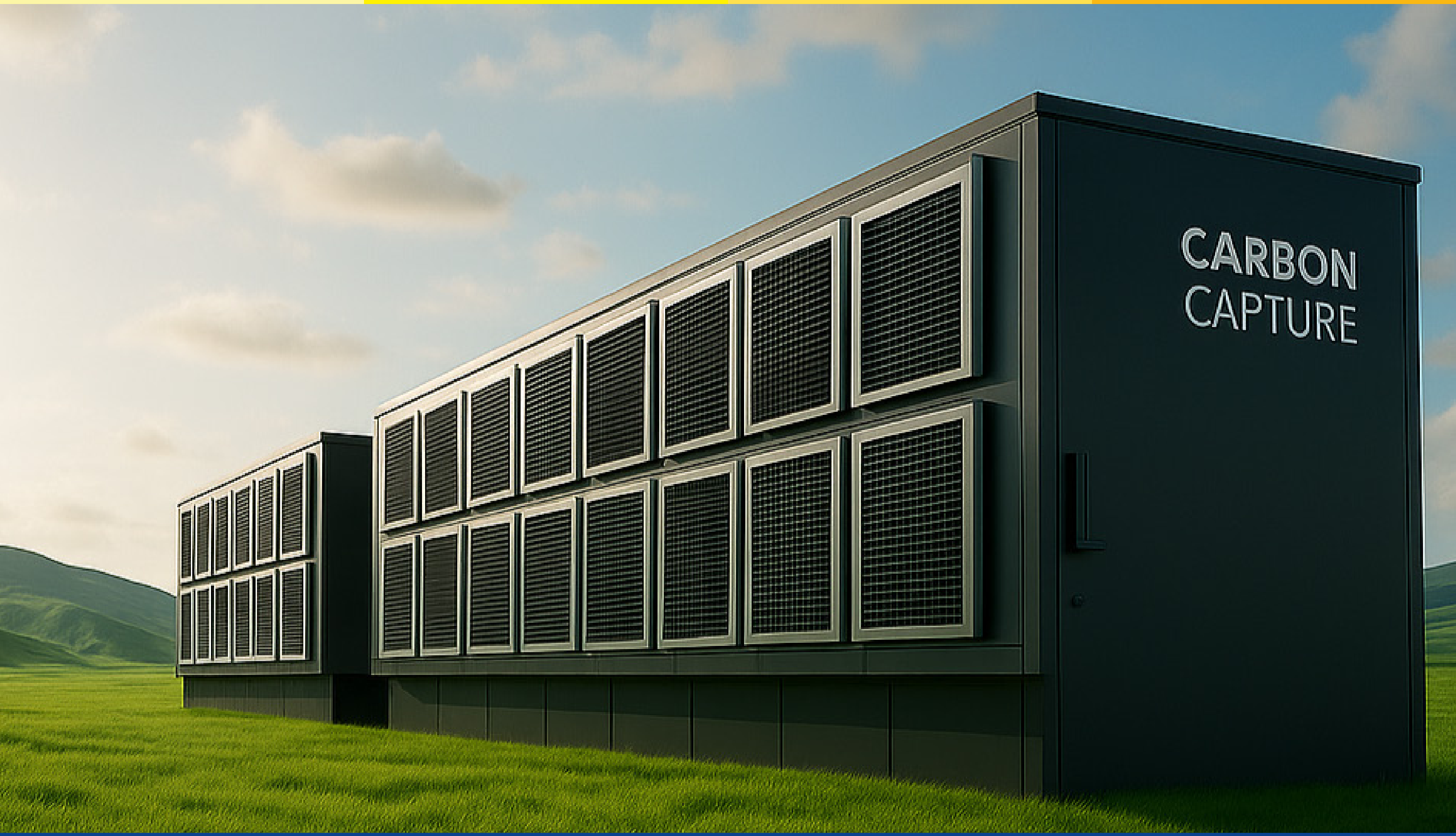

The State of Direct Air Capture Technology and Industry

Waterloo Climate Institute Technical Brief

UNIVERSITY OF WATERLOO | WATERLOO Climate Institute

DIRECT AIR CAPTURE

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ABSTRACT

Direct Air Capture (DAC) is an innovative engineering approach to directly removing carbon dioxide (CO_2) from the atmosphere, which can be used for combating climate change when combined with permanent storage solutions. Given the low concentration of CO_2 in the atmosphere (approximately 400 ppm or 0.04%) and the presence of other gases like water vapor, DAC technologies face substantial challenges. These technologies are typically categorized based on the primary material used for CO_2 capture: liquid and solid sorbents. Additionally, they can be classified by their method of sorbent regeneration for reuse. Although thermochemical processes currently dominate the industry, other approaches such as electrochemical techniques, membrane capture, and redox-active materials are also being explored. The following sections will provide information about these technologies, highlighting their advantages and challenges. A categorical summary based on sorbent and regeneration is provided in Table 1.

Keywords: Direct air capture, negative emissions technology, CO_2 capture, utilization, and storage

KEY MESSAGES

- A wide range of materials and processes are being explored for DAC.
- Thermochemical technologies currently dominate due to a select number of more established companies in the industry; however, electrochemical technologies are gaining traction.
- Reducing energy consumption across all technologies is key to driving down costs.
- The development of and access to CO_2 pipelines is critical for DAC to be a negative emissions technology.
- Governments should introduce compliance carbon markets as the voluntary market alone is not enough for the long-term funding of the DAC industry.

Table 1. Classification of DAC Technologies

	Thermochemical Technology		**Electrochemical technology**	
Regeneration Temperature	Liquid Sorbent	Solid Sorbent	Liquid Sorbent	Solid Sorbent
High Temperature	Aqueous Alkaline Solvents	Limestone and Lime		
Low Temperature	Amino Acid Solution	Adsorption column: • Zeolites • Activated Carbon • Metal Organic Frameworks	Monopolar or Bipolar Membrane Electrodialysis	Electro-chemically Mediated CO_2 Capture

THERMOCHEMICAL TECHNOLOGY

The first step in Direct Air Capture (DAC) involves removing CO_2 from the air using either solid or liquid sorbents. For thermochemical DAC, the second step is the high or low temperature regeneration of the sorbents, releasing a concentrated stream of CO_2 for utilization or storage.

Liquid Sorbent Technology

Liquid DAC technology, one of the primary methods employed, leverages the chemical properties of liquid sorbents to capture CO_2 from ambient air. This technology utilizes aqueous solutions, such as strong bases, or amines, to absorb CO_2 efficiently even at low concentrations.

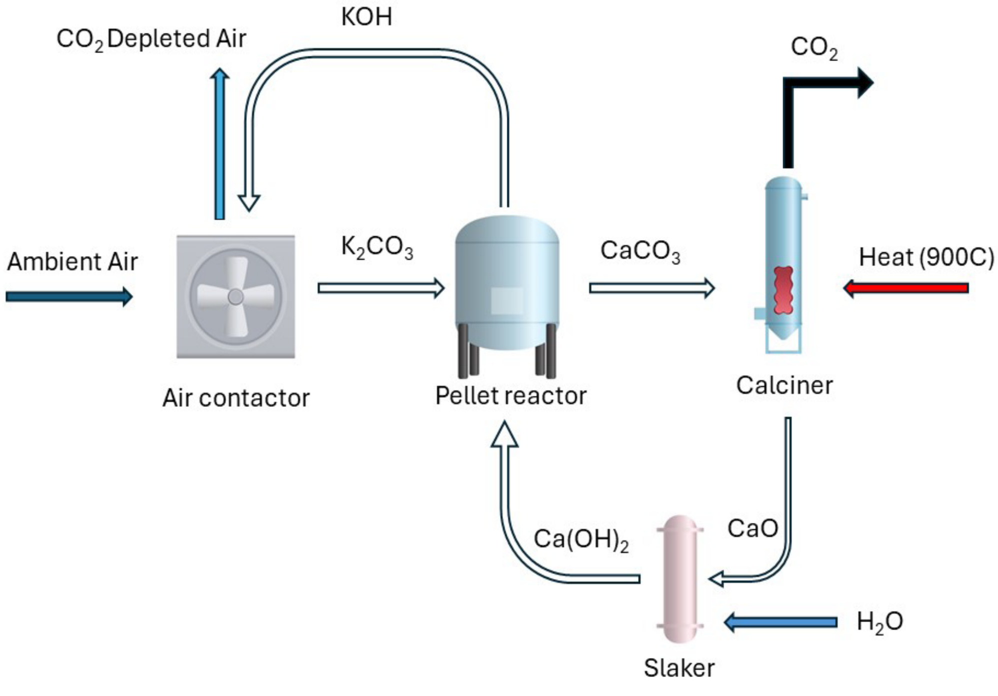
1. AQUEOUS ALKALINE SOLVENTS

A solution of alkaline substances, such as potassium hydroxide (KOH) or sodium hydroxide (NaOH), can be used to extract CO_2 from the ambient air. The process typically involves passing air through a contactor, where it interacts with the aqueous alkaline solution. The CO_2 dissolves in the solution and chemically reacts to form carbonate or bicarbonate ions, effectively capturing the CO_2.

Once captured, the CO_2 can be separated from the solution through a series of chemical reactions and thermal decomposition. This process generally involves several key units, including a pellet reactor, a calciner, and a slaker (see Figure 1). In the pellet reactor, calcium hydroxide ($Ca(OH)_2$) reacts with potassium carbonate (K_2CO_3) to form calcium carbonate ($CaCO_3$) and regenerated KOH. The $CaCO_3$ forms solid particles, while the KOH solution is recycled back to the contactor for further CO_2 capture.

Next, the $CaCO_3$ is sent to a calciner, where it is subjected to high temperatures of approximately 900-1000°C. In the calciner, the $CaCO_3$ decomposes into calcium oxide (CaO) and releases purified CO_2 gas or a mixture of CO_2 and steam, the latter being easily removed. The CaO is then transferred to the slaker, where it reacts with water at temperatures of around 100-150°C to form $Ca(OH)_2$, which can then be used again in the pellet reactor. This integrated process allows for the continuous regeneration and reuse of the alkaline solution, making it an efficient method for atmospheric CO_2 removal [1]. This technology is currently the most advanced liquid sorbent-based capture system with Carbon Engineering (now part of Occidental) leading the development.

Figure 1. Schematic diagram of a typical aqueous alkaline solvent DAC process

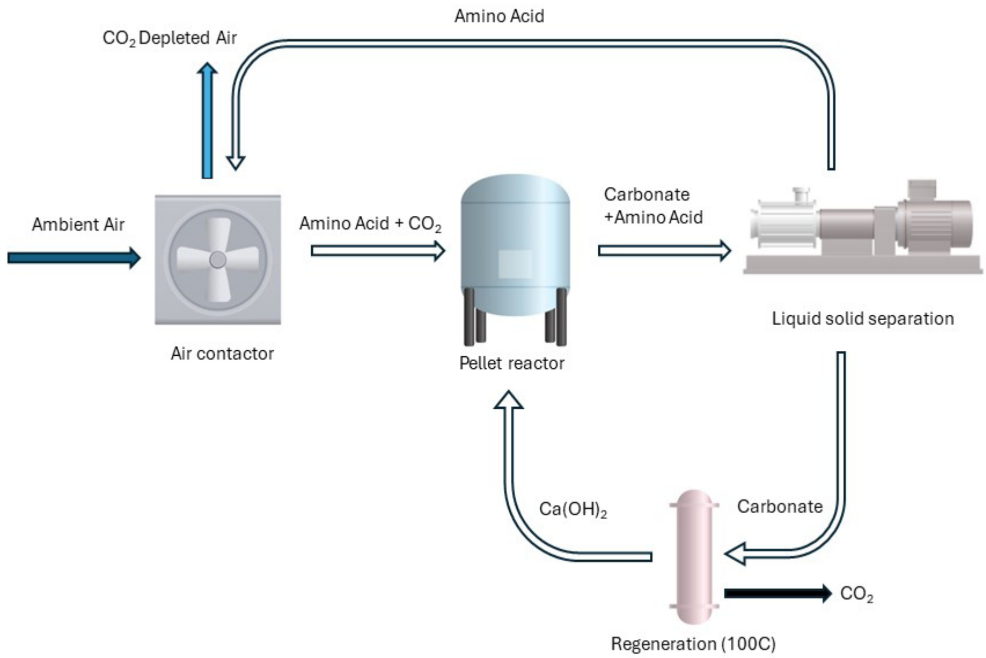


2. AMINO ACID SOLUTION

Using aqueous amino acid solutions for DAC also involves exposing the air to the solution via a contactor, where CO_2 reacts with the amino acids to form carbonate or bicarbonate compounds. This reaction typically occurs at ambient temperatures, around 25-35°C, depending on the specific amino acids and solution conditions. Figure 2 shows the process of using amino acid solution for DAC.

A potential key advantage of amino acid solution compared to alkaline solvents is the much lower regeneration temperature, where the thermal desorption step generally takes place at temperatures between 90°C and 120°C. At these temperatures, the carbonate or bicarbonate compounds decompose, releasing CO_2 gas. The released CO_2 is then collected for further use or storage, while the cooled amino acid solution is recycled back into the system for continuous CO_2 capture [2]. However, the use of amino acids also comes with disadvantages, such as lower absorption capacity, slower kinetics, and poor thermal stability. These drawbacks make amino acid solutions currently less favourable for large-scale CO_2 capture compared to alkaline solutions.

Figure 2. Schematic diagram of a typical amino acid solution.



Soild Sorbent Technology

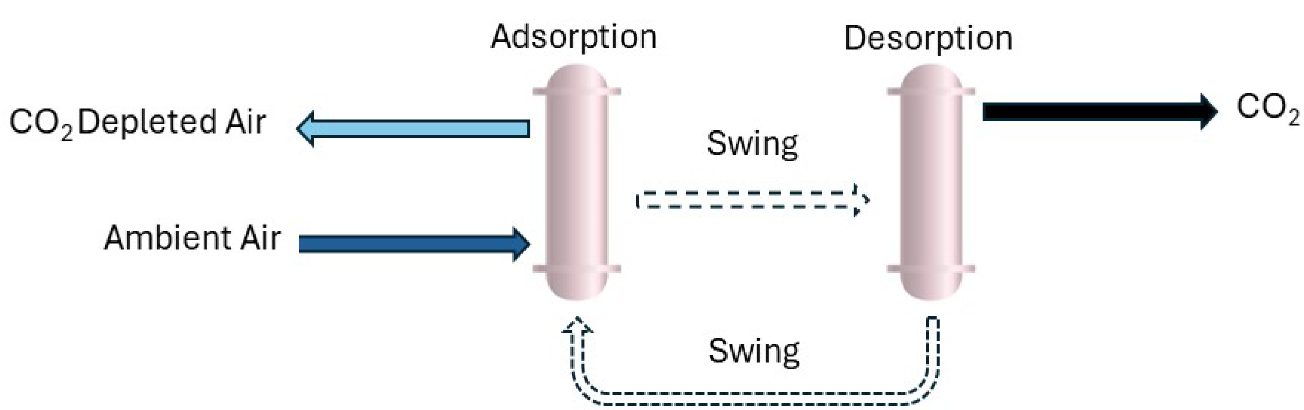
1. ADSORPTION COLUMN

Many specifically engineered solid adsorbent materials that can selectively adsorb CO_2 molecules are also being utilized for DAC. Solid adsorbents explored include metal-organic frameworks (MOFs) [3], zeolites [4], amine-functionalized polymers [5], and activated carbon [6]. They are chosen for their high surface area, high porosity, and the presence of chemical groups that have a strong affinity for CO_2.

The process consists of two main steps: adsorption and desorption (see Figure 3). During the adsorption phase, air is passed over the adsorbent material at ambient temperature, where CO_2 molecules are captured and held on the surface of the adsorbent. In the desorption phase, the captured CO_2 is released by creating driving forces through altering conditions such as humidity, temperature (typically raising it to 80-120°C) or pressure (by applying a vacuum) [7], or a combination thereof.

- **Desorption/Regeneration**: To release the CO_2 for isolation, it undergoes desorption from the solid sorbent, thereby allowing the sorbent to be regenerated for reuse. Although other methods exist, applying heat, reducing pressure (vacuum), or a combination of both are the most popular.
  - **Temperature Swing Adsorption (TSA)**: The material is usually heated to low temperature to release the CO_2. Increasing the temperature reduces the sorbent's affinity for CO_2, causing it to be released. TSA is common for amine-based adsorbents, though care is needed to avoid oxidative degradation [8].
  - **Vacuum Swing Adsorption (VSA)**: VSA involves decreasing the pressure to create a vacuum to facilitate desorption. This method is energy-intensive but effective for large-scale CO_2 capture [9].
  - **Temperature Vacuum Swing Adsorption (TVSA)**: A combination of TSA and VSA which is commonly used in solid sorbent-based DAC.
  - **Moisture Swing Adsorption (MSA)**: MSA leverages humidity oscillations instead of traditional energy-intensive processes. Initially proposed by Wang et al. [10], MSA often uses amine-based anion exchange resin sorbents, which capture CO_2 when dry and release it upon exposure to moisture, with water evaporation driving the cycle. This method offers advantages over conventional TSA, including reduced energy requirements, no need for heating or cooling units, and flexibility in equipment placement.

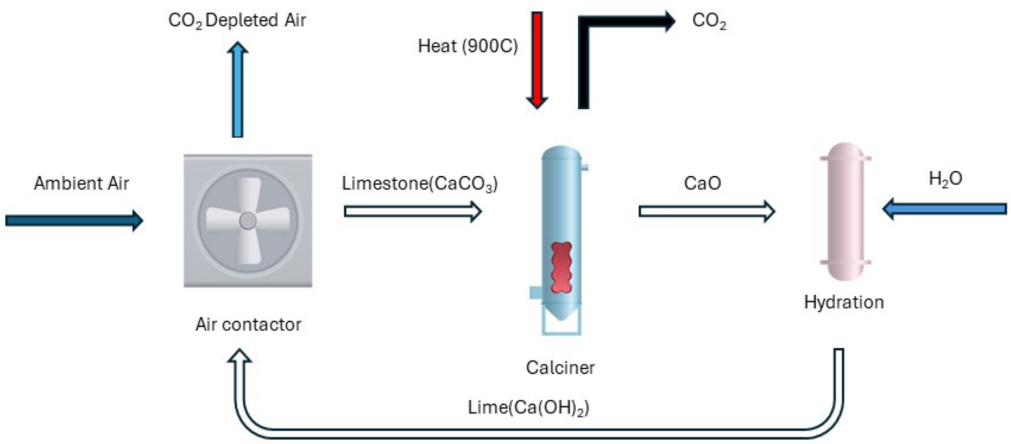
Figure 3. Simplified schematic of a typical adsorption column.



2. LIMESTONE AND LIME

DAC using solid lime/calcium hydroxide ($Ca(OH)_2$) involves a three-step process. First, atmospheric CO_2 reacts with $Ca(OH)_2$ at ambient temperatures, typically around 25-30°C, to form limestone/calcium carbonate ($CaCO_3$) and water. The $CaCO_3$ is then transported to a calciner, where it undergoes calcination at high temperatures, generally around 900°C. During this step, $CaCO_3$ decomposes into calcium oxide (CaO) and releases high concentration CO_2 gas. The released CO_2 can be isolated for storage or use. In the third step, CaO is rehydrated to regenerate $Ca(OH)_2$, enabling the cycle to repeat. Figure 4 shows a schematic diagram of this process. Note that companies typically start with quarried limestone which is first processed into $Ca(OH)_2$ to begin the capture process.

Figure 4. Schematic diagram of a typical limestone ($CaCO_3$) and lime ($Ca(OH)_2$) technology.



ELECTROCHEMICAL TECHNOLOGY

Electrochemical technologies use electricity to drive chemical changes or reactions and can be used to capture CO_2 and/or regenerate sorbents, depending on the technology.

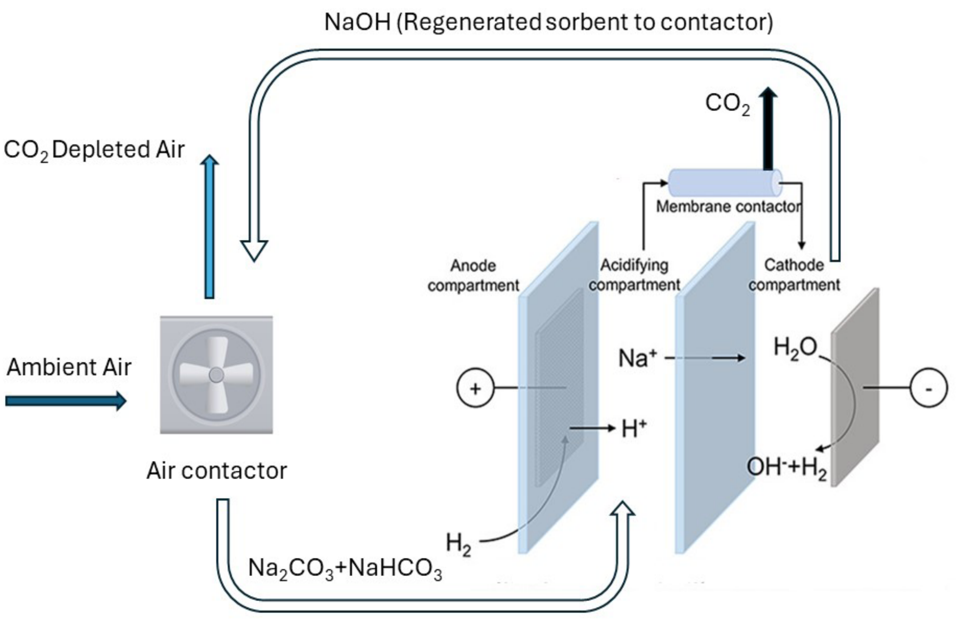
Liquid Sorbent (Aqueous Alkaline Solvent)

1. MONOPOLAR MEMBRANE ELECTRODIALYSIS

The electrochemical regeneration of spent alkaline absorbents in Direct Air Capture (DAC) systems follows a similar CO_2 capture process to that of conventional alkaline solution technology (see section 1.2.2). However, instead of relying on a calciner for regeneration the carbonate or bicarbonate ions formed during CO_2 capture pass through an electrochemical cell. A monopolar cell consists of an anode, a cathode, and a membrane that separates the two compartments. In the anode compartment, the carbonate or bicarbonate ions are oxidized under an applied electric current, releasing CO_2 gas and regenerating hydroxide (OH^-) ions. The CO_2 is then separated and can be stored or utilized [12]. Figure 5 shows a simplified schematic of the process.

The regeneration process occurs at moderate temperatures, typically around 60-80°C, which is sufficient to maintain the fluidity of the solution and support efficient electrochemical reactions. The regenerated OH^- ions can be reused to capture more CO_2, thus closing the cycle. This method of regeneration is advantageous because it avoids the need for high temperatures required in thermochemical processes, which can exceed 900°C. By operating at lower temperatures and using electrical energy, when located in a low-carbon power grid, the electrochemical regeneration process can potentially be more energy-efficient and environmentally friendly.

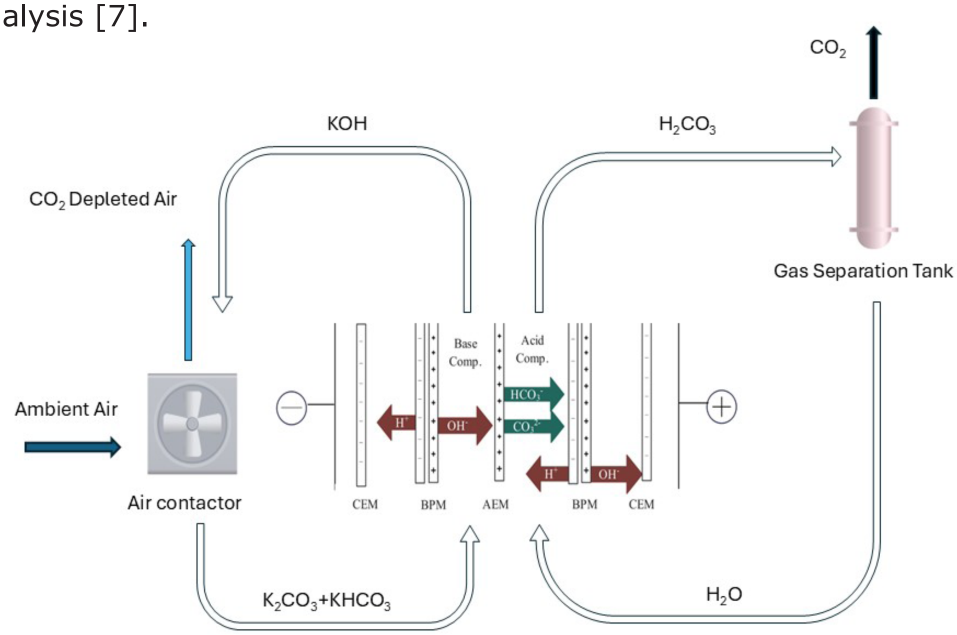
Figure 5. Schematic diagram of a typical electrochemical regeneration of aqueous alkaline solvents, adapted from [12].



2. BIPOLAR MEMBRANE ELECTRODIALYSIS

After using aqueous alkaline solvent to remove CO_2, bipolar membrane electrodialysis (BPMED) can be used to separate and recover acids and bases from solutions containing dissolved salts (K_2CO_3, $KHCO_3$, see Figure 6), serving as an alternative to high-temperature regeneration methods. BPMED utilizes electrochemical principles and membranes to achieve the regeneration of alkaline solutions, offering a potentially more energy-efficient approach. The BPMED system employs a series of membranes, including bipolar membranes, cation exchange membranes (CEM), and anion exchange membranes (AEM). A bipolar membrane comprises two layers: one selectively permits the passage of positive ions (cations), while the other allows negative ions (anions) to pass through. When an electric current is applied, the bipolar membrane facilitates the splitting of water molecules into hydrogen ions (H^+) and hydroxide ions (OH^-). These ions move in opposite directions, resulting in the formation of acidic and basic streams in separate compartments. This process typically occurs at moderate temperatures, around 30-50°C, which helps maintain the stability of the membranes and enhances the efficiency of ion transport. The main advantage of BPMED is its ability to produce acids and bases without external chemical additives, relying solely on the electrical splitting of water [13].

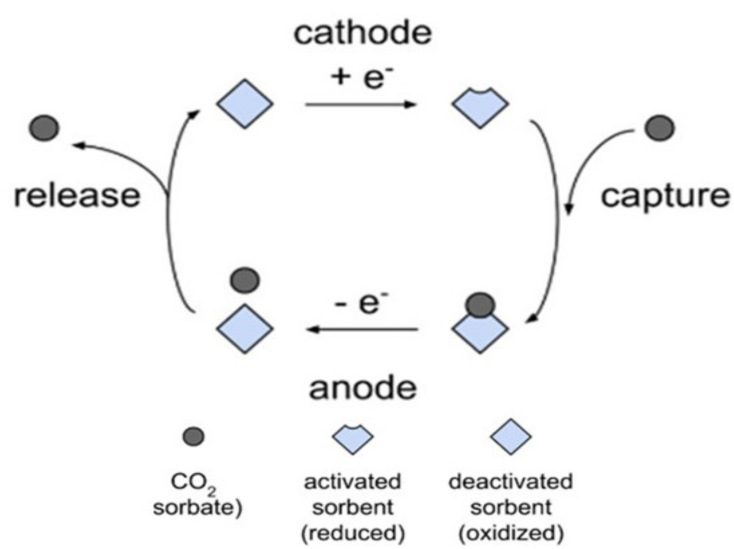
Figure 6. Schematic diagram of a typical Bipolar Membrane Electrodialysis [7].



Solid sorbent – Electrochemically Mediated CO_2 Capture

Electrochemically Mediated CO_2 Capture (EMCC) involves the use of a solid sorbent that is electrochemically activated and deactivated to adsorb and desorb CO_2, respectively (see Figure 7). The CO_2 sorbent itself is redox-active, meaning its ability to capture CO_2 is directly altered by applying an electrical current [14]. This technology is promising but quite new and needs further research and demonstration beyond pilot scale.

Figure 7. Operating principle of the EMCC process, adapted from [14].



TECHNOLOGY READINESS, LIMITATIONS AND IMPLEMENTATION

Technology Readiness and Limitations

Most of the current Direct Air Capture (DAC) technologies are rated at 6 or below in terms of technology readiness level (TRL) as outlined by Küng et al [15,16]. Many companies have demonstrated lab-scale proof of concepts and have plans to deploy pilot or demonstration projects in the field (TRL 6) [17]. While there is no consensus on estimated required annual CO_2 removal by 2050, the lower estimate is 1.5 to 3 gigatons [18], which we are on track for according to Wood Mackenzie [19]. For DAC to achieve gigaton scale by 2050, megaton scale needs to be reached by 2030, indicating that companies should have a TRL of at least 7 in the next 5 years. The current gap emphasizes the critical action needed in this decade on several fronts to reach what is considered an ambitious but achievable carbon removal goal [15].

Several challenges for DAC deployment exist, a major one being cost. As seen from Table 2, current actual and projected capture costs range up to $1000/t$CO_2$

but need to reduce to $100-200 by 2050, which is in line with the cost of solid waste removal in high-income countries [20]. While cost is driven by different categories depending on the technology, for a first-of-a-kind plant, large contributors generally include capital cost as well as direct equipment and installation costs. Capital costs are expected to fall more quickly than operational costs via learning and scaling over time. In addition, modular DAC approaches would be expected to have higher technological learning rates, and thus lower capital cost for a nth-of-a-kind plant compared to technologies utilizing economies of scale [15].

Feeding into cost are various energy-related challenges including the energy consumption of DAC, access to low-carbon energy and low energy prices. Many companies are focused on a Temperature Swing Adsorption (TSA) or Temperature Vacuum Swing Adsorption (TVSA) approach. The energy required for both solid or liquid sorbent technologies using TSA is roughly 80% thermal and 20% electrical [21]. High temperature liquid sorbent DAC requires the use of natural gas, generating 0.012tCO_2 per ton captured, although electrical alternatives are being explored [22]. Several low-temperature or electrochemical based DAC technologies have emerged, which would reduce or eliminate the thermal energy requirement for the sorbent regeneration process. However, access to low-carbon electricity and overall reductions in energy consumption is more critical for these technologies to achieving net-negative emissions and reducing net-removal costs if they are tied into existing energy supply systems [15]. For all technologies, energy price has a larger influence on net capture cost compared to CO_2 intensity of the energy, which highlights the need to reduce energy consumption across the industry [15].

Aside from energy consumption there are several other technological and infrastructure-related obstacles that exist for DAC. Further research and development can explore new materials, improve material stability and recyclability, process design, process intensification, equipment design, and study system integration in different climates [15], to name a few. However, it should be noted that the current lack of public data available about many DAC technologies being commercialized, due in part to proprietary concerns and low industry TRL, can inhibit progress in addressing some of the obstacles [15].

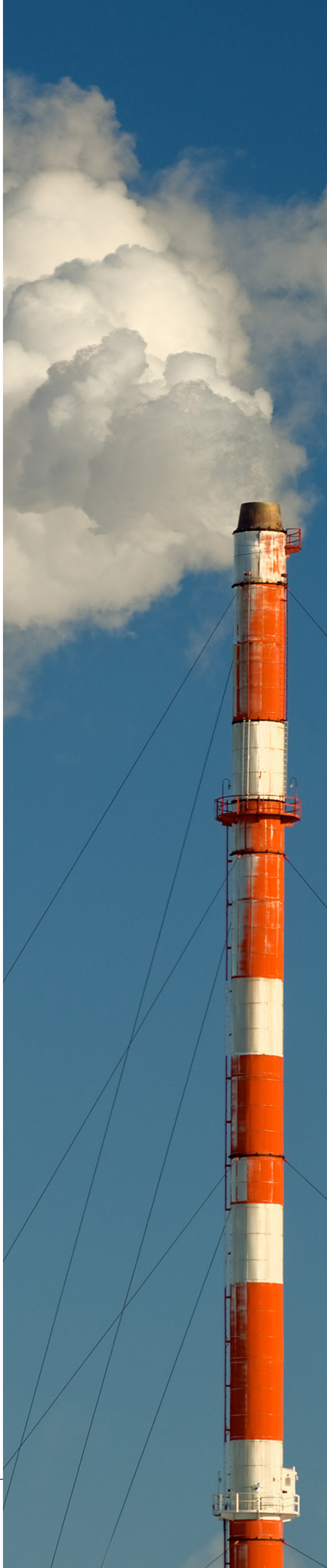
Implementation

From a technological perspective, besides considering the access to low-carbon energy (whether on or off grid) when siting DAC plant, other factors including water access (especially for liquid DAC), local and regional climate conditions such as humidity, land area requirements, and CO_2 transport infrastructure and storage suitability are critical to the success of a DAC project. Currently existing CO_2 pipelines are linked to oil and gas infrastructure and primarily used for enhanced oil recovery (EOR) [23]. New CO_2 pipelines are being proposed to connect point sources of carbon capture with geologic sequestration sites. While governments have announced financial support [24–26], these pipelines are facing public pushback as well as political [27] and regulatory hurdles which have led to project uncertainties and cancellations [28,29]. In the U.S., concerns are driven from a pipeline rupture in 2021 in Mississippi that led to dozens of hospitalizations. Opponents cite the poor safety regulation (which is now being updated) and lack of emergency preparedness for a leak or rupture as the main concerns [23,30]. Until these issues can be addressed, it may be challenging for pipeline developers to secure landowner agreements which ultimately will negatively impact both CCS and DAC development. Although there are opportunities for CO_2 utilization in EOR and conversion into chemical feedstocks, the vast majority of captured CO_2 must be sequestered to effectively lower the global temperature.

The lifecycle assessments on DAC must consider whether it is grid connected, taps into existing clean energy infrastructure or develops and stores its own renewable energy on site. While Climeworks has been able to tap into waste geothermal heat for their projects in Iceland, ultimately, additional clean energy will need to be developed to support DAC. For a megaton DAC plant, it is estimated that 0.4 (only natural gas) to 34 km^2 (only solar) of land would be required to produce the 270-280 MW of power needed [22], which does not include the land required for the DAC plant itself. By 2100, it is estimated that DAC with sequestration could require 50 EJ/year of electricity which is about 10-15% of the projected global generation [31]!

As DAC is a relatively new industry, it has the opportunity to be implemented in an environmentally, socially and economically just manner. As with any large infrastructure undertaking, proper environmental assessments should be conducted to reduce the impact on local flora, fauna, water resources, and any existing industry such as agriculture, not only during construction but during the lifetime of the plant. Developers should also conduct meaningful community engagement to ensure local support of the project [32]. Historically in North America, Black, Indigenous, and/or people of colour have been excluded from the decision-making processes on projects which can negatively impact their communities. While the environmental and health risk to the vicinity of a DAC plant is considered low, particularly for non-natural gas fuelled DAC, other factors like increased traffic and noise still need to be considered [22]. With proper planning and utilization of resources for responsible deployment [33], DAC can be an economic opportunity for low-income communities and those in industrial/economic transition by creating new jobs and tax revenue. As DAC technology is not well known, educating the public is also key to building the positive perception needed to help drive the DAC industry and ultimately meeting carbon removal goals.

Lastly, another major challenge for DAC companies is revenue due to the current lack of market for carbon removal. Voluntary markets are still small and most buyers are focused on credits for emissions reduction and avoidance. In compliance markets, there is limited access due to a lack of standards and project-specific protocols, of which their future development is dependent on the success of DAC companies overcoming the numerous aforementioned roadblocks. Notably, there is ample opportunity for governments to play a role in supporting DAC in research and development, demonstration, and deployment [34].



DIRECT AIR CAPTURE COMPANIES

According to the Direct Air Capture (DAC) Coalition [35] which currently consists of 51 member organizations, there are at least 30 operational DAC facilities globally for a total capacity of <44,000 tCO_2/yr, ranging from small demonstration plants with a capacity of one ton to the operation of the first collectors on the Climeworks Mammoth plant with an expected capacity of 36,000 tCO_2/yr (as of summer 2024). Another 24 are under construction and several other projects which are in other stages of development including front-end engineering design (FEED), pre-FEED, or announced. Table 2 provides an overview of some of these companies.

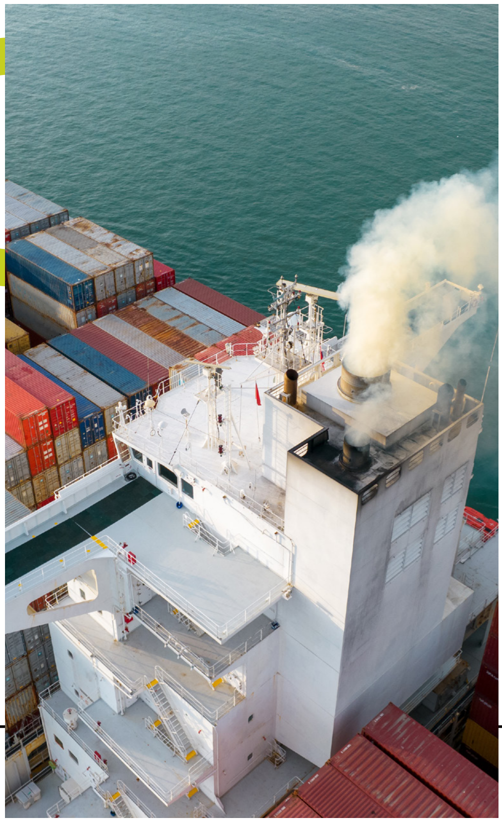


Table 2. DAC Company Information Summary

Sorbent State	Company	Sorbent	Desorption Method	Capacity (CO_2/yr.)1	Capture Cost ($/t$CO_2$)	Country of origin	Representative Patent(s)[2]
Liquid	Carbon Engineering (Oxy Low Carbon Ventures)	KOH	High-temperature calcination	365 t; 500 kt–1 Mt (2024)	$94–232	Canada	[36,37]
Liquid	1pointfive (subsidiary of Occidental)	KOH	High-temperature calcination	500 kt (2025); 500 Mt (2035)	Unknown	United States	Carbon Engineering
Liquid	Carbon Blade	NaOH	EDBM	Unknown	~$100	United States	[38]
Liquid	Greenlyte Carbon Technologies	PEG or polyols, and K_2CO_3, Na_2CO_3, amino acids or mixtures	Electrolysis	100 t; 200 t (2025); 100 Mt (2050)	~$275 (2025); ~$165 (2030)	Germany	[39]
Liquid	Mission Zero Technologies	PEI (polyethyleneimine)	Electrochemical	50 t; 550 t (2024)	Unknown	Great Britain	[40]
Solid	Climeworks	Amine-functionalized nanofibrillated cellulose	TVSA	6.9 kt; 42.9 kt (2024); 742.9 kt (2030)	$600–800; $250–350 (2030)	Switzerland	[41–43]
Solid	Zero Carbon Systems/ Global Thermostat	Aminopolymer	TVSA	1 kt; 3.5 kt (2026); 53.5 kt (2028); 1 Mt (2030)	$300 (2025)	United States	[44–47]
Solid	Hydrocell/ Soletair Power	Amine-polystyrene beads	TVSA	~44 t; 64 t (2025)	Unknown	Finland	[48,49]
Solid	Skytree	Benzylamine-based ion-exchange resin beads	TSA	904 t (2024)	~$678	Netherlands	[50]
Solid	Carbon Collect	Ammonium functionalized polymer	MVTSA (TVSA & MVSA capable)	33 t	$100 target	Ireland	[51,52]
Solid	Carbon Capture	Zeolites	TVSA	5 Mt (2030)	Unknown	United States	[53,54]
Solid	Verdox	Polyanthraquinone	Electroswing adsorption	Unknown	$50–100	United States	[55–57]
Solid	TerraFixing	Zeolites	TVSA	1 kt	$404	Canada	[58]
Solid	Noya	MgO, Al_2O_3, K_2CO_3, activated carbon, monoethylamine, glycine or sarcosine	TVSA	~1 t; 350 t (2024)	<$100	United States	[59]
Solid	Heirloom	Lime/limestone	High-temperature calcination	1 kt; 17 kt (2026); 117 kt (2027); 317 kt (2030)	$600–1000; $50 target	United States	[60]
Solid	Sustaera	Sodium carbonate on monolith	TSA	1 t	$175; ≤$100 (2027)	United States	[61,62]
Solid	Octavia Carbon	Amine-functionalized sorbent	TVSA	1 kt (2024)	$300–500	Kenya	Not available
Liquid	Capture6	NaOH from brine/ saltwater	Electrochemical	500 t (DAC) + 500 t (CCS); +25 kt (unknown)	Unknown	United States, New Zealand	[63,64]
Liquid	Holocene (Oxy Low Carbon Ventures)	Amino acid, then guanidine	TSA	10 t; 2 kt (2026); 102 kt (2028); 1 Mt+ (2030)	Unknown	United States	[65]
Solid	280 Earth	Amine-functionalized sorbent	TVSA	500 t	>$600	United States	[66]
Solid	Skyrenu	Amine-functionalized polymer	TSA	50 t (2024)	Unknown	Canada	[67]
Solid	Heimdal	Lime/limestone	TSA	5040 t	<$200	United States	Not available

CONCLUSION

In summary, there are various technologies being explored in the field of Direct Air Capture (DAC). The industry is growing quickly with most companies being founded in the last 5 years as government incentives for DAC have increased. As such, most companies have demonstrated their technology only at small scales, but major and rapid scale-up to gigaton capacity is needed, likely requiring decades to achieve. Across the industry, the problem of capture cost remains; however, this is expected to lower as the technology scales up. Hence, at this stage it is not clear if one specific technology will emerge as the most favourable. There may be location and climate considerations that impact the success of each technology.

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