

## Review

Current status and pillars  
of direct air capture technologiesMihrimah Ozkan,<sup>1,2,3,\*</sup> Saswat Priyadarshi Nayak,<sup>1</sup> Anthony D. Ruiz,<sup>1</sup> and Wenmei Jiang<sup>1</sup>

## SUMMARY

Climate change calls for adaptation of negative emission technologies such as direct air capture (DAC) of carbon dioxide (CO<sub>2</sub>) to lower the global warming impacts of greenhouse gases. Recently, elevated global interests to the DAC technologies prompted implementation of new tax credits and new policies worldwide that motivated the existing DAC companies and prompted the startup boom. There are presently 19 DAC plants operating worldwide, capturing more than 0.01 Mt CO<sub>2</sub>/year. DAC active plants capturing in average 10,000 tons of CO<sub>2</sub> annually are still in their infancy and are expensive. DAC technologies still need to improve in three areas: 1) Contactor, 2) Sorbent, and 3) Regeneration to drive down the costs. Technology-based economic development in all three areas are required to achieve <\$100/ton of CO<sub>2</sub> which makes DAC economically viable. Current DAC cost is about 2–6 times higher than the desired cost and depends highly on the source of energy used. In this review, we present the current status of commercial DAC technologies and elucidate the five pillars of technology including capture technologies, their energy demand, final costs, environmental impacts, and political support. We explain processing steps for liquid and solid carbon capture technologies and indicate their specific energy requirements. DAC capital and operational cost based on plant power energy sources, land and water needs of DAC are discussed in detail. At 0.01 Mt CO<sub>2</sub>/year capture capacity, DAC alone faces a challenge to meet the rates of carbon capture described in the goals of the Paris Agreement with 1.5–2°C of global warming. However, DAC may partially help to offset difficult to avoid annual emissions from concrete (~8%), transportation (~24%), iron-steel industry (~11%), and wildfires (~0.8%).

## INTRODUCTION

Carbon dioxide (CO<sub>2</sub>) is one of the six main greenhouse gases. Its lifespan in the atmosphere is between 300 and 1,000 years, many human generations. According to the Mauna Loa Observatory in Hawaii, the atmospheric CO<sub>2</sub> levels increased to an average of nearly 420 parts per million today, about 50% higher than before the Industrial Revolution (280 ppm), prompting climate change mitigation discussions in Paris, on December 12 2015. More than 2,000 GtCO<sub>2</sub> has been emitted by humans since the Industrial Revolution. As per the IPCC's 2021 report on climate change (Masson-Delmotte et al., 2021), "Human influence has warmed the climate at a rate that is unprecedented in at least the last 2000 years". The report focuses on possible climate futures, and ways to limit human-induced climate change. In the Paris meeting, limiting global warming below 2°C, preferably to 1.5°C, compared to preindustrial levels was defined as the global goal. By mid-century, participating countries would aim for a carbon neutral world by reducing greenhouse gas emissions as soon as possible. To address the gravity of this from a policy perspective, several countries have recently started initiatives that are designed to reduce emissions. For instance, Argentina has four new initiatives that aim at reducing the use of fossil fuels and reducing carbon emissions (United Nations Environment Programme, 2019). Brazil has taken ambitious climate action by setting a target for low-carbon alternatives and the utilization of 100 percent CO<sub>2</sub>-free new vehicles (United Nations Environment Programme, 2019). China has placed a ban on coal-fired plants along with also setting a target for the use of 100 percent CO<sub>2</sub>-free new vehicles. The European Union, India, Japan, and USA have also set a goal of phasing out the use of gasoline vehicles while introducing zero-emission cars (United Nations Environment Programme, 2019). Recently, the Breakthrough Energy Catalyst program within the COP26 Glasgow meeting aims to raise up to \$30bn in investments and bring down costs for green hydrogen, Direct

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<https://doi.org/10.1016/j.isci.2022.103990>

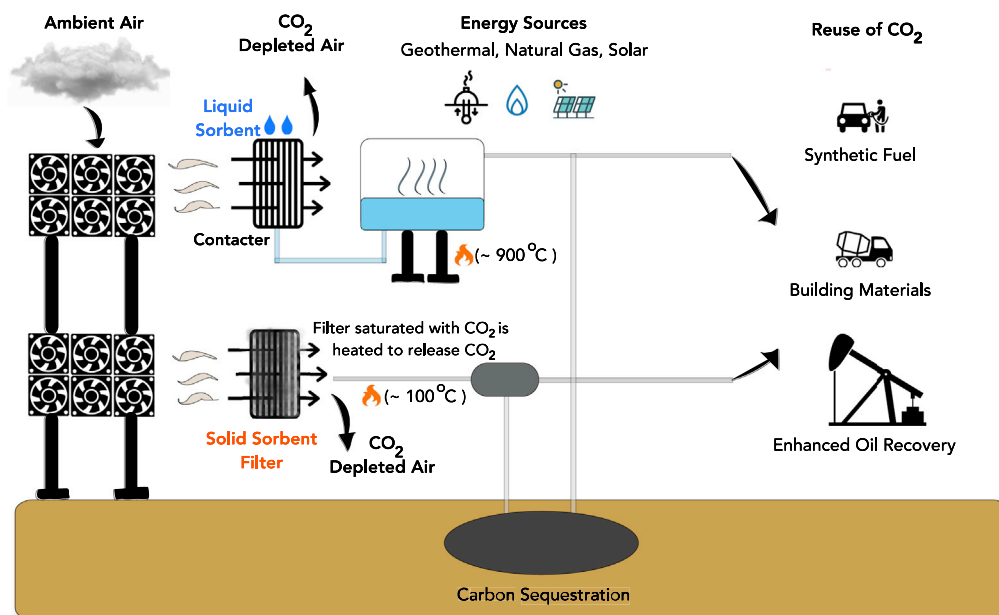


Air Capture of CO<sub>2</sub>, and long-duration energy storage. Given the gravity of climate change, several countries are now taking what is considered ‘ambitious climate action’ to aid in climate change mitigation efforts. This binding agreement among the participating countries, for the first time, brings all nations into combat with climate change and implementations of related mitigation technologies.

Along with aggressive emissions reductions, the IPCC indicates that by 2050 the world needs to remove 2–20 gigatons of CO<sub>2</sub> from the atmosphere annually. This will likely require a portfolio of carbon removal approaches. There are six major technical approaches to remove CO<sub>2</sub> and sequester: Coastal blue carbon, Terrestrial carbon removal and sequestration, Bioenergy with carbon capture and sequestrations (BECCS), Carbon mineralization, Geological sequestration, and Direct air capture (DAC). DAC among the six approaches is the most expansive carbon removal method (National Academies of Sciences, 2018). There is a lot of indecision from policy makers and those in search of new groundbreaking technology. Each of the technical approaches mentioned above have their own share of pros and cons, when it comes to the land use. DAC garners much attention because unlike BECCS and Coastal blue method it does not require hectares of land and does not have to be near a coastal region. DAC, using liquid or solid sorbents to capture CO<sub>2</sub> directly from the air using contactors with large surface area for better air contact, and later release and store the captured CO<sub>2</sub>, does not require arable land. In addition, DAC can help with difficult to avoid emissions and emissions from distributed sources. These include annual emissions from concrete (~8%), transportation (~24%), iron-steel industry (~11%), and wildfires (~0.8%). Furthermore, the highest concentration of CO<sub>2</sub>, 420 ppm, in the vertical scale of the atmosphere is near 1.5 km from the surface of earth. CO<sub>2</sub> concentration is about 0.5% less at nearly 4 km altitude in the atmosphere (Le Quéré et al., 2020). Hence, installation of DAC plants on the surface of earth can help to capture the vertically highest levels of CO<sub>2</sub> present through the atmosphere.

There are currently 19 DAC plants operating worldwide, capturing an average of 10,000 tCO<sub>2</sub>/year, with a one MtCO<sub>2</sub>/year capture plant in advanced development in the United States (Direct Air Capture – Analysis, 2021). As per our calculations, an estimated number of 1250 DAC plants with a capacity of one MtCO<sub>2</sub>/year each, would be required to remove 25 GtCO<sub>2</sub> by 2030, assuming a linear growth of carbon capture and storage from the current capacity of 0.0385 Gt per year (Global CCS Institute, 2018) to a capacity of 20 Gt per year (National Academies of Sciences, 2018) in 2020. The analysis assumes a linear growth for simplicity, but the DAC technology might follow an exponential growth like several other technologies in the last few decades. This would mean acceleration in the DAC operations over the next few decades. A single plant with capacity 1MtCO<sub>2</sub>/year would require an area of 0.2 km<sup>2</sup> equivalent to 28 soccer fields. The land area and water requirements and related analysis are discussed in the future sections. Beware that, for a liquid solvent DAC technology today to capture one ton of CO<sub>2</sub> nearly 1–7 tons of water is used (Lebling et al., 2021) and in some cases this may reach to 13 tons (in a conventional monoethanolamine absorption with 30% humidity). Such amount of water needs is an important parameter together with the required land size for a plant, and could play an important role in choosing the DAC plant’s scale and location.

To have a meaningful impact on the climate, DAC needs to realize gigaton scale at less than \$100/ton by 2050. One of the major challenges with the current DAC technologies are the capital cost, running energy cost because of inherent low concentrations of CO<sub>2</sub> in air, nearly 0.04%, and thermal regeneration process. Partial pressure is almost 300 times less than the CO<sub>2</sub> amount from a typical coal flue gas, at nearly 12%, hence the capture process requires nearly 3 times more energy. Furthermore, the regeneration step requires 900°C for liquid sorbents and 80–120°C for solid sorbents, being the most energy demanding part of the DAC process (Chatterjee and Huang, 2020; National Academies of Sciences, 2018). Today, the range of costs for DAC vary between \$250–\$600 and with the use of renewable energy sources for DAC operations, based on the technology choice, the costs for captured CO<sub>2</sub> is calculated as nearly \$125/tCO<sub>2</sub> in the year 2030 (Breyer et al., 2020). Pioneering new approaches to drive the cost down are actively being investigated by many startup companies today specifically in areas of air contactors, sorbents, and regeneration methods. Passive air contacting to draw the air to the system, modular implementation and advances in chemistry of sorbents with increased CO<sub>2</sub> capture rate, and reduced cost of the sorbents themselves are the most active areas in DAC technologies (Ozkan et al., 2022). Furthermore, the regeneration step takes approximately 7–13 GJ of energy for every ton of CO<sub>2</sub> captured from the air. To drive down the operational energy cost, a tailored regeneration method is emerging by subjecting the entire sorbent chamber to huge temperature swings. Now DAC technology is still in its infancy and within the next decade many innovative approaches in all three areas are highly expected.



**Figure 1. CO<sub>2</sub> captured from air using liquid and solid sorbent DAC plants, storage, and reuse**

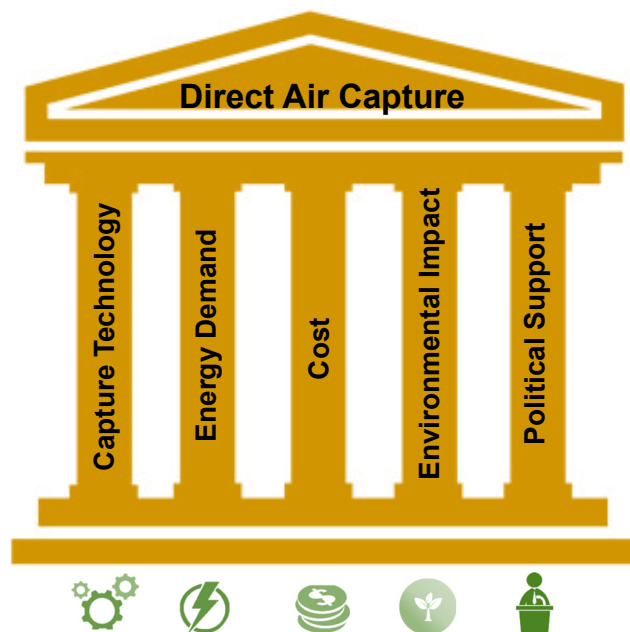
The ambient air is sucked in through large fans which is then treated with a chemical sorbent (Liquid or Solid) and heated to extract CO<sub>2</sub>. This CO<sub>2</sub> is then either sequestered or used in other industries as shown.

To this end, there is a need for investment in DAC technology development and de-risking now, so that DAC can mature fast enough to meaningfully contribute to a portfolio of carbon removal approaches in the coming decades. Several governments have enacted various initiatives and funding programs to aid in the adoption of DAC and to overcome current grand challenges. The US recently announced its funding of 24 million dollars to be used for R&D of DAC along with a newly reformed 45Q tax. The UK similarly announced their funding of 70 million euros for research in DAC and greenhouse gas removal, whereas the European Union's funding of DAC recently ended with their project "Store&Go". The Canadian government has also demonstrated their support of DAC by donating 24 million dollars to Carbon Engineering (Carbon Engineering, 2022; Direct Air Capture et al., 2020; Materials and Chemical Sciences Research for Direct Air Capture of Carbon Dioxide, 2021). Third Derivative and other investment firms are providing early investment to enable startups in this field to pursue innovations in air contactors, sorbents, and energy efficient regeneration methods.

In this article, we discussed the current status of DAC, pillars of technology, and new projects that are planned for the near future. Based on a selected case study, land and facility size requirements for different DAC technologies are estimated and presented. Latest techno-economic analysis, capital and operational costs for different DAC technologies, and how they alter by the energy from different sources are discussed in detail. Carbon footprint of technology and their potential environmental impacts are also reviewed extensively under the section -life cycle analysis. The purpose of this review will be to lay out the principles of existing DAC technologies and bring out the level of challenges that need attention for the main pillars of capture and release DAC technology such as cost, energy demand, environmental impact, and political support that are highly critical for the successful deployment of DAC.

### THE STATUS OF CURRENT AND PLANNED DAC PROJECTS

The 19 DAC plants currently in operation capture nearly 10,000 tCO<sub>2</sub> per year (Direct Air Capture – Analysis, 2021). Many such DAC are ramping up their capture capacity and expanding throughout the globe. A DAC operates on the principle of extracting the atmospheric carbon dioxide to reuse it in other industries or sequestering it in the ground as shown in Figure 1. In this section the developments in commercial DAC projects are first discussed. The main focus is on companies like Climeworks, Carbon Engineering, Global Thermostat, and Passive Direct Air Capture Technology (PDAC) by MechanicalTree. Although most of the companies like Climeworks and Carbon Engineering rely on large fans for the intake of air followed by



**Figure 2. The five pillars of direct air capture**

Factors like carbon capture sorbent technology, electrical and thermal energy demand, cost, the environmental impact, and political support from different regimes affects the adoption of the DAC technology. These pillars need to be balanced well for the successful deployment of diverse DAC technologies.

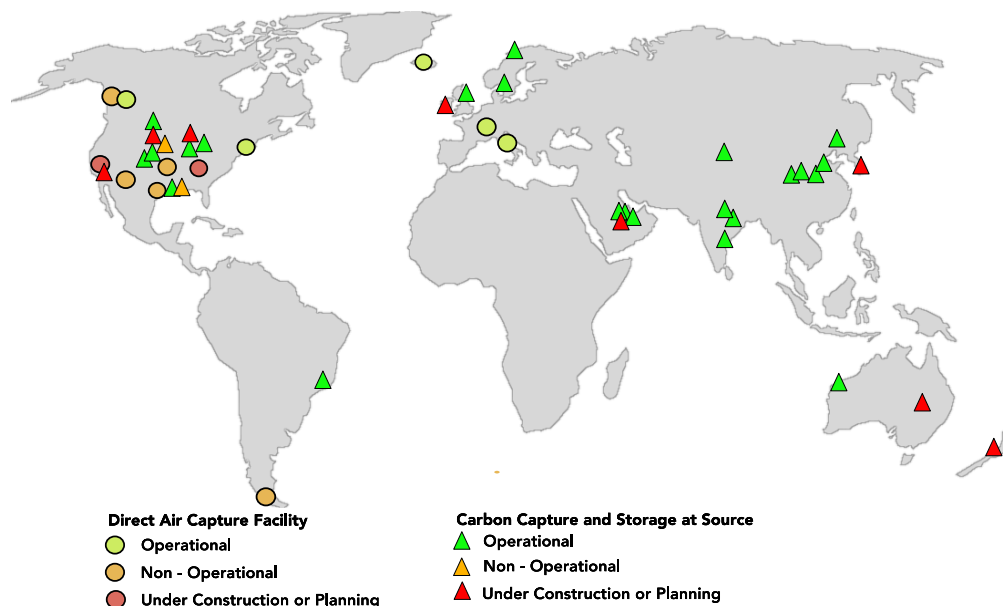
carbon capture and storage, MechanicalTree seems to have found a novel approach of capturing carbon without fans. The PDAC technology relies on flowing wind rather than forced air intake ("[MechanicalTree, 2020](#); [Shi et al., 2020b](#); [Arizona State Press, 2020](#)). The following sections discuss the techno-economic and life cycle analysis of the DAC for different types of sorbents, cost, energy demands, environmental impact, and the political support for the production & operation of the DAC plants. The five pillars of DAC: capture technology, electrical and thermal energy demand, cost, environmental impact, and political support are shown in [Figure 2](#) and these technology pillars need to be balanced well for successful deployment of DAC.

[Table 1](#) shows some of the major existing and the current operating DAC plants. Two of the companies, Climeworks and Carbon Engineering have been working in this area since the last decade and have plants currently operating in Europe and North America, respectively. Ongoing projects include 4,000 metric tons per year plant by Climeworks being built in Hellisheidi, Iceland, which went operational in September, 2021. Carbon Engineering is also building a commercial plant in Texas, USA, with a CO<sub>2</sub> capture and removal capacity of one million tons per year ([Lebling et al., 2021](#); [The Commercial Case for Direct Air Capture of Carbon Dioxide, 2021](#)). Global Thermostat is currently building two plants with a capacity of 2,000 metric tons per year each in Oklahoma, USA and is due completion in 2021 ([Point of View, 2020](#)). Engineering firm Black and Veatch were awarded the DOE funding to build a 100,000 ton per year capacity DAC plant using Global Thermostat's technology ([Black & Veatch Awarded, 2021](#)). The DAC mentioned are based on the principle of sucking in air from the atmosphere and removing the CO<sub>2</sub> using sorbents and heat. There is another kind of DAC which is passive and does not require any dynamic parts and has no thermal energy requirements ([Shi et al., 2020b](#)). The Passive DAC - MechanicalTree is designed by the researchers at Arizona State University. A cluster of 12 such trees could remove 1 ton of CO<sub>2</sub> per day. A prototype model from MechanicalTree is to be deployed in 2022–23 in Arizona, USA ("[MechanicalTree, 2020](#); [INEWS, 2021](#); [Arizona State Press, 2020](#)). Apart from these companies, there are other private companies/startups ([Merchant, 2022](#)) working on the DAC technology such as Heirloom Carbon ([Heirloom, 2020](#)), Mission Zero ([Mission Zero Technologies, 2022](#)), Sustaera ([Sustaera, n.d.](#)), Noya ([Noya, n.d.](#)), and Verdox ([Verdox, 2022](#)). Carbon Infinity is focusing on manufacturing small, modular, easily deployable DAC units which could bring down the cost for the end users ([Modular direct air capture technology for net-zero, 2022](#)). Carbon Capture ([About, 2022](#)), on the other hand, is trying to reduce the operating costs of

**Table 1. Current DAC plants and future projects**

Company	Plant type/status	Location	CO <sub>2</sub> removal capacity (metric tons/yr)	Sorbent type	Thermal energy source	Market application	Date of operation
Climeworks	14 Pilot & Commercial Plants/Operational	Across Europe	Net: 2,000	Solid	Geothermal, Waste heat etc.	Renewable fuels, food, beverages, and agriculture	2015–2020
	Pilot plant/Operational	Kanton Zurich (Switzerland)	900	Solid	Waste Incineration (Climeworks, 2022)	Greenhouse	2017
	1 Commercial plant/Operational	Hellisheidi (Iceland)	4,000	Solid	Geothermal	CDR services - Microsoft, Shopify, Audi & Storage by mineralization	2021 (Climeworks Begins Operations Of Orca, The World's Largest Direct Air Capture and CO <sub>2</sub> Storage Plant, 2022)
Carbon Engineering (Gallucci, 2021)	Pilot plant/Operational	Squamish, British Columbia (Canada)	350	Liquid (Wikipedia, 2021)	Natural Gas (Baker, 2015)	Carbon neutral Fuel	2015
	Innovation center/ Under construction	Squamish, British Columbia (Canada)	1,500			CO <sub>2</sub> capture and storage for shopify and virgin	2022 (The Story Behind Carbon Engineering, 2022)
	Commercial plant/ Under construction	Permian basin, Texas (USA)	1,000,000			Enhanced oil recovery and Carbon sequestration	Mid-2020s
Global Thermostat (The GT Solution, 2022)	Pilot plant (DAC + Flue)/ Nonoperating	Menlo Park, California (USA)	10,000	Direct CO <sub>2</sub> capture from air	Residual heat from Industry (Affordable carbon capture with a soda on the side, 2018)	Not for Commercial use	2013
	Pilot plant/Nonoperating	Huntsville, Alabama (USA)	4,000			Not for Commercial use	2019
	Pilot plant/planning	Magallanes (Chile) (Global Thermostat, 2021)	250 kg/h		Wind power	Synthetic Gasoline	2022 (Thompson, 2021)
	2 Commercial plants / Under construction	Sapulpa, Oklahoma (USA)	2,000 / Plant		Natural Gas (Point of View, 2020)	CO <sub>2</sub> based fuel, CO <sub>2</sub> as industrial gas	2021 (The Commercial Case for Direct Air Capture of Carbon Dioxide, 2021)
Mechanical Tree	Prototype /Under construction	Arizona (USA)	30 tons from a single tree	Moisture driven CO <sub>2</sub> sorbents	None, Passive DAC	Agriculture, CO <sub>2</sub> based fuel, Building materials, Sequestration	2022-23 (INEWS, 2021; Arizona State Press, 2020)
	Commercial Farms/Planning	Global	4 million/Farm	(Shi et al., 2020b)			Second Half of 2020s (MechanicalTree, 2020)
Infinitree	Pilot Plant/Operating	New York (USA)	100	Ion exchange sorbent material (Technology, 2017)	Humidity Swing mechanism (Technology, 2017)	Greenhouse application	2014–2018

The table is adapted from reference (Lebling et al., 2021; The Commercial Case for Direct Air Capture of Carbon Dioxide, 2021).



**Figure 3. DAC and CCS plants around the globe**

Green, Red, and Orange circles denote the operational status of the plants - Operating, Under Construction, or Planning, Nonoperating, respectively.

capturing CO<sub>2</sub> by using molecular sieves. They have designed their systems to use low-cost renewable energy such as solar for fulfilling the thermal needs.

The DAC has a wide market as the captured CO<sub>2</sub> could be used in agriculture, food, beverages, synthetic fuels, and even storing it underground through sequestration. The current status of the DAC plants around the world is shown in Figure 3 along with CCS (Carbon Capture and Storage) facilities which collect the carbon dioxide at the source like thermal power plants and industries. The CCS facilities are often a part of the industrial process and reduce the emission from the industries (Global CCS Institute, 2018).

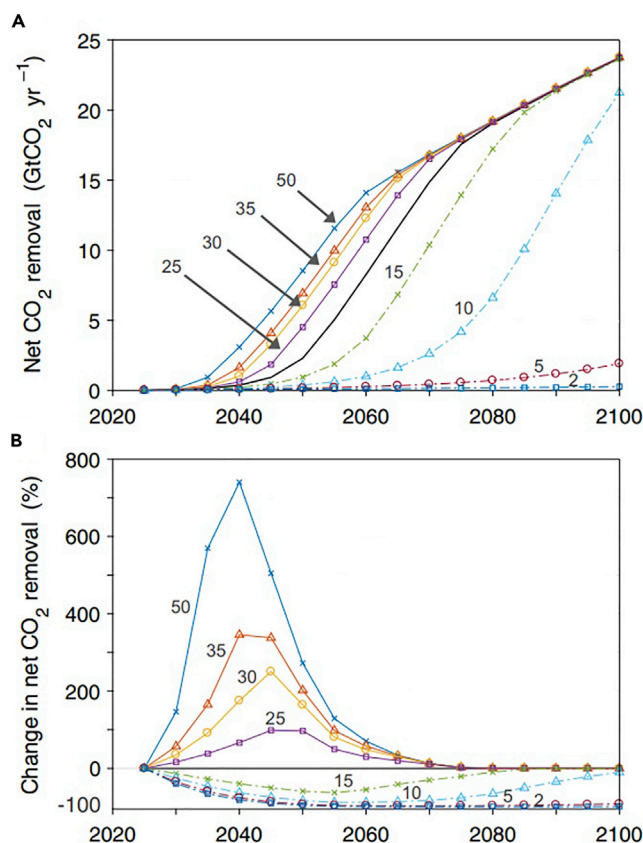
### Case study - Paris agreement standards

This section discusses the Paris agreement's goal of keeping the temperature rise under 2°C by 2,100 and the initiative that would be required to achieve this goal.

The current concentration of CO<sub>2</sub> in the atmosphere is about 420 ppm or 3,237 GtCO<sub>2</sub> (CO<sub>2</sub>.Earth, 2022, p. 2). 20 GtCO<sub>2</sub> of CO<sub>2</sub> capture and removal per year would be required by the end of the century to keep the temperature rise under 2°C (National Academies of Sciences, 2018). The current global carbon dioxide capture and storage is 0.0385 GtCO<sub>2</sub> per year (Global CCS Institute, 2018). This number also includes the current DAC capacity of 9,000 tCO<sub>2</sub> per year. Assuming a linear growth in the net global CO<sub>2</sub> capture and storage capacity from current 0.0385 GtCO<sub>2</sub> per year to 20 GtCO<sub>2</sub> per year by the end of the century, an estimated 798 Gt of CO<sub>2</sub> has to be removed from the atmosphere. At the current rate of 0.0385 GtCO<sub>2</sub> removal per year it would take around 21,000 years to reach the goal. Hence, there is an urgency in the deployment of DAC plants globally which could meet the Paris agreement's goal of keeping the temperature rise under 2°C.

We are considering two DAC plants for our case studies. The first one is a 4,000 metric tons per year capacity DAC plant, named 'ORCA', built by Climeworks partnering with Carbix in Iceland (Climeworks New Large-Scale Carbon Dioxide Removal Plant Orca," 2022). It went operational in September 2021. The second one is a one million metric tons per year capacity DAC plant being built by Wikipedia, 2021 Carbon Engineering in Texas, USA and will go operational in the mid-2020s.

Assuming that the plants operate at 100% efficiency and maintain the same capacity over the years, it is estimated that a total of 2.4 million Climeworks plants and 9,980 Carbon Engineering plants with a capacity



**Figure 4. Effect of industry growth rate on NET CO<sub>2</sub> removal**

(A) Net CO<sub>2</sub> removal with varying industry growth rate (in % per year). The unmarked black line denotes the nominal growth rate (20% per year) and the varied growth rates are denoted with marked colored lines and labels.

(B) Percent change in net CO<sub>2</sub> removal relative to the nominal case. Markers show the mean of all scenarios by year. The funding is from the club of democracies. (The Figure is taken from the reference (Hanna et al., 2021) with author's permission).

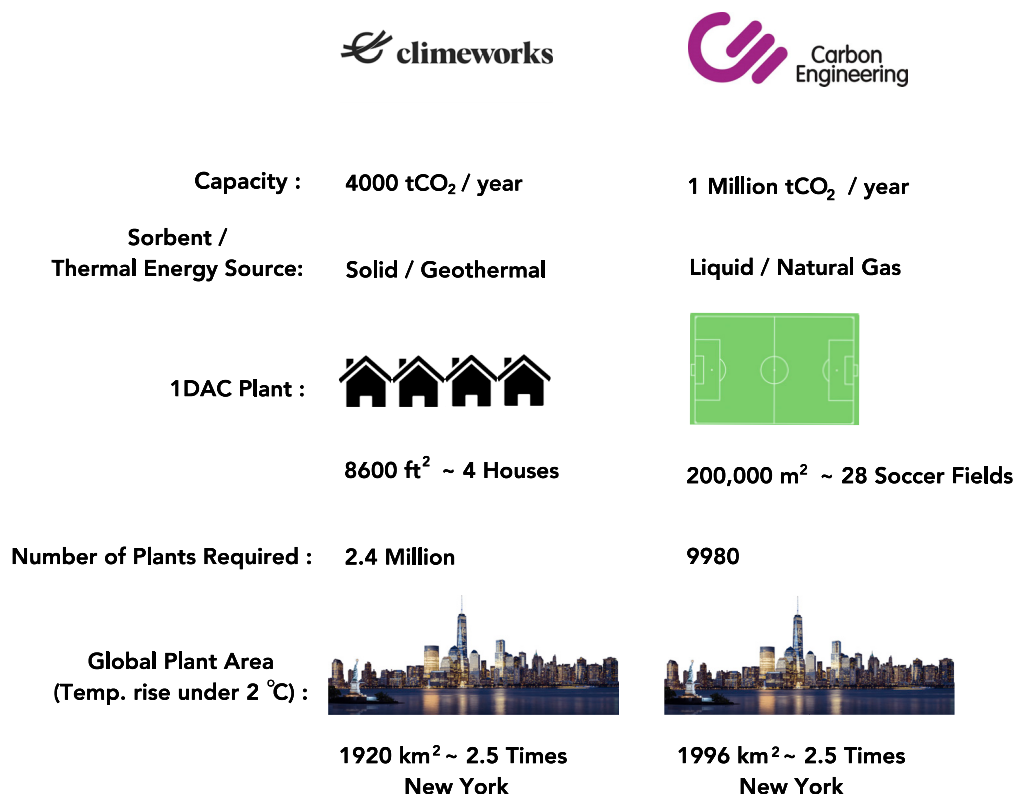
of 4,000 and one million metric tons per year, respectively, would be needed to meet the Paris agreement's goal. It is even harder to revert earth's climate to preindustrial revolution phase (CO<sub>2</sub> concentration - 280 ppm), which requires a removal of 135 ppm (1,053 Gt) of CO<sub>2</sub> from the atmosphere.

### Increasing capacity of DAC plants

Hanna et al. have discussed the emergency deployment of DAC (DAC) plants to tackle the climate crisis in their paper (Hanna et al., 2021). Different aspects such as cooperation between regimes throughout the globe on funding & deployment of DAC along with the cost & energy requirements (Creutzig et al., 2019; Fuhrman et al., 2020; Heck et al., 2018) have been explored in the paper. Industry growth rate and its effect on the Annual Net CO<sub>2</sub> removal have been studied (Bento and Wilson, 2016; Realmonte et al., 2019). An industry growth rate of 20% and more per year suggest more removal of net CO<sub>2</sub> in 2030–2050 as compared to the baseline. It is estimated that once the initial stage is set for the deployment of the DAC with a growth rate of 20% and higher, the industry growth rate stops constraining the deployment and operation of the DAC post 2050 (Bento and Wilson, 2016; Hanna et al., 2021). On the other hand, an industry growth rate less than 20% annually can rapidly drop the net annual CO<sub>2</sub> removal. The scenarios are illustrated in Figure 4 with an industry growth rate of 2–50%.

### Facility size and land area requirements

The size of the DAC plant depends on the type of sorbent used in the process and the source of thermal energy (Lebling et al., 2021). Plants may use either a solid or a liquid solvent along with a variety of thermal energy sources like Geothermal, Natural gas, Photovoltaic etc.



**Figure 5. DAC plant land area requirement**

The left column represents Climeworks and the right column represents Carbon Engineering. Both of them require an area of 0.2 km<sup>2</sup> per one million of CO<sub>2</sub> removal for the given sorbent and thermal energy source combination.

The first plant in study, the 'ORCA' by Climeworks (Climeworks, 2022; Climeworks New Large-Scale Carbon Dioxide Removal Plant Orca," 2022) in Iceland uses a solid sorbent and its thermal energy needs are met by Geothermal energy. For this combination of sorbent and thermal energy source a land area of 0.2 km<sup>2</sup> would be required to capture one million tons of CO<sub>2</sub> (Lebling et al., 2021). With a capacity of 4,000 metric tons per year, a single Climework plant would require a size of 8,600 square feet which is equivalent to four urban houses. An estimated land area of 1,920 km<sup>2</sup>, about 2.5 times the New York city, would be required worldwide for deploying 2.4 million climework plants to meet the Paris agreement goals. The second plant in study, the one million tons per year DAC plant by Carbon engineering will be using a liquid sorbent and the thermal needs being met by Natural gas. Such a facility would also require a land size of 0.2 km<sup>2</sup> to capture one million tonnes of CO<sub>2</sub>. An estimated area of 200,000 square meters (equivalent to 28 soccer fields) would be required for a single plant and a land area of 1,996 km<sup>2</sup> (2.5 times New York) would be required to build 9980 carbon engineering plants and meet the Paris agreement goals. This analysis is illustrated in Figure 5. However, this analysis on land area requirement is based on the existing plant configuration and operating capacity. This can be further optimized when the plants will operate at a higher capacity than the current capacity and the DAC could be placed in an array. This would reduce the deployment of additional units for water or energy management at the DAC facilities.

Based on data (Lebling et al., 2021), If we were to opt for Solar Photovoltaic plants as the thermal energy source then it would require a land size about 5–6 times the estimated land sizes. But, the land requirements for DAC plant deployment (0.2 km<sup>2</sup> per million tons of CO<sub>2</sub> Removal) is minimal when compared to the area needed for Reforestation (862 km<sup>2</sup> per million tonnes of CO<sub>2</sub> Removal). This means opting for solar energy to meet the energy demands would help in drastic reduction of carbon dioxide from the atmosphere (Breyer et al., 2020; Madhu et al., 2021; McQueen et al., 2021b; Renewable Power for Carbon Dioxide Mitigation, 2021), both through direct and indirect means. Even the residential solar schemes can decrease the dependency of DAC on large solar farms which might require additional land for its



deployment and operation (Banoni et al., 2012; Chand et al., 2019; Future of solar photovoltaic, 2019; Hernandez et al., 2015; Mokarram et al., 2020; Perpiña Castillo et al., 2016).

## A TECHNO-ECONOMIC ANALYSIS OF DAC

### DAC technologies

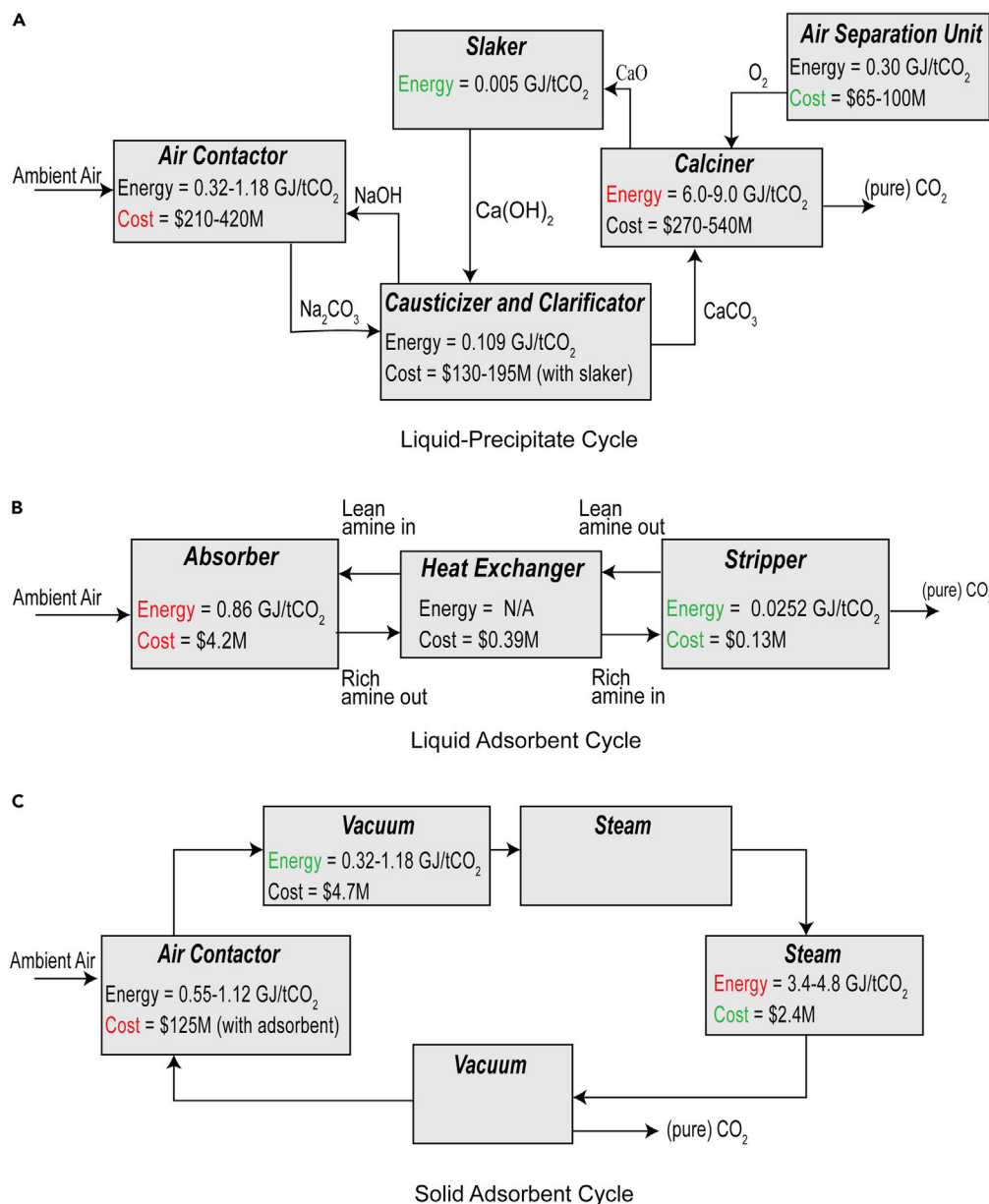
Since the Paris Agreement, carbon capture technology has been on the rise. Being fairly new, it is essential to briefly examine the struggle areas of emerging carbon capture technology. Afforestation and reforestation, Bioenergy with carbon capture and storage, DAC, etc., are a few examples of carbon capture technologies that struggle in similar areas. Specifically, these areas are energy demand, costs, environmental impact, and political support. From a technical point of view, these mean different things with respect to each technology. These areas are crucial for the success of any of these technologies, so having recent life cycle analyses are important. Well, looking at many of the latest life cycle analyses of DAC, one true message is portrayed. The common point is that the technology readiness levels are not high enough to accurately make any predictions or calculations for future DAC performance (Somoza-Tornos et al., 2021). This is largely because of the technology being in its infancy. For instance, the earliest deployment of DAC, seen in Table 1, is Global Thermostat in 2013. With only eight years since its first deployment, it is sensible that the technology is met with struggle areas. The issue of available data regarding the few DAC plants is reachable because of the data not being released to the public. This is of course a common situation that occurs with many industries. Given what is currently public knowledge, what status does DAC have regarding the struggle areas mentioned above?

DAC technology continues to be of interest in several countries and public administrations. Unfortunately, this technology currently faces several challenges that are stunting its adoption and deployment across the globe. Briefly discussed above, the struggle areas for DAC are energy demand, costs, environmental impacts, and political support. The following sections will attempt to review the status of these areas as well as provide a few essential visual/numerical data for better illustration of DAC's status. To better understand DAC and a few of the costs and energy demands that are required, a visual representation is shown in Figure 6, which will be referred to in later sections. As seen in the figure, these systems have the option of utilizing a liquid or solid sorbent (Hanusch et al., 2019; Luo et al., 2018; Shi et al., 2020a; Zeng et al., 2017). Explained previously, Climeworks uses a solid sorbent whereas Carbon Engineering uses a liquid sorbent (Carbon Engineering, 2022; Climeworks Offers a Technology to Reverse Climate Change, 2022).

The three systems in Figure 6 illustrate the generic process of liquid and solid-based DAC systems, along with their energy requirements and expenses. Each system contains red and green text, which is used to highlight the least and most energy and cost demanding components. Red text signifies the most demanding cost and/or energy equipment piece whereas green text highlights the least demanding. As expected, cost and energy are two areas that challenge this technology, and they will both be explained further in the following sections. The prices shown in Figure 6 are explained by the assumption of a 30 years life expectancy of a generic facility with a removal capacity of one MtCO<sub>2</sub>/year.

### Cost analysis

There is a high level of uncertainty and difficulty when providing this technology with a particular cost given that it remains in its early stages. Because of this, high costs continue to be a major challenge. How does this compare to that of other carbon capture technology? Well, the expense for several other carbon capture technology ranges from low to high, given that other 'limiting factors' follow. A famous competitor for DAC is bioenergy with carbon capture and sequestration, BECCS, and has a price range of \$20–100/tCO<sub>2</sub>. This is lower than that of DAC which is currently always greater than \$100/tCO<sub>2</sub>. Other technologies such as coastal blue carbon and terrestrial carbon removal and sequestration are much lower than DAC with a cost of \$0–20/tCO<sub>2</sub> (National Academies of Sciences, 2018). The main reason that DAC has much more promise for success than the other technologies listed is because of the limiting factors that follow. These limiting factors are related to high costs, minimal fundamental understanding, and issues for scaling. This is more promising than the limiting factors for the other technologies such as available land area, forestry management, and demand for wood (National Academies of Sciences, 2018). Feasibility, in this case, is in favor of DAC. To provide context, the previously named commercial DAC companies have their capture prices listed. Climeworks reports a cost of \$600/tCO<sub>2</sub> and Carbon Engineering has a cost between \$94/tCO<sub>2</sub> and \$232/tCO<sub>2</sub> (Azarabadi and Lackner, 2019; Gambhir and Tavoni, 2019; Kusmer, 2020; Ozkan, 2021; Sutherland, 2019). These are widely considered to be high costs, but they are a result of the current status of the technology being relatively new. More recently, experts in the field have undergone analyses which



**Figure 6. DAC technologies**

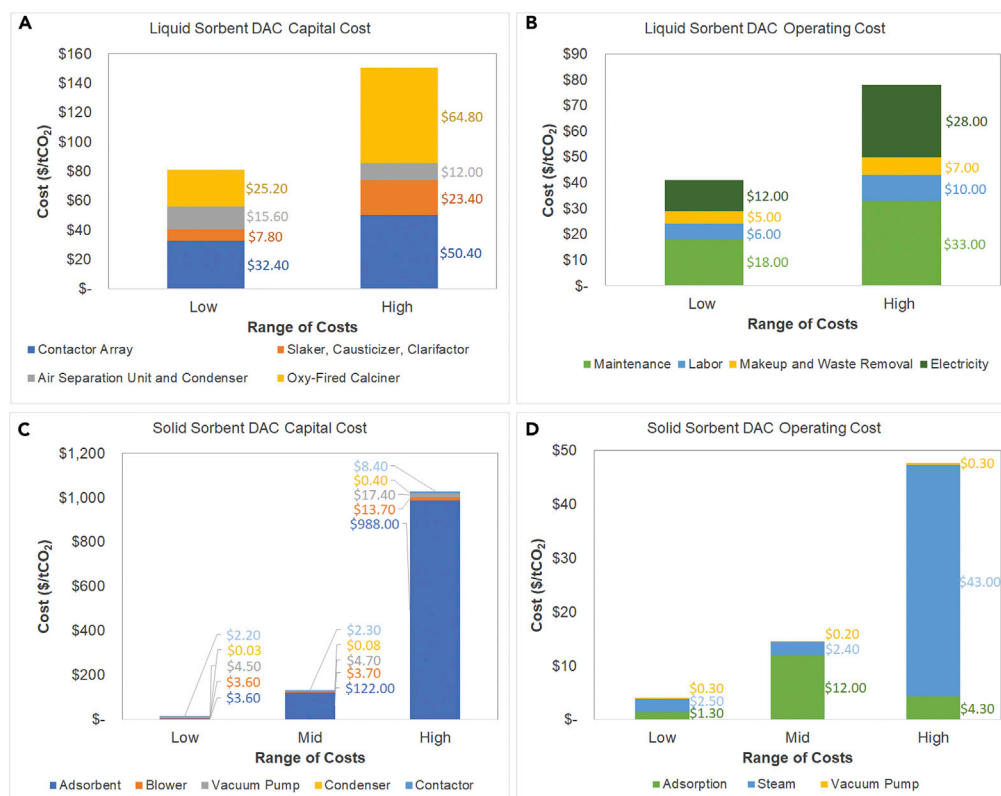
(A) Liquid-Precipitate Cycle.

(B) Liquid Adsorbent.

(C) Solid Adsorbent Cycle. Steam and vacuum values in (C) are included in only one of their respective boxes. Not included in (B) are the energy requirements from recirculation pump and blower work, which gives the overall system an energy requirement of 5.23 GJ/tCO<sub>2</sub> (Broehm et al., 2015; Kiani et al., 2020; National Academies of Sciences, 2018; Socolow et al., 2011).

have resulted in a hopeful future capture cost of between \$100/tCO<sub>2</sub> and \$200/tCO<sub>2</sub> and even dropping below \$60/tCO<sub>2</sub> by 2040 or 2050 (Bipartisan Policy Center, n.d.; Sutherland, 2019). Of course, this is with the assumption that technology will continue to scale. Several articles report varying costs for DAC, which results in a range of costs rather than a definite cost. An important question to ask is ‘what causes the fluctuation in costs?’.

To answer this, there are many factors that contribute to the overall price. The first of those prices is the capital costs, which includes the prices of equipment pieces that make up the DAC system. The second



**Figure 7. DAC cost breakdown and comparison**

All systems are presented with data that assumes a plant with removal capacity of one MtCO<sub>2</sub>/year and a fixed charge factor of 12%.

(A) Liquid Solvent DAC Capital Cost with low and high range.

(B) Liquid Solvent DAC Operating Cost with low and high range.

(C) Solid Sorbent DAC Capital Cost with low, mid, and high range.

(D) Solid Sorbent DAC Operating Cost with low, mid, and high range. Low and high bounds are the result of the type of material used for a specific part, factoring in new technology, and varying costs from vendors (National Academies of Sciences, 2018).

factor is the operating costs, which involve the maintenance and labor for the various equipment pieces and the facility. The final factor, which proves to be one of the most vital parts, is the sorbent used in the system (Azarabadi and Lackner, 2019). The choice of sorbent is extremely vital because, as discussed previously, it can affect the required land area of a facility and amount of energy that would be needed. The sorbent to be utilized can be either a liquid sorbent, similar to that of Carbon Engineering, or a solid sorbent, similar to that of Climeworks (Azarabadi and Lackner, 2019). These expenses will be further explained in the following sections as they are vital in DAC technology. For a more visual representation, Figure 7 displays a side-by-side comparison of the capital and operating costs of generic liquid and solid-based DAC systems.

### Capital cost

The capital cost for liquid and solid DAC systems are cost intensive and contribute to the majority of costs, as seen in Figure 7. This cost alone is recorded as reaching prices around \$1,000/tCO<sub>2</sub> for solid based systems and \$150/tCO<sub>2</sub> for liquid systems; however, the low range provides cost estimates of ~\$80/tCO<sub>2</sub> and ~\$200/t CO<sub>2</sub> for liquid and solid systems, respectively (Fuss et al., 2018). Not included in this expense is the additional cost from the required energy supply. For a liquid-based system and natural gas as an energy supply, the estimated cost range is \$147–264/tCO<sub>2</sub> (National Academies of Sciences, 2018). A large additional expense is not seen with solid systems because of a smaller energy demanding process when compared to a liquid-based system. Essentially, capital expenses consist of the cost of individual equipment components for the overall system whose price breakdown can be

seen in [Figure 6](#). Three systems are listed in the figure: (A) Liquid-Precipitate Cycle, (B) Liquid Adsorbent Cycle, and a (C) Solid Adsorbent Cycle. Each system has its respective cost breakdown because of different component pieces and maintenance requirements that it demands. For system (A), the range of prices for the equipment pieces is \$65–420 million, with the highest price belonging to the air contactor and lowest belonging to the air separation unit ([National Academies of Sciences, 2018](#)). For system (B), the range is \$0.13–4.2 million with the costs belonging to the stripper and absorber, respectively ([Kiani et al., 2020](#); [National Academies of Sciences, 2018](#)). Lastly for system (C), the range is \$2.4–125 million for the steam and air contactor, respectively ([National Academies of Sciences, 2018](#)). Unlike sorbents, the several listed components do not experience degradation because of weather conditions and other outside factors. This allows the pricing of these pieces to maintain and not see as much fluctuation as is seen with sorbents ([Azarabadi and Lackner, 2019](#)).

### *Operating and maintenance cost*

With capital costs contributing to the majority of the cost requirement, operating and maintenance (O&M) make a smaller contribution; however, O&M are essential for the upkeep of facility and equipment wellbeing. A few of the costs that are included in this section are for maintenance, labor, and makeup and waste removal, which correspond to liquid O&M expenses. For solid O&M, the prices correspond to adsorption, steam, and the vacuum pump. Seen in [Figure 7](#), the price ranges with respect to both systems fall below \$100/tCO<sub>2</sub>. The low and high ranges for the liquid system are ~\$40/tCO<sub>2</sub> and ~\$80/tCO<sub>2</sub>, respectively. The low, mid, and high ranges for the solid system are ~\$5/tCO<sub>2</sub>, ~\$15/tCO<sub>2</sub>, and ~\$50/tCO<sub>2</sub> ([National Academies of Sciences, 2018](#)). Combining capital and O&M expenses results in very large costs that could cause for less of an impact of DAC on climate change mitigation, if not reduced. Evidently, cost reduction by means of research and precise modeling is necessary for the rapid adoption and deployment of DAC.

Capital and O&M expenses are currently considered areas of struggle for the technology, whereas a cost from potential energy sources has not yet been considered. The energy source for this technology is crucial, and its current expense often varies between sources. This cost should be considered because it adds a large expense to the technology.

### *Cost from energy sources*

Not seen in [Figure 7](#) are the prices from the selected energy source, which often limit cost relief of the technology ([House et al., 2011](#)). Energy needs to be supplied in electric and thermal forms to supply electricity and heat to the appropriate parts in the system. The energy sources to do this are available as solar, wind, natural gas, coal, and nuclear. Each of these sources will result in a different price per ton of CO<sub>2</sub>, affecting the overall cost examined in the previous sections. The following sources result in various capture costs: Solar would result in a cost of \$430–690/30tCO<sub>2</sub>, wind results in a cost of \$360–570/tCO<sub>2</sub>, natural gas results in a cost of \$88–228/tCO<sub>2</sub>, coal results in a cost of \$88–228/tCO<sub>2</sub>, and nuclear results in a cost of \$370–620/tCO<sub>2</sub> ([McQueen et al., 2021a](#); [National Academies of Sciences, 2018](#)). Evidently, the several listed energy sources can greatly affect the capture cost of DAC systems, and therefore, its appeal to the public. An important factor seen from these prices is the difference in costs between renewable energy and fossil fuels. Clean alternatives, such as solar and wind, result in high prices of at least \$430/tCO<sub>2</sub> and \$360/tCO<sub>2</sub>, respectively. On the other hand, coal and natural gas result in a significantly lower price of \$88/tCO<sub>2</sub> with its maximum price at \$228/tCO<sub>2</sub>, both prices lower than the clean alternatives. This is important, specifically, when examining the carbon footprint by renewable energy and fossil fuels. Although discussed in later sections, the carbon footprint is greater when utilizing a purely fossil fuel source. This poses a complex challenge for DAC. For example, this technology strives for lower costs while maintaining a high rate of CO<sub>2</sub> removal. When using renewable energy, high removal rates could be achieved but at very high costs and with little carbon footprint. With a fossil fuel source, high removal rates are also achieved; however, at lower costs and with a larger carbon footprint. With a goal for effectiveness and low cost, the question of energy and expenses require much more modeling to determine a more effective system. The next section will discuss the energy demand required and how it may also pose a problem for this technology.

Given the costs associated with O&M, capital, and energy sources, will DAC seem fit for countries to invest in? There are cost targets set in place that are much more desirable than the current prices discussed thus far. The next section will provide context to the critical targets needed for the cost of CO<sub>2</sub> removal.

### Critical targets for the cost of CO<sub>2</sub> removing

The critical and unsettled question is how much DAC will cost and whether companies and countries will decide they can afford it. DAC needs to achieve gigaton scale CO<sub>2</sub> removal at <\$100/ton by 2050. Approaching \$100 per ton is basically the point of economic viability. Current cost of CO<sub>2</sub> removal using DAC is between \$200-\$600/ton, which is far from the desired cost target. Lackner and Azarabadi explain that with a capital investment of several hundred million dollars could buy down the cost of DAC as \$100/ton (Lackner and Azarabadi, 2021). Mass manufacture of DAC units to increase in number rather than the size of units are thought to lower the cost. Using the learning-by-doing rules in mass manufacturing of DAC, the cost is expected to come down rapidly. After lowering the capital cost by mass manufacturing, operational cost can be reduced with advancements and optimizations in contactors, sorbents, and regeneration units. Specifically, modular units and passive air contactors are some of the recent considerations. Moisture swing may reduce the energy needed in regeneration. Similarly, electro swing may avoid the need for thermal energy. Using low cost renewable power sources to operate DAC plants such as natural gas and recycling of waste heat could lower the operational cost even more.

Development of a viable merchant market for captured CO<sub>2</sub> use could certainly drive in more private and federal money toward further development of DAC technology and its deployment. Current markets for CO<sub>2</sub> are oil companies, plastic and concrete industry, beverage industry, and carbon fiber producers (Ozkan, 2021). New pathways to use CO<sub>2</sub> in the production of fuels and building materials can increase the current global market size of CO<sub>2</sub> more than 230 Mt/yr. Close to \$1 Billion in investment toward new startups for CO<sub>2</sub> use is an exciting development from industry, investors, and governments. Commercial and regulatory barriers are accepted to be more dominant compared to technological limitations to scale up CO<sub>2</sub> use. Future prospects for CO<sub>2</sub> use will be determined by policy support and investment decisions by keeping in mind the following factors: 1) A robust life cycle analysis that provides quantified climate benefits, 2) Identify early market opportunities that are scalable and commercially feasible, 3) Introduce public procurement guidelines for low carbon products, 4) Set up performance based standards for fuels, building materials and chemicals, and 5) Support research, development, and pilot demonstration projects (Putting CO<sub>2</sub> to Use – Analysis, 2019).

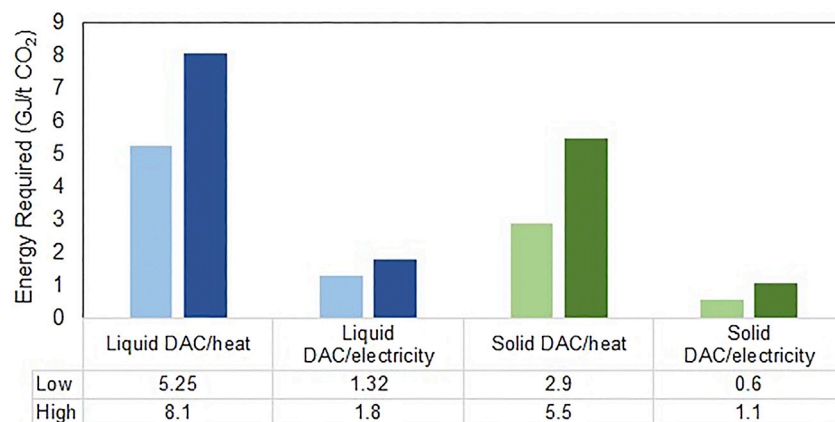
Political support is certainly one of the enabling pillars of DAC (Figure 2) and is highly critical to drop down the cost of DAC below \$100/t. Especially, early stage investments and supporting policy frameworks are necessary to implement mass manufacturing and deployment of more DAC plants. Facilitating multiple sites to demonstrate reliable performance and gain broader acceptance is becoming more critical. To this end, the global status of political support for DAC deployment will be discussed in a separate section called -political support.

### LIFE CYCLE ANALYSIS OF DAC

#### Energy demand of DAC

The cost mentioned in the previous sections is undoubtedly a challenge that DAC currently seeks to overcome. Another major concern to examine is the energy demands and carbon generation (footprint) of these systems. To be accepted globally, the required energy and generated CO<sub>2</sub> must be within an acceptable range so that the technology does not appear ineffective, and therefore, less appealing. Currently, the energy requirements for DAC are high and a concern for most as the demand currently is labeled as 'unrealistic' and impractical (Chatterjee and Huang, 2020; Mac Dowell et al., 2017; Majumdar and Deutch, 2018; Van der Giesen et al., 2016). The following figure will aid in visualizing these requirements.

There are many factors that contribute to the energy requirement of DAC systems. What are those factors? Well, for a successful DAC plant, energy is a crucial part for extracting CO<sub>2</sub> via the processes listed in Figure 6, sequestering the CO<sub>2</sub>, and capturing carbon generated from each step in the DAC process. An important note is that, with the signing of the Paris Agreement, a goal of reaching a global warming of below 2°C was determined. To do so, around 30 GtCO<sub>2</sub>/year would need to be removed (Chatterjee and Huang, 2020). With this rate in mind, some scientists believe that the energy demand by DAC would be too large. For reference, Figure 6's 'Liquid-Precipitate Cycle' requires 6.57–9.9 GJ/tCO<sub>2</sub> because of the necessity of ~900°C required for regeneration (Chatterjee and Huang, 2020; Lebling et al., 2021). With the energy demand being extremely large, upwards of 13.1 TW-year would be required, which would make up more than half of the total global energy supply in a year (Chatterjee and Huang, 2020; Realmonte et al.,



**Figure 8. Energy requirements for solid and liquid DAC systems**

'Low' is used for the lower range values, and 'high' is used for the higher range values. Values found from reference (Chatterjee and Huang, 2020; Kiani et al., 2020; Krekel et al., 2018; Luis, 2016; National Academies of Sciences, 2018; Realmonte et al., 2019; Rochelle et al., 2011).

2019). A DAC system utilizing a solid sorbent requires 5–8.3 GJ/tCO<sub>2</sub>, which can be seen to be lower than the energy required for systems with a liquid sorbent. A comparison between the heat and electricity demand can be further examined in Figure 8. To provide a better illustration, in 2020 the US consumed  $0.98 \times 10^{20}$  J of energy; therefore, to meet the expectation of 30 GtCO<sub>2</sub>/year, DAC would require  $1.97 \times 10^{20}$  J of energy (U.S. Energy Information Administration, 2021). That is approximately twice that of the energy of the US in one year. This is also provided that the energy requirement meets the low range as seen in Figure 8. Essentially, the current energy demand calls for concern with regard to the hope of rapid DAC deployment and scale-up; however, researchers believe deployment remains a necessity (Realmonte et al., 2020). Looking to other carbon capture technology, a large energy demand is not seen. The several other technologies, however, do require more in other areas. For example, more land and water would be required for BECCS and afforestation and reforestation along with the latter seeing a potential loss of nutrients in soils (Courvoisier, 2018). In addition, BECCS would also require  $10^{18}$  J, a large amount of energy (Courvoisier, 2018). Energy is an issue that requires continued R&D and global support. Having examined these requirements, it is also crucial to discuss the amount of carbon that is generated as a result of energy sources.

### Carbon footprint

The main desire of DAC is to capture the excess amount of CO<sub>2</sub> that fills the air. It is essential to note the amount of CO<sub>2</sub> that the DAC process then leaves behind to determine if the technology is deserving of funding and research. To do so, the following table includes the generated carbon from various energy sources for heat and electricity. Of course, several energy sources need to be examined because of the carbon footprint being too high when using fossil fuels for DAC to be effective (National Academies of Sciences, 2018).

Made evident in Table 2, renewable energy is the most efficient option because of the carbon footprint being very low. For a comparison, using a solar source for both electricity and heat would result in a footprint of 0.0084–0.018 Mt/year of CO<sub>2</sub> whereas a coal source would result in 0.47–0.74 Mt/year of CO<sub>2</sub>. The fossil fuel source can then be considered counterproductive as it has the potential of producing more than half of the desired 1 Mt/year of CO<sub>2</sub> removal. This also provides a better understanding of the topic mentioned in the previous cost section. In that section, an explanation of clean energy and fossil fuels are given and examined, along with their expenses. The footprints above illustrate how large of a range is seen provided both types of energy generation.

A main concept that can be related to every topic discussed thus far is that expanding this technology could possibly cause costs, carbon footprint, and energy demand to increase. This is a huge concern that is often considered. The issue of scaling will be discussed in the following section.

**Table 2. Carbon footprint of DAC systems with respect to several energy sources**

Sorbent	Electricity	Heat	Carbon generated from heat (MtCO <sub>2</sub> /year)	Carbon generated from electricity (MtCO <sub>2</sub> /year)
Liquid	Solar	Natural Gas	0.47–0.66	0.01–0.03
Liquid	Wind	Natural Gas	0.47–0.66	0.004–0.009
Liquid	Nuclear	Natural Gas	0.47–0.66	0.01–0.02
Liquid	Natural Gas	Natural Gas	0.47–0.66	0.11–0.23
Liquid	Coal	Natural Gas	0.47–0.66	0.18–0.38
Solid	Solar	Solar	0.008–0.01	0.0004–0.008
Solid	Nuclear	Nuclear	0.004–0.005	0.002–0.004
Solid	Solar	Natural Gas	0.22–0.30	0.0004–0.008
Solid	Wind	Natural Gas	0.22–0.30	0.002–0.003
Solid	Natural Gas	Natural Gas	0.22–0.30	0.07–0.14
Solid	Coal	Coal	0.32–0.44	0.15–0.3

Adapted from reference (National Academies of Sciences, 2018).

### Scaling

Having examined the current challenges for DAC, it is evident that cost and energy prove to be areas for concern with this technology. It is important to note that these systems are relatively new and in early stages, which gives hope for cost relief as more research is conducted (Nemet et al., 2018). An analysis by Realmonde et al. illustrates the scale-up for DAC being much more promising than that of other existing carbon capture technologies such as BECCS (Creutzig et al., 2019; Realmonde et al., 2019). For example, the capture rate at which DAC is predicted to scale-up is 1.5 GtCO<sub>2</sub>/year (Realmonde et al., 2019). At this rate, a desired removal rate of 30 GtCO<sub>2</sub>/year could be achieved in 20 years (Realmonde et al., 2019). However, scaling also poses its own challenges and concerns. What can be expected with a rapid scale-up for DAC? Well, as facilities and capture rates increase, the cost and energy demand will soon follow in the upward trend. Such an ambitious upscaling to meet the Paris Agreement standards would result in an almost 80% increase in capital cost and a dramatic increase in the energy requirement (Keith et al., 2018). This, of course, excludes the potential for any relief in cost or energy given future research in the area of carbon capture.

Costs and energy demand will of course scale in an upward direction with the progression of DAC; however, the availability of material for the required DAC plants is another topic that demands attention especially scaling-up in mind. Regardless of the type of sorbent, large amounts of steel and concrete would be required for a typical plant compared to the several other carbon capture technologies (McQueen et al., 2021b). Large air contactors and conventional cooling towers require significant amounts of steel as well. The amount of steel and concrete for DAC plants are non-negligible. In addition, sorbents can require potassium hydroxide, calcium carbonate, aluminum, copper, etc., whose supply chain is still in development (Gebald et al., 2014). This means that the desired carbon removal rate would need to be met with a more developed supply chain (McQueen et al., 2021b).

Another important factor that will contribute to the rate at which this technology will scale is the public acceptance and global support that it receives. This is a topic that will be discussed within the next few sections. Given the need for rapid climate change mitigation, upscaling is an essential part of the process for DAC. Although there are challenges and concerns regarding the rate of scaling, it is a necessary process that requires more analysis, modeling, and research. An anecdote for hope would be viewing the rate at which photovoltaics (PV) scaled. From the years of 2000–2010, PV experienced a growth rate of 70% with the aid of financial incentives (Meckling and Biber, 2021). A similar growth rate would allow DAC removal rates to be 80 GtCO<sub>2</sub>/year by 2050 (SolarPower Eur, 2018; Maycock, 2005; McQueen et al., 2020; Nemet, 2019; Perea et al., 2016). Such rates provide hope that scaling, yet a challenge, is not impossible.

### Environmental impacts

Below we will discuss the relationship between DAC plants and environment from two aspects: first, the impact of the environment on the DAC plants — this has been discussed in the previous sections; second, the other is the impact of the DAC plants on the environment.

**Table 3. Environmental impacts of the construction for the engineered DAC plant and the future DAC plant according to the European Commission's Joint Research Center**

Environmental impacts	Engineered DAC plant	Future DAC plant	Unit
Climate change	$5.68 \times 10^{-3}$	$2.72 \times 10^{-3}$	Kg CO <sub>2</sub> e
Ozone depletion	$1.29 \times 10^{-10}$	$4.97 \times 10^{-11}$	Mole H+ equiv
Particulate matter	$2.69 \times 10^{-10}$	$1.06 \times 10^{-10}$	Disease incidences
Acidification, terrestrial, and freshwater	$1.93 \times 10^{-5}$	$7.49 \times 10^{-6}$	Kg CFC-11 equiv
Eutrophication, freshwater	$4.23 \times 10^{-7}$	$1.56 \times 10^{-7}$	Kg P equiv
Eutrophication, marine	$5.09 \times 10^{-6}$	$1.98 \times 10^{-6}$	Kg N equiv
Eutrophication, terrestrial	$5.63 \times 10^{-5}$	$2.19 \times 10^{-5}$	Mole N equiv
Ionizing radiation	$2.38 \times 10^{-4}$	$8.45 \times 10^{-5}$	kBq 235U equiv
Photochemical ozone formation	$1.60 \times 10^{-5}$	$6.22 \times 10^{-6}$	Kg NMVOC equiv
Human toxicity, cancer	$1.40 \times 10^{-10}$	$5.47 \times 10^{-11}$	CTUh
Human toxicity, noncancer	$6.25 \times 10^{-10}$	$2.44 \times 10^{-10}$	CTUh
Ecotoxicity, freshwater	$1.81 \times 10^{-3}$	$7.01 \times 10^{-4}$	CTUe
Land use	$2.23 \times 10^{-2}$	$7.99 \times 10^{-3}$	Pt
Water scarcity	$1.59 \times 10^{-3}$	$4.98 \times 10^{-4}$	m <sup>3</sup> world equiv
Resource depletion, energy	$5.19 \times 10^{-2}$	$2.04 \times 10^{-2}$	MJ
Resource depletion, mineral, and metals	$2.87 \times 10^{-8}$	$1.00 \times 10^{-6}$	Kg Sb equiv

Adapted from reference (Deutz and Bardow, 2021).

One of the impacts of the DAC process on the environment is the depletion of CO<sub>2</sub> in the air discharged from the contactor (National Academies of Sciences, 2018; Stolaroff, 2006). The area of CO<sub>2</sub> consumption may depend on the nearby crop efficiency and the overall ecological health of the region. Then, when the CO<sub>2</sub> is consumed, which means that the carbon dioxide is diluted, the difficulty of capturing increases with the decrease of the diluted concentration, showing a negative correlation (Broehm et al., 2015). The uncaptured combustion emissions and uncaptured upstream emissions will both cause a lower net capture rate (Jacobson, 2019). In addition, carbon capture plants also increase air pollution and overall social consumption, while coal-fired power is related to air pollution and climate costs, compared to no capture (Jacobson, 2019). Though using fossil fuel to generate electricity would release more CO<sub>2</sub> than captured CO<sub>2</sub>, the theoretical minimum energy required to extract CO<sub>2</sub> from ambient air is about 250 kWh per tonne of CO<sub>2</sub>, while capturing from natural gas and coal power plants requires about 100 and 65 kWh per ton of CO<sub>2</sub> (Cairns, 2020; Nielsen, 2019), respectively. Therefore, such implied energy requirements could have a new set of environmental impacts in the future.

The impacts of the DAC system on the environment are within a certain range of energy demand. Nowadays, the carbon footprint of captured CO<sub>2</sub> has been less dependent on the electric grid, which reduces the waste of coproduction of heat and electricity. Besides, the DAC plant construction of CO<sub>2</sub> capture and collector, process unit, and auxiliaries lead to nonintuitive environmental impacts (Deutz and Bardow, 2021). In addition, the sorbents of raw materials and scrap processing have different degrees of impact. For instance, the adsorbents have a negative effect on the environmental impacts because of the low carbon footprint (Deutz and Bardow, 2021). In addition, the results of sorbents on the previous table as well as the following sections also demonstrate the environmental impact because of the impact of the production and raw material provision. The good thing is that the plants would optimize the absorbents in heat recovery and management, which indicates the importance of connecting DAC operating systems with renewable energy.

The following Table 3 shows the DAC plant within the environmental impact categories, according to the recommended life cycle impact assessment method by the European Commission's Joint Research Center in the European context (Deutz and Bardow, 2021). Though the environmental impact categories were evaluated rigorously, the impact on the environment is still not intuitive because of the complex units in



the results. Overall, the environmental impacts of DAC systems should be considered in the direction of the construction of plants, the low-carbon energies, and the choice of sorbents.

As seen in [Table 3](#), removing CO<sub>2</sub> via DAC does have a few potential impacts on the environment; however, what can be said about the other greenhouse gases in the atmosphere? Without a doubt, there are other gases in the atmosphere that negatively affect the planet. The most common gases are carbon dioxide, methane, and nitrous oxide. As explained in the introduction, several countries have new initiatives that aim to reduce these greenhouse gases because of their negative impacts on the environment. DAC technologies solely target the carbon dioxide in the atmosphere as there is an alarming amount of it in the air today. Reducing CO<sub>2</sub> would greatly reduce global warming to the goal set in the Paris Agreement. The additional greenhouse gases should also be of concern, however, they are not considered in DAC.

The reason behind DAC is to help the planet. Environmental impacts are extremely essential to consider because ensuring that this technology does not cause any harm to the planet is absolutely necessary. A technology created to help the planet should not be responsible for causing additional harm to the environment. Without any further research, solutions to this problem would not be discovered. This is the reason that support from governments is critical for the progression of DAC. The next section will discuss this topic and provide context to the necessity for political support.

## POLITICAL SUPPORT

In recent years, more and more governments would like to develop the technology of carbon capture and storage with the benefits of social, economics, and environment. Since 1972, when the first ValverdeCO<sub>2</sub>-EOR major CCS (Carbon Capture and Sequestration) project began operations in the Sharonridge field in Texas, 65 commercial CCS projects have been up and running or under construction worldwide by 2020 ([Global CCS Institute, 2018](#); [Understanding CCS, 2022](#)).

The US DOE invested \$24 million to advance transformational air pollution capture in March, 2021 ([Energy.gov, 2022](#)). The federal Section 45Q, which has an incentive of \$20 per metric ton for saline and other forms of geologic CO<sub>2</sub> storage and \$10 per metric ton of CO<sub>2</sub> stored geologically through enhanced oil recovery ([Credit for Carbon Oxide Sequestration, 2021](#)). Until 2020, the US has 207 projects related to carbon capture. Through the tax law, the tax preferential policies can help to support corresponding energy infrastructure. However, 45Q can only provide tax support for DAC units that capture more than 100,000 tons of CO<sub>2</sub> per year until 2024 ([Jones and Sherlock, 2021](#)). California's Low Carbon Fuel Standard (LCFS) and the Buy Clean California Act could also explicitly benefit DAC technology. LCFS sets a carbon emission intensity standard for transportation fuel over its lifetime, and the Buy Clean California Act plans to set CO<sub>2</sub> life cycle standards for building materials that California agencies must comply with when purchasing building materials in 2021 ([Cortes et al., 2022](#)).

In Canada, related projects have already started in 2019. The DACCS project, funded by the Pacific Institute for Climate Solutions, plans to capture CO<sub>2</sub> from ambient air and use seafloor for storage; in addition, a DAC project, financed by Natural Resources Canada and industrial partners, aims to mineralize CO<sub>2</sub> in mine tailings ([Direct Air Capture, 2021](#)). Besides, Canada's most valuable company, the online retail platform Shopify, invests at least \$5 million annually on environmental initiatives, including \$1 million for sequestering carbon ([News and E&E, 2021](#)).

At the climate summit in April, China made a bold pledge to achieve net zero carbon emissions by 2060 ([BBC News, 2021](#); [Fuhrman et al., 2021](#)). By the end of last year, China had undertaken nine carbon capture demonstration projects and 12 utilization and storage projects. Though China does not have any clear policies about regulating activities until now, the National Energy Corporation had a plan about the development routine of CCUS in 2019 ([Britannica, 2022](#); [Zhang et al., 2015](#)).

The UK planned to invest £70 million in DAC and other technologies in Greenhouse Gas Removal ([Sixth carbon Budget, 2020](#)). Meanwhile, Climeworks, in Europe, received over € 50 million in total from investors to commercialize the DAC system ([PM, 2020](#)). In addition, because of the European Union having clear policy frameworks, the EU has invested 80 billion euros in the past seven years and will invest 10 billion euros in 2020–2030 for innovative low-carbon technologies ([Cabuzel, 2019](#)).

South Africa's low-emission development strategy 2050, introduced in February 2020, is a response to the Paris Agreement's call, which points out that the South Africa's government has already encouraged companies to develop green projects (Ica, 2020). The corresponding tax incentives have been included in the Income Tax Act of South Africa. Though more than 90% of South Africa's energy is generated from coal, the government still believes in the importance of a "just transition" to clean energy (Clim. Home News, 2020).

## FUTURE PROSPECTS

DAC could potentially be a key factor in the climate change mitigation fight. As explained previously, providing a price to these costs is rather difficult because DAC is in its early stages. Depending on the sorbent used, current prices for this technology can range from \$264–1,000/tCO<sub>2</sub>. Current prices for commercial DAC are alarmingly high; however, experts have concluded that future capture costs of between \$100/tCO<sub>2</sub> and \$200/tCO<sub>2</sub> are likely to be a reality with extensive research.

There are several areas of the DAC process in which more developments could result in some cost relief: 1) Contactors, 2) Sorbents, and 3) Regeneration. This could relate to the choice of sorbent or individual equipment pieces (i.e., air contactors and adsorbents). Mass production is likely to result in capital and operational expense relief while advancements in the technology could lead to lower energy consumption requirements (Fasihi et al., 2019). As for the equipment, there is much fluctuation in the costs caused by the material that is used to make the components. Any developments in the production and/or creation of these components could potentially lower expenses for the overall system. Developments in sorbent creation are also extremely essential as they have the potential of carrying a large part of the expense for the technology. Fortunately, sorbents with better capture rates and regeneration aspects are made every year giving hope to future cost reduction (Azarabadi and Lackner, 2019; Ozkan et al., 2022; Sanz-Pérez et al., 2016). A sorbent will experience much deterioration as the sorbent undergoes many loading and unloading cycles (Azarabadi and Lackner, 2019). This process causes the sorbent quality to diminish over time, and ultimately compromises the effectiveness of carbon capture while also reducing its capacity (Azarabadi and Lackner, 2019; Goepfert et al., 2019). Current operational DAC plants that run with liquid sorbents such as amines suffer from stability and longevity of amines, furthermore corrosivity on chemical plant piping still remains as a problem that could potentially increase the operational cost of these plants in the long run. In the case of solid adsorbents, they often lack significant CO<sub>2</sub> capture capacity that can also impact the operational costs. Therefore, creating higher capacity versions using abundantly sourceable sorbents such as biochars and silica, finding higher energy efficient metal oxide DAC sorbents, and Zeolite sorbents sufficiently to bring them to market for DAC applications are required (Ozkan et al., 2022). With more research in sorbents and the factors that affect their lifetime, such as degradation from weather, there is potential for more durable sorbents and a better DAC system.

Energy demand is another area which results in the technology being less appealing and deemed having 'unrealistic' energy requirements. As discussed, liquid systems require 6.57–9.9 GJ/tCO<sub>2</sub>. More than half of this energy is the heat required for regeneration in which the sorbent requires heating of up to 900°C (Chatterjee and Huang, 2020; National Academies of Sciences, 2018). The large energy demand causes reason for concern as it has the potential of consuming more than half of the world's energy supply in a given year, provided that the technology is scaled-up. Contrasting the large energy requirement for the liquid sorbent process, 6.57–9.9 GJ/tCO<sub>2</sub>, the solid sorbent process has a demand of 3.5–6.6 GJ/tCO<sub>2</sub>. A quick explanation for this is solid sorbent-based systems are less intensive, which is because of a smaller heat and electric demanding process. With higher energy demands expected with scale-up, a major challenge is formed. A question of clean energy and/or fossil fuels also poses concern. The largest amount of carbon that is generated from clean energy sources is 0.0084–0.018 Mt/year of CO<sub>2</sub> when utilizing a purely solar source whereas coal would result in a footprint of 0.47–0.74 Mt/year of CO<sub>2</sub> (National Academies of Sciences, 2018). Using fossil fuels as an energy source seems to render the whole process ineffective because of more than half of the CO<sub>2</sub> capture to be released again by the energy source itself. Given the footprints of clean energy and fossil fuels, a preference is given to renewable energy as it allows for a more effective and efficient process. Examining the expense of these sources shows that less costly sources of energy are fossil fuels, which can range from \$88–228/tCO<sub>2</sub>, whereas the preferred renewable energy costs are much higher (i.e., solar has a price of \$430–690/tCO<sub>2</sub>) (National Academies of Sciences, 2018). Evidently, a grand challenge is seen when examining energy sources as the preferred source is the most costly. The use of waste heat from the DAC system or free waste heat from other sources can lower the levelized cost of low temperature DAC. In some cases this may decrease the cost by between 40 and 60%.

By examining these multiple challenges, the concept of scaling is often mentioned because of it being extremely important. The scale-up rate for DAC will ultimately be governed by the public acceptance and global support that it receives in the coming years, which thus far has been limited (Cox et al., 2020; Marcucci et al., 2017; Realmonte et al., 2019; van Vuuren et al., 2018). There have been promising analyses, specifically by Realmonte et al., that report a potential removal rate of 30 Gt/year of CO<sub>2</sub> within 20 years given that the scale-up maintains a 1.5 GtCO<sub>2</sub> removal per year. Other analyses report a potential for an almost 80% increase in capital cost and a dramatic increase in the energy requirement. Expectedly, cost and energy requirements will rise as scaling continues. A factor that might be easy to overlook is the amount of material that would be needed to maintain the numerous DAC plants required to remove the needed CO<sub>2</sub> in the atmosphere. Several raw materials contribute to the entire plant, such as concrete, steel foundation, stainless steel, aluminum, copper, plastics, and insulation (Deutz and Bardow, 2021). It is essential to not overlook the necessity for each of these raw materials as they all are required for the creation of the components in a DAC plant. A continuous look at the supply chain, which contains these materials, is essential because there will be a requirement for a large amount of the listed raw materials as this technology continues to scale. Like the other examined challenges, there is much room for additional research, analysis, and modeling to be done in this field. Current affairs are more pressing, and therefore, relevant in the world; however, a necessary look to the future is strongly needed for current adoption and deployment of DAC. This would provide hope for relief in areas such as cost and energy as the technology continues to scale (McQueen et al., 2020). Luckily, humanity has the option of overcoming the learning curve that is evident in DAC. This would result in fewer challenges and better understanding of the technology and what it means for the future (Caldera and Breyer, 2017).

Another discussion is the land needed for setting up a DAC plant that is dependent on several factors such as availability of thermal energy sources and fresh water. There is a huge push for the use of renewable energy to meet the thermal needs of a DAC plant. But, not all the places get enough sunlight to have Photovoltaic plants or river systems to harness hydroelectric power. Countries should utilize their existing energy sources to sustain such plants while investing in newer technologies that will reduce the carbon footprint. The gradual decrease in cost of development and operation of solar farms does bolster the green initiative. However, the growing population and rapid urbanization around the globe does put a load on the freshwater sources especially in arid regions. Passive Direct Air Capture technologies like Mechanical-Tree might be a possible solution to this problem as it reduces the need for thermal energy and freshwater. Many countries are focusing on mitigating climate change with other strategies like increasing the vegetation cover and opting for more eco-friendly agricultural practices (United Nations Environment Programme, 2019). Aside from land requirements, one area that does not have issues is sequestration. According to Carbon Engineering, a properly maintained storage site can store CO<sub>2</sub> for millions of years with little risk (Carbon Engineering, 2022).

Modular and simple DAC technical approaches are believed to reduce the cost because parts are easier to mass produce and deploy. Large volumes of standard parts production may accelerate DAC's deployment and shorten technology learning curve to drop down the cost. Passive air contact, modular design, and using natural sorbents are some of the current trends adopted by many DAC startup companies. As a result, removal of carbon at a cost of <\$100/ton by the mid-2030 is expected.

In brief, moving forward, work and attention are needed for DAC in sorbent creation, political support, reducing costs and energy demands, and increasing deployment. The progression of this technology could see a few barriers with regard to improvements to the technology. This could include a lack of funding, public acceptance, and political support, which are areas that are extremely important for success. The cost of carbon at the European Union Emission Trading System is nearly \$70/tCO<sub>2</sub> and is projected to reach \$100/tCO<sub>2</sub> in the near future and this could help to lift the pressure on the cost of carbon capture. Recently, the Breakthrough Energy Catalyst program within the COP26 Glasgow meeting pledged to raise up to \$30bn in investments to bring down costs for green hydrogen, Direct Air Capture of CO<sub>2</sub>, and long-duration energy storage are exciting news for the successful scaling up of DAC projects. Furthermore, increasing the number of regional DAC hubs to accommodate diverse technical DAC approaches may ramp up the development.

### Limitations of the study

Mentioned several times in this review, DAC technology is fairly new compared to decades old silicon technology or others which results in a lack of definite data related to the technology and because of

confidentiality of existing technology details, it is difficult to make long term life cycle analysis. The manner in which this review was conducted was to review the latest literature of DAC to determine its current status, challenges, and main pillars of technology that need attention. We find that when comparing any two articles, data will appear to be within a range of values. This means that it is rather difficult to find more than two articles that will report the same data for DAC because of system and generation variations in technology. This review takes a neutral approach by reporting data on both liquid and solid sorbent DAC with the latest data.

## AUTHOR CONTRIBUTIONS

M.O. proposed the topic of the manuscript. M.O., S.P.N., A.R., and W.J. investigated the literature and wrote the manuscript. All authors discussed the manuscript and prepared the outline. All authors revised the review critically for complete and comprehensive intellectual content. All authors read and approved the final version of the manuscript.

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