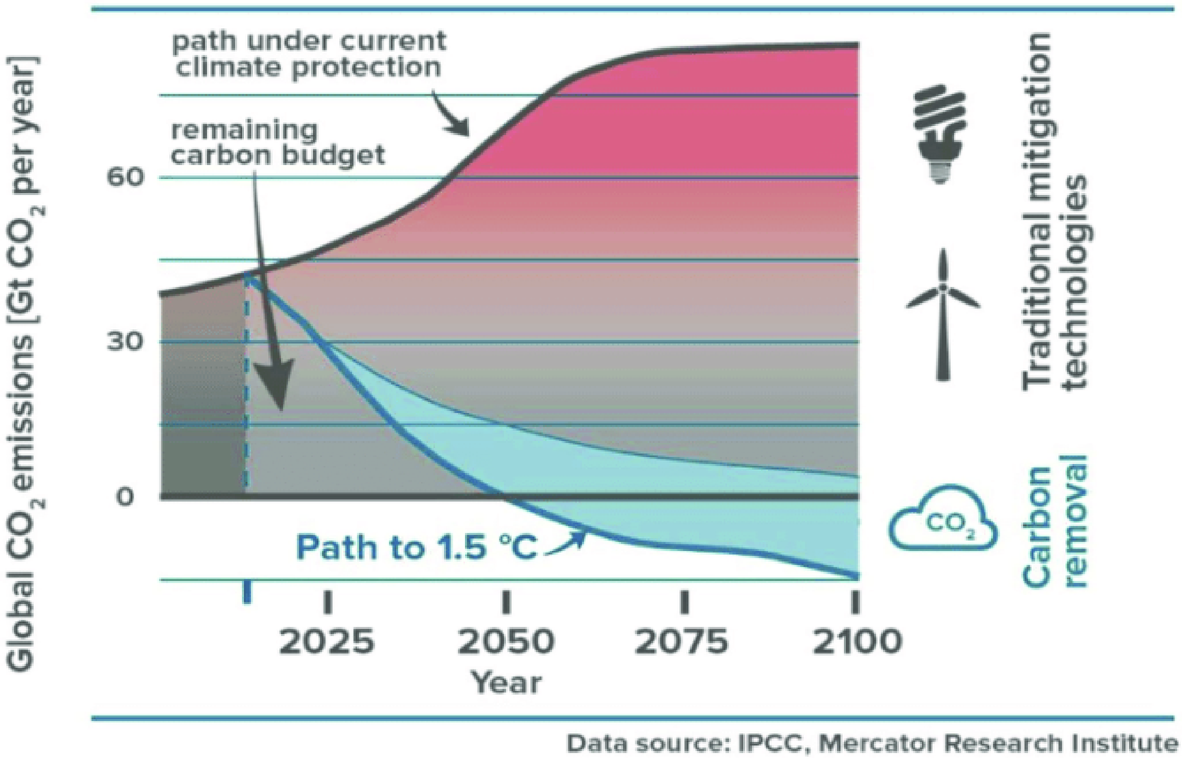

Fig. 1 Illustration of the Path to net zero with Carbon sequestration (IPCC)

bent is commonly heated to release the captured CO_2 in the sorbents into storage (usually injected deep underground afterward), thereby effectively reviving sorbents for further use.

Solid Sorbent DAC typically has these advantages:

- High CO_2 Capture Efficiency: Solid sorbents, especially amine-based chemisorbents, have a high affinity for CO_2 molecules, allowing for efficient capture from low-concentration ambient air.
- Well-Established Technology: Solid sorbent DAC technology is relatively mature and has been studied extensively, making it a well-understood approach for carbon capture.
- Scalability: Solid sorbent DAC systems can be scaled to capture significant amounts of CO_2, making them suitable for large-scale industrial applications.
- Modularity: The modular design of solid sorbent DAC units allows for flexibility in system configuration, enabling adaptation to various operational requirements.

On the contrary, Solid Sorbent DAC also has these disadvantages:

- Energy-Intensive: The process of heating solid sorbents to release captured CO_2 consumes a substantial amount of energy, contributing to high operational costs.
- Resource Requirements: Solid sorbents may require specialized materials, and the regeneration process can consume resources, adding to the overall environmental footprint.
- Chemical Handling: The use of amine-based sorbents involves handling potentially hazardous chemicals, posing safety and environmental risks.

Alternatively, liquid sorbent DAC employs a more complex process. It involves a reaction between a liquid solvent (usually potassium hydroxide) and carbon dioxide, forming a precipitate. A pellet reactor is generally used afterward to further break down these precipitates into pellets along with the original solvent which is reused. These pellets are then heated to release CO_2. Figure 3 shows the path of CO_2 through liquid DAC.

Liquid Sorbent DAC typically has these advantages:

- Chemical Specificity: Liquid solvents can be tailored to

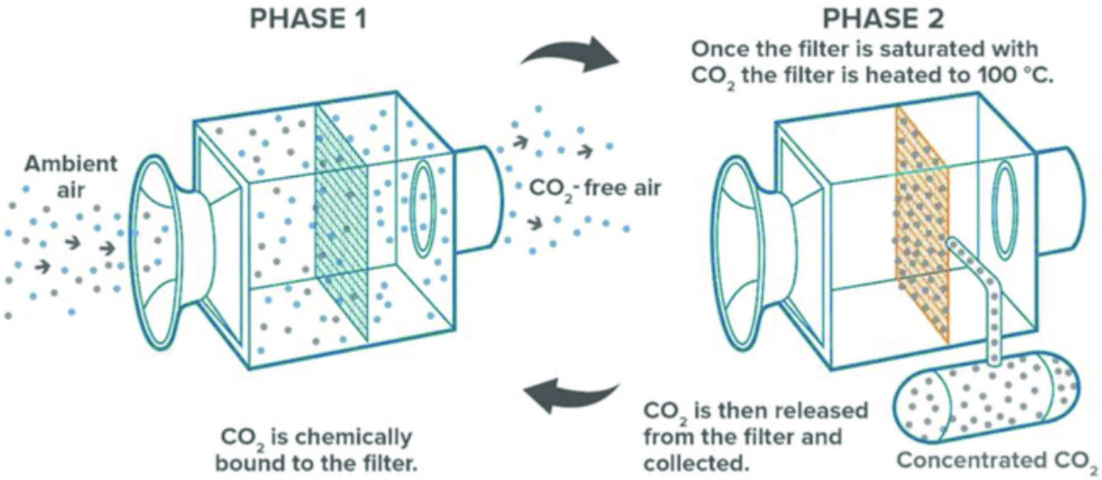

Fig. 2 Process of Solid Sorbent DAC

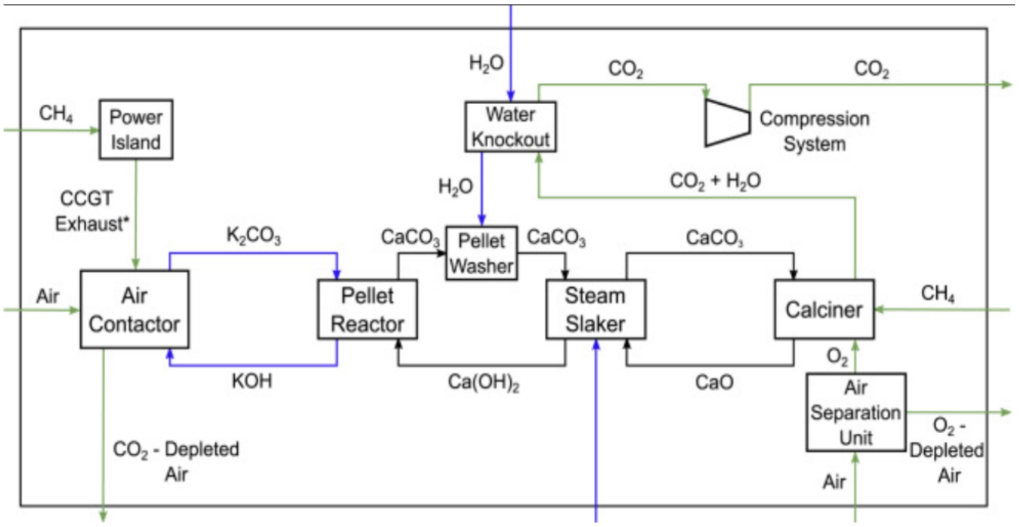

Fig. 3 Reaction Pathway of CO_2 through Liquid Sorbent DAC

have high selectivity for CO_2, minimizing the capture of other gases, which is particularly advantageous in low-concentration environments.

- Potential for Energy Efficiency: Liquid solvent DAC systems may offer opportunities for energy optimization in the CO_2 release step, potentially reducing overall energy consumption.
- Adaptability: Liquid solvent DAC can be customized by selecting different solvents, allowing for flexibility in system design and optimization.

On the contrary, Liquid Sorbent DAC also has these disadvantages:

- Complex Process: The chemical reactions and pellet formation process in liquid solvent DAC can be intricate, requiring careful control and monitoring.

- Solvent Management: Managing and recycling the liquid solvent can be challenging and resource-intensive.

- Energy Requirement: While liquid solvent DAC may have energy efficiency advantages in certain scenarios, it still demands a considerable amount of energy for CO_2 release.

- Environmental Impact: The choice of solvents and their potential environmental impact, including toxicity and disposal, must be carefully considered.

The processes behind direct air capture make it significantly more energy intensive compared to other CCS technologies[1]. This is not only because of the required energy for sorbent heating but also because of the comparatively lower concentration of CO_2 in the atmosphere that is targeted by DAC[2] as opposed to the higher concentration of CO2 in flue gas targeted by other CSS technologies. However, the high energy cost of DAC is arguably compensated for by the security of yield; compressed CO_2 from DAC is stored deep underground with a significantly low risk of release back into the atmosphere as compared to sequestered CO_2 via natural CCS technologies (e.g. afforestation) which are released back into the atmosphere through forest fires and decomposition of biomass[3]. Another advantage of DAC is how simple it is to quantify the amount of CO_2 sequestered, which can be quite a challenge with natural methods. Quantifying CO_2 sequestered can make research and development with DAC easier, with results that are clear.

As of 2022, there are 19 DAC facilities throughout the world, with the majority being pioneered by the company Climeworks[4]. These 19 facilities are estimated to sequester around 8,000 tonnes of CO_2 per year, though this number is expected to increase with the construction of 9 additional DAC capture plants planned by 2030[4]. If all additional facilities are built as planned, CO_2 sequestration through DAC would increase 380-fold[4] thereby increasing the total amount of CO2 captured per year from 8,000 tons to 3 megatons[4]. Notably, although this is an immense step forward in total carbon capture, 3 megatons of captured CO_2[4] accounts for a mere 3.4% of the sequestration needed to achieve the net zero goal set forth by the IEA[5]. Figure 4 shows the DAC capacity increase in the past, with data taken from the IPCC report[6].

Results

The suite of carbon capture technologies presents various economic advantages and disadvantages. Figure 5 shows the cost per ton of CO_2 for select carbon capture technologies (with data taken from the IPCC DAC report[7]). Figure 5 illustrates the potential and cost-related advantages and disadvantages of different CCS technologies. Notably, this figure fails to show the permanence of the stored carbon. While natural processes such as biochar and afforestation are safe and effective ways to store carbon, years of stored carbon can be released in a matter of hours with forest fires or unfacilitated decomposition processes[8].

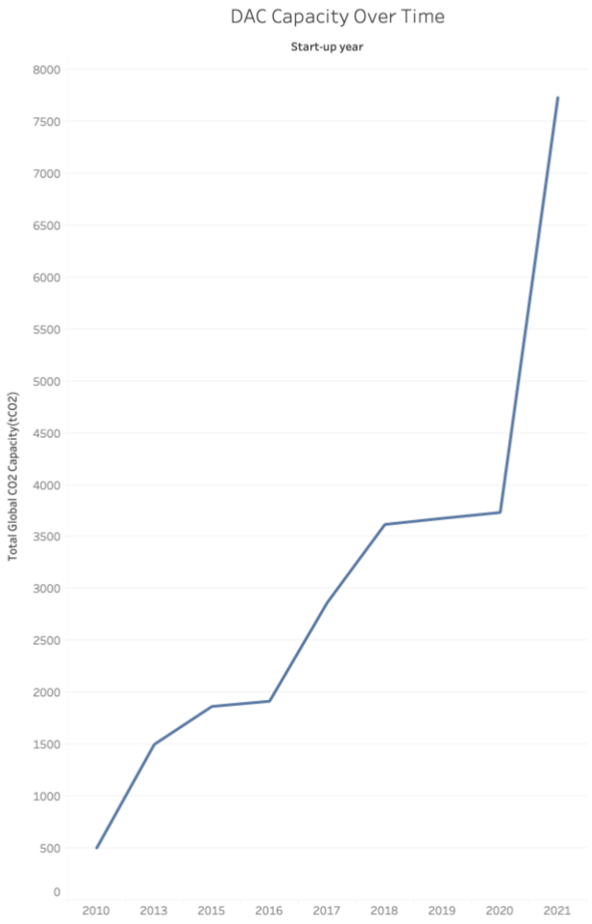

Fig. 4 Worldwide DAC Capacity growth over Time

DAC (Solid Sorbent and Liquid Solvent): DAC typically involves a higher initial capital cost and operational expenditure due to its energy-intensive processes. The energy requirement, expressed in kWh per ton of CO_2 removed, varies depending on the specific DAC technology and energy source. On average, DAC may require approximately 2,000 to 2,400 kWh per ton of CO2 removed, costing between USD 125 and USD 335 per tonne of CO2 removed[3]. DAC offers the advantage of be-

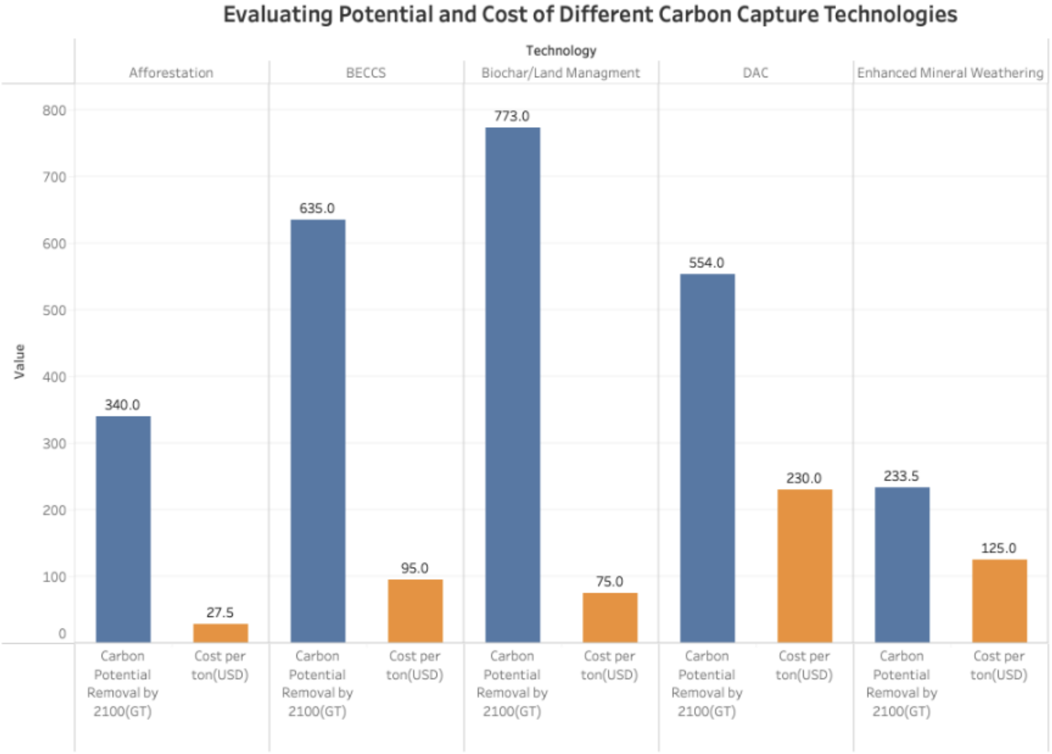

Fig. 5 Evaluation of Cost and Potential of Different CCS Technologies

ing capable of capturing CO2 directly from ambient air, which is especially valuable in addressing emissions from hard-to-decarbonize sectors. However, it presents challenges related to energy consumption and resource utilization. Achieving cost-effectiveness and reducing the energy footprint are key areas for improvement. Deployment of DAC should also consider the availability of clean energy sources to minimize its carbon footprint.

BECCS (Bioenergy with Carbon Capture and Storage): BECCS is known for its potential to remove significant amounts of CO_2 from the atmosphere. However, its efficiency varies based on factors such as feedstock, biomass type, and location. Generally, BECCS may require less energy per ton of CO2 removed compared to DAC, but it necessitates substantial land area for biomass cultivation and significant water resources for processing; carbon removal via BECCS could reach just under 50MtCO2/yr by 2030, costing between USD 60 and USD 250 per ton of CO2 sequestered[1]. BECCS has the advantage of using biomass feedstock, which can be renewable and carbon-neutral if sustainably managed. However, challenges include the need for large areas of land for biomass cultivation, potential competition with food crops, and sustainability concerns. Efficient carbon capture and long-term storage are also essential for the success of BECCS.

Enhanced Mineral Weathering: Enhanced mineral weathering involves the natural process of carbon mineralization, which is relatively energy-efficient. The energy requirements are generally lower compared to DAC, and its costs range from 60 USD to 200USD per ton of CO2 removed. However, this strategy demands substantial amounts of crushed minerals (such as olivine) and land area to spread these materials, which may limit its scalability and require careful consideration of resource availability[1]. Enhanced mineral weathering benefits from relatively lower energy requirements and can leverage natural geological processes. However, it relies on the availability of specific minerals, such as olivine, and extensive land areas for spreading these minerals. The best-suited locations are warm and humid areas, particularly in India, Brazil, South-East Asia, and China, where almost 75% of the global potential can be realized[9]. The transportation and processing of minerals also pose logistical challenges.

In summary, a quantitative assessment reveals that DAC tends to have higher energy requirements per ton of CO_2 removed compared to BECCS and enhanced mineral weathering. However, DAC's advantage lies in its ability to capture CO2 directly from ambient air. BECCS offers the potential for carbon-neutral biomass utilization but requires significant land and water resources. Enhanced mineral weathering is relatively energy-efficient but relies on specific minerals and extensive land use.

Operational considerations and feasibility assessments should consider these factors in conjunction with regional resource availability and environmental impacts to determine the most suitable CCS strategy for a given context. Further research and innovation are crucial to improving the efficiency and feasibility of each strategy in the broader context of carbon capture and storage.

DAC does not come without its own drawbacks. For example, although sequestered CO_2 via DAC will typically not reenter the atmosphere, DAC technologies require an immense amount of energy and a relatively higher cost per ton.

Furthermore, it is important to consider where the energy for DAC technologies can be derived. As mentioned above, DAC covers a significant energy footprint. For example, Climeworks calculates that in the long term, 2,000 kWh/tCO_2 is needed[1]. U.S.-based company Carbon Engineering believes that 2,400 kWh/tCO_2 is required per tonne in the long run[3]. Following Climeworks' estimations of energy required, Figure 6 shows the energy consumed over the last decade, amounting to approximately 15.6 million kWh of energy per year in 2021, assuming all previously built plants are still in operation. To put these numbers into context, the proposition by the Bipartisan Policy Center's DAC Council and the Rhodium Group has a goal of 7-9 million tonnes of CO_2 sequestered through DAC every year in the US by 2050[4]. The energy required by this would be around 0.3-0.4% of the US's current electricity generation. Thus, DAC would require a sizable share of worldwide energy consumption, not to mention that the energy sources for these operations have to be clean. For example, a Climeworks system is predicted to have a 2,000 kWh/tCO_2 energy requirement[1], which, if this energy is taken from a fossil fuel source like coal which has an average of 2.23 pounds of CO_2 emitted per kWh (eia.gov), then 4,460 lbs of CO_2 are released to sequester 2,205 lbs of CO_2, thereby releasing more CO_2 (2,256 pounds) than it sequesters and undermining the ultimate goal[1].

Climeworks owns 14 of the 19 DAC facilities worldwide and sequesters approximately 5,870 tonnes of CO_2 annually. Notably, more than half of all sequestered CO_2 by Climeworks is captured in Iceland, mainly owing to the country's unique geography that allows geothermal heat to be used in the process of DAC[2] along with basalt rock composition that allows almost all sequestered CO_2 to be injected into the ground. Figure 7 shows the capture capacity of the 3 major companies involved with DAC, and Figure 8 shows the major[3] DAC projects in operation or under development[4].

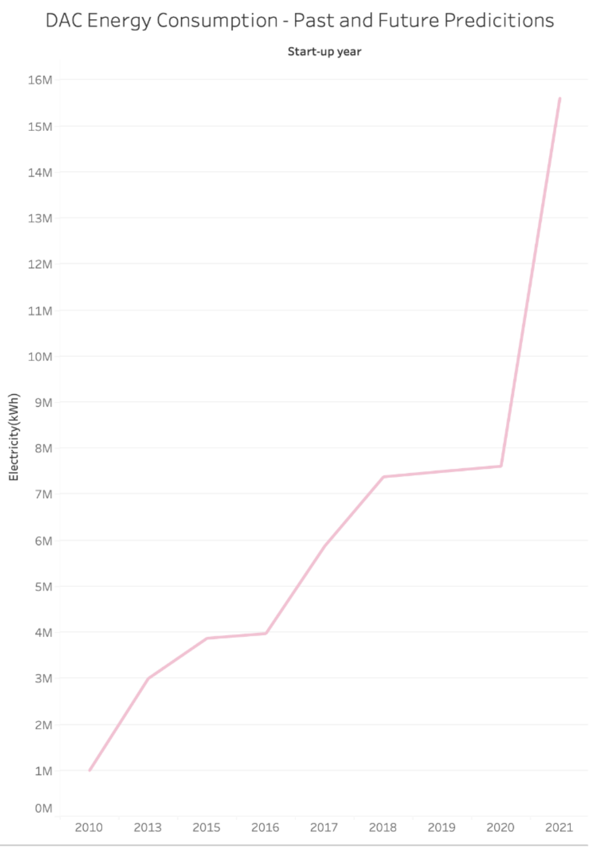

Fig. 6 DAC Energy consumption in the Past

Looking further into Climeworks, the Switzerland-based company employs a stackable, modular design that performs solid DAC in closed units that can each capture up to 50 tonnes of CO_2 annually, with this number only set to increase in the future[5].

Climeworks is in possession of some of the most notable DAC plants, including the world's first commercial DAC project based in Hinwil, Switzerland, with sequestration starting in 2017. This plant removes 900 tonnes of CO2 per year, exporting the captured carbon to a greenhouse about 400 miles away via pipeline to help grow vegetables (Climeworks 31.05.2017). Another notable DAC project from Climeworks was the development of the CarbFix injection plant (Figure 9), a collaboration between Climeworks and Reykjavik Energy. This project also finished in 2017 (started in 2012) and funded by the EU, was the first DAC plant to store captured CO2 permanently, which in this case occurred through mineralization in local basaltic rock[6].

Two other notable companies that deserve attention are Carbon Engineering and Global Thermostat.

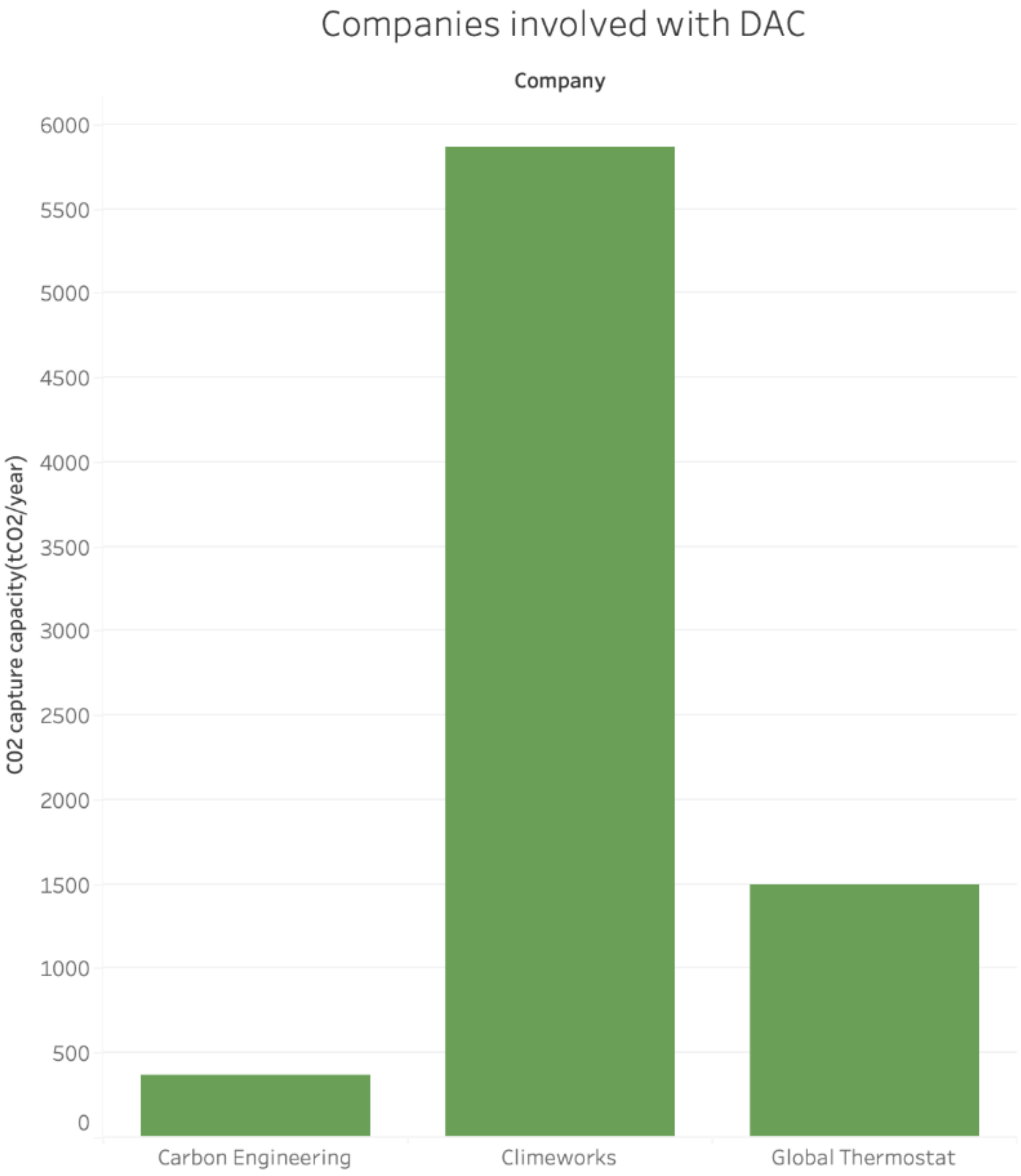

Fig. 7 CO_2 Capture Capacity of Existing DAC COmpanies

Carbon Engineering, based in Vancouver, British Columbia, has gained prominence for its innovative DAC technology. Their approach primarily involves the use of liquid sorbent DAC. Their DAC plants employ a liquid solvent, typically potassium hydroxide, which reacts with carbon dioxide to form a precipitate. A pellet reactor further processes these precipitates into reusable pellets along with the original solvent. One significant advantage of Carbon En-

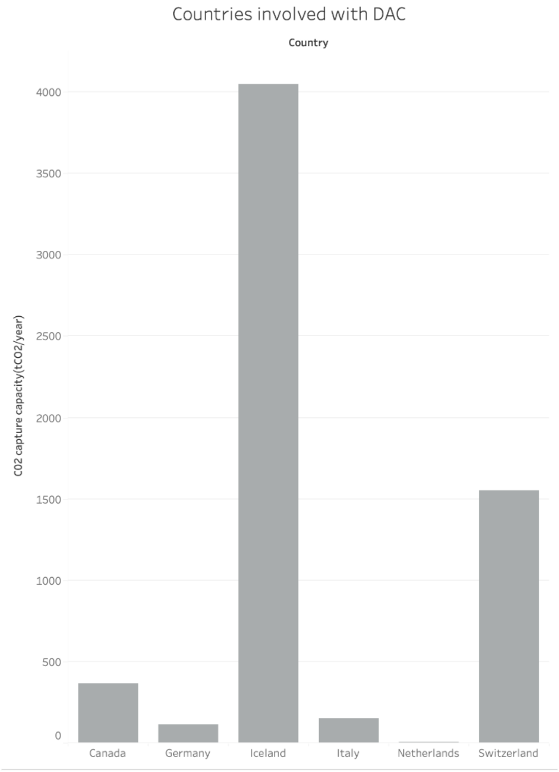

Fig. 8 CO_2 Capture Capacity per country

gineering's approach is its scalability. Their DAC plants can be designed to capture large quantities of CO2, making them suitable for industrial-scale carbon capture. However, like other DAC methods, Carbon Engineering's technology demands a substantial amount of energy, and the energy source must be considered carefully to ensure its sustainability.

Global Thermostat, headquartered in New York, takes a unique approach to DAC. Their technology employs a solid sorbent-based system that involves chemisorption to capture carbon dioxide directly from the atmosphere. This approach has the potential to offer advantages in terms of energy efficiency and process simplicity. Global Thermostat's DAC technology is modular and stackable, making it adaptable to various settings and capacities. The versatility of their approach allows for potential integration into a wide range of industries and applications.

It is essential to analyze and compare the strategies, costs, and environmental impacts of these companies alongside Climeworks to gain a comprehensive understanding of the DAC industry's current landscape. Such comparisons can provide valuable insights into the future directions and potential improvements within the carbon DAC industry.

Discussion

Assessing the future of DAC as a whole, there are a number of known and anticipated problems associated with this technology. DAC could play a vital role in reaching the +1.5°C goal of the Paris Agreement but remains limited in its applications. For example, it is likely unrealistic to envision a world in 2050 that emits a great amount of carbon with all of it being captured through CCS flue gas capture or DAC. As a result, this leads to hybrid carbon capture scenarios. For example, in the ETC (energy transition commission) base scenario, out of 6.9 Gt of carbon capture, only 3.2 Gt, around 30 percent, of CCUS is actually done through DAC, with the rest being CCUS technologies that capture flue gas. The IEA estimate for DAC in the future is even more conservative, with a greater focus on decarbonizing energy sources, which, from an economic perspective, is far more efficient given the costs of DAC.[7]

The characteristics of other available technologies put into question whether DAC is "worth it" — specifically due to its high costs and low fruition compared to other technologies. Ultimately, because of this, DAC is almost always used in combination with other technologies. In order to further categorize technologies, the ETC separated CCS technologies into the following:

1. Restorative solutions: Restoration of natural carbon sinks[8]
2. Improved management solutions: Enhancing of natural carbon sequestration processes[10]
3. Hybrid and engineered approaches: Man-Made CO_2 removal processes[11]

While DAC usage is burgeoning, its total CO_2 removal may be less significant than the potential for CO_2 removal by other sequestration processes, notably natural solutions[1]. Another important question is simply, when? The cost to deploy DAC technologies is likely to decrease in the coming years. As a result, it may be advantageous for certain industries to wait a period of time (e.g., 10 years) to deploy extensive DAC operations. However, critics may argue that such technological development would not be able to compensate for a 10-year deficit. Both timelines for deploying DAC technology have their own risks and benefits. Nevertheless, the plan to start DAC operations as soon as possible is widely supported, with companies like Climeworks following this plan[2].

Economic Buy-Ins for DAC

Economic incentives also play a significant role in DAC. As of now, most DAC projects are widely supported through philanthropy rather than financial benefits. Global investors keep the projects well funded. For example, Climeworks raised $650 million USD in May 2022 through an equity round[1]. However, in the future, it may be unrealistic to envision DAC as a philanthropically funded entity, rather than a profitable industry. While excess CO_2 can be sold for industrial purposes, more is needed to make any sort of profit, making funding a dilemma that future investors and DAC leaders will both have problems with. Ultimately, the use of DAC will need to become an economically self-sufficient and sustainable industry.

Conclusion

Direct Air Capture as a whole is a promising technology that may be humankind's only option to solve anthropogenic climate change. By directly absorbing CO_2 from the atmosphere, it can lower global CO_2, but with a mammoth energy footprint, in turn, leading to large operating costs. By exploring DAC; both its strengths and weaknesses, one can foresee future problems, create solutions, and incentivize global investors to invest in this potentially world-altering technology, and use it as an important tool in achieving the exceptional goal of net zero.

Methods

Literature Review

A comprehensive review of existing literature and research papers was conducted to gather information on the current state of Direct Air Capture (DAC) technology and its comparison to other carbon sequestration strategies. Relevant studies, reports, and publications were analyzed to gain insights into the principles, processes, and challenges associated with DAC. The review focused on identifying key DAC technologies, including solid sorbent DAC and liquid solvent DAC, their mechanisms, and energy requirements. Additionally, information on DAC facilities, their capacity, and carbon sequestration rates was collected from reliable sources such as industry reports, scientific publications, and official websites.

Data Collection

To collect data on DAC technologies and their performance, a systematic approach was employed. Information regarding the efficiency, energy consumption, and costs of DAC technologies was gathered from technical documentation, research papers, and reports from reputable sources. Data on DAC facilities, including their location, scale, and operational parameters, were also collected. Furthermore, information on other carbon sequestration strategies such as biochar, afforestation, and enhanced mineral weathering was gathered for comparative analysis. This data collection process aimed to provide a comprehensive and up-to-date understanding of DAC technology and its position in the field of carbon capture and storage (CCS).

Comparative Analysis

A comparative analysis was performed to assess the advantages and disadvantages of DAC in comparison to other carbon sequestration technologies. The collected data, including costs, land and water requirements, energy consumption, and CO_2 storage permanence, was systematically analyzed for each CCS technology under consideration. The data was synthesized and compared to identify the unique characteristics and trade-offs of DAC. Special attention was given to understanding the scalability, technological readiness, and potential environmental impacts of DAC in relation to other strategies.

Future Outlook

The future prospects of DAC were evaluated based on projections, expert opinions, and industry trends. Reports such as those from the Intergovernmental Panel on Climate Change (IPCC), Energy Transitions Commission (ETC), and International Energy Agency (IEA) were consulted to understand the role of DAC in achieving global climate goals. The potential challenges and risks associated with DAC implementation, including technological advancements, scalability, and economic viability, were discussed based on the available literature. This analysis aimed to provide insights into the potential trajectory of DAC and its role in mitigating climate change.

Economic Analysis

An assessment of the economic aspects of DAC was conducted to understand its financial implications and potential for commercialization. Information on funding sources, investment trends, and financial aspects of DAC projects was gathered from reputable sources. This included examining philanthropic support, global investors, and equity rounds in the DAC industry. The economic viability of DAC and the transition towards a self-sustaining industry were analyzed based on the current funding landscape and potential revenue streams. This analysis aimed to provide insights into the economic feasibility and market potential of DAC technology.

Synthesis

The gathered information and analysis were synthesized to provide a comprehensive overview of the current status and future promises of DAC technology. The strengths, weaknesses, opportunities, and threats of DAC were discussed, considering its potential role in achieving net-zero carbon emissions. The findings from the literature review, data analysis, and future outlook were used to form a well-rounded understanding of DAC as a carbon sequestration strategy. The synthesis aimed to present a balanced perspective on the current state and future potential of DAC in addressing climate change.

Acknowledgments

I would like to extend my sincere appreciation to Dr. Kieran Gilmore, an esteemed professional from Cambridge with a Ph.D. in Earth Sciences, and Mary Burak, a Ph.D. Candidate at the Yale School of the Environment. Their expertise, support, and mentorship have been instrumental in the successful completion of this project.

References

1 I.P.C.C., *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
2 Climeworks, *Direct Air Capture and Storage: A Review*.
3 C. Engineering, *A Process for Capturing CO2 from the Atmosphere*.
4 B. P. C. D. Council and R. Group, *The Potential for Direct Air Capture to Help Meet U.S*, Climate Goals. Bipartisan Policy Center, Washington, DC.
5 N. A. Sciences, Engineering and Medicine, *Negative Emissions Technologies and Sustainable Development*, The National Academies Press, Washington, DC.
6 W. R. Institute, *Insights: Direct Air Capture Resource Considerations and Costs of Carbon Removal*, World Resources Institute, Washington, DC.
7 B. Scientific, *CCS, BECCS and DAC - What is the difference?*, Biolin Scientific, Gothenburg, Sweden.
8 *ETC (energy transition commission*, ETC, Brussels, Belgium.
9 A. Gambhir and M. Tavoni, *One Earth*, **1**, 405–409.
10 Climeworks, *Climeworks starts the world's first commercial direct air capture and storage plant*.
11 CarbFix, *CarbFix: Permanently storing carbon dioxide in basalt rock*.