

Review article

A comprehensive review on regeneration strategies for direct air capture[☆]

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ABSTRACT

Direct air capture (DAC), which removes CO₂ directly from ambient air, is a critical negative emission technology for mitigating global climate change. Efficiency and the source of energy are crucial considerations for DAC to enable negative emissions. Substantial technological progress has been made in DAC technologies, and promising opportunities exist for commercial-scale deployments. However, DAC technologies require high regeneration energy to release CO₂ from sorbents. Various approaches have been tested and optimized for different DAC systems. This review demonstrates that the work equivalent regeneration energy demand (supported by either the electric grid or fossil fuel combustion) ranges from 0.5–18.75 GJ/t-CO₂ for solid sorbent DAC systems and 0.62–17.28 GJ/t-CO₂ for liquid solvent DAC systems. The regeneration process is the energy-demanding process in DAC that is a key step for efficient operation. Potential methods to lower the regeneration energy demand include microwave, ultrasound, magnetic particle heating, and electric swing. Although the potential methods to date are still at the lab scale, significant work is being done to optimize DAC system processes.

1. Introduction

Climate change mitigation pathways are aimed at meeting the long-term target of limiting climate change to well below 2 °C, which may lead to different levels of increasing risks during the coming decades [1–4]. The climate scenarios are based on the integrated assessment models that represent linkages and trade-offs among energy, land use, climate, economy, and development [5–7]. Climate change is predicted to exceed 1.5 °C within decades and 2.0 °C by 2050 in all but the most optimistic scenarios [8]. The remaining budgets for limiting the warming to 1.5 °C or 2 °C have been estimated, respectively, at about 420 and 1170 Gt of CO₂. With unchanged present emissions of about 40 Gt CO₂/year, these budgets would be exhausted in as few as 10 and 30 years, respectively. Most of the Intergovernmental Panel on Climate Change emission scenarios that meet a global 2 °C target in 2100 overestimate the carbon budget at first and then remove the excess carbon with large negative emissions, typically from 400 to 2100 Gt CO₂ [8]. Scenarios for meeting ambitious climate targets rely on large-scale negative emission technology (NET) deployment. NETs have recently received increasing attention as a key element of climate change

mitigation pathways that limit temperature rise to 1.5 °C or 2 °C. As shown in Fig. 1, the global energy portfolio will have to significantly change to achieve net-zero emissions in the near future. For instance, reaching net-zero emissions requires a huge decline in the use of fossil fuels such as coal, oil, and gas. Furthermore, nearly 90% of electricity generation will have to come from low-emission energy sources such as wind, solar, and nuclear power. However, tens of gigatons of CO₂ removal is essential to achieve net-zero emission scenarios because various emissions from fossil fuel industries are difficult to avoid [9–11]. Extensive articles exist that explore the potential opportunities, risks, and trade-offs of relying on negative emissions [12–17]. Among the NETs, CO₂ capture from air, or direct air capture (DAC), uses different materials or chemicals for carbon capture processes and their applications [18]. In recent years, DAC companies have gained increasing attention, and governments are moving to include negative emissions into climate and energy policies [19]. To meet the emissions goals of the Paris Agreement [8], a noticeable development to scale up DAC is essential.

Several studies have focused on critically reviewing CO₂ capture systems [16,18,20–28] but have not examined the details of

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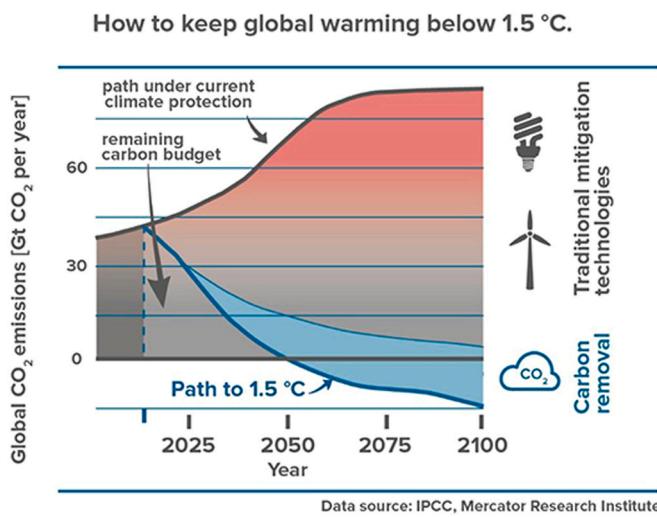


Fig. 1. The role of CO₂ removal in climate change mitigation. Reproduced from ref [10] under CC BY 4.0.

regeneration processes. In this work, conventional and state-of-the-art regeneration processes of DAC systems were reviewed to fill potential knowledge gaps and discuss possible advances to make DAC commercially feasible. Capturing and postprocessing CO₂ via commercial-scale DAC requires substantial thermal and electrical energy [9,29–32]. Regeneration is a key process in DAC systems that consumes significant heat and electrical energy. Therefore, significant research and development on sorbent regeneration is required to scale up and commercialize DAC systems for the market within the next few years. The current capture cost of DAC systems is much higher than the required cost of \$100/t-CO₂ to make DAC economically viable, and it depends highly on the source of energy used [33]. For a liquid solvent DAC system, a high temperature is generally required for the calcination or regeneration of the solvent, and the regeneration energy requirement is 4.05 GJ/t-CO₂ captured [27,34], which is 46–72% of the total energy demand. For regeneration of a solid sorbent-based DAC system, a low temperature (80–120 °C) is needed, which can be provided by thermal energy from waste heat, heat pumps, or electric heaters. In the International Energy Agency Net Zero Emissions by 2050 Scenario [35], DAC technologies are projected to capture more than 85 Mt CO₂ in 2030 and approximately 980 Mt CO₂ in 2050, requiring a large and accelerated scale-up from approximately 0.01 Mt CO₂ today [35]. To enable the widespread and rapid deployment of DAC systems, more funding dedicated to research and development, the procurement of CO₂ offsets, and the implementation of improved policies to incentivize carbon capture [36], utilization, and storage technologies is needed. To the best of the authors' knowledge, no reviews currently exist regarding sorbent regeneration methods and their energy demands for different DAC systems. Therefore, this study explores current commercialized DAC systems, regeneration methods, and limitations and provides potential pathways for efficient regeneration processes for DAC systems.

2. Commercialized DAC systems

Many DAC companies have launched around the world in recent years with different technical approaches for CO₂ capture. Two major categories for DAC exist for commercial applications: liquid solvent and solid sorbent. For the liquid solvent process, aqueous-based solutions, such as alkaline solutions, are widely used. The solutes may only be present up to 30 wt percent (wt%) in the solution because of the corrosive nature of the base, which limits the number of interactions with CO₂ [18]. However, solid sorbents have the advantage of the base chemically binding to the porous material of the sorbent, which increases the number of contact sites with CO₂ [22]. Unlike continuous

liquid solvent systems [34,37], most solid sorbent DAC systems require near-vacuum conditions (e.g., 0.1–0.3 bar) at each cycle in the regeneration process, likely requiring massive energy inputs at the commercial scale [38–44]. Commonly, the operational duration of the solid sorbent is generally under 1 year, implying a need for recurrent procurement of the sorbent over the facility's operational lifespan. A contemporary research initiative has encompassed a range for sorbent longevity, spanning from a minimum estimate of 0.25 years to a maximum projection of 5 years [18,45]. Tables 1 and 2 provide information regarding commercial DAC companies from 2009 to 2022. Carbon Engineering is a commercial Canadian business that used a hydroxide solution to capture atmospheric CO₂ using an identified vendor of commercial hardware that meets the process specifications or identified commercial hardware that can be adapted to perform the process [34]. The commercial-scale DAC plant will start up in the Permian Basin by a partnership between Carbon Engineering and Occidental Petroleum. The plant is expected to capture 0.5 Mt CO₂ each year and could become operational in late 2024 [35]. In 2009, Climeworks (located in Switzerland) developed a novel temperature vacuum swing adsorption (TVSA) system using an amine-based solid sorbent that requires a low temperature (100 °C) for the regeneration process under vacuum [46]. The TVSA process comprises five steps: adsorption, evacuation, pressurization, desorption, and cooling. Since 2020, the Climeworks CarbFix project has captured CO₂ from the atmosphere and blended it with geothermal fluids for injection and underground storage in basalt rock formations at depths below 1300 m [47]. The project is the first operating large-scale carbon capture and storage method that will convert CO₂ into rock within decades through enhanced mineralization. The plant was recently expanded to capture 4000 t CO₂/year, making it the largest DAC plant removing CO₂ from the atmosphere to date. Global Thermostat is a US company that employs an amine-modified monolith as an adsorbent to capture atmospheric CO₂, and the company's reported regeneration temperature is 85–90 °C [46]. The method of regeneration involving moisture-swing exhibits a CO₂ purity that is considered appropriate in scenarios where lower purity CO₂ is needed, particularly for applications in agricultural greenhouses. On the other hand, among the various reported regeneration techniques, temperature-vacuum swing adsorption (TVSA) emerges as the predominantly preferred approach, exhibiting minimal drawbacks, particularly in cases demanding high purity CO₂ levels exceeding 95% [48].

These three major commercial companies (Carbon Engineering, Climeworks, and Global Thermostat) only capture a few thousand tons of CO₂ each year, and other recently launched DAC companies (as described in Tables 1 and 2) are still at the lab scale and therefore lack available information on the technical and operational data to perform life cycle emission or economic studies.

3. Regeneration methods for liquid solvent DAC

Although aqueous alkaline sorbents generally have the advantages of availability and relatively fast absorption kinetics, they are highly corrosive. Furthermore, sorbent regeneration is energy-intensive, requiring temperatures of approximately 900 °C [16,18,63]. Liquid DAC systems typically use a strong basic solution to bind dilute CO₂ in the air. When the CO₂ dissolves in water, the solution becomes slightly acidic and therefore reactive to the basic solution with fast kinetics. These solvents are generally light metal hydroxides (e.g., NaOH [64–66], KOH [34,67,68]) that are dissolved in a water solution and react with CO₂ to make carbonates. Because the reaction is thermodynamically favorable, it is broadly used for atmospheric CO₂ capture [69]. A representative process flow diagram for the liquid solvent DAC system is shown in Fig. 2, which includes the capture and regeneration cycles [34]. For the regeneration cycle, approximately 60% of the total energy (Fig. 3) is needed to detach the absorbed CO₂ from CaCO₃ to recycle solvent for successive cycles of CO₂ capture. The liquid and solid DAC desorption processes both require a large amount of energy because of the strong bind of CO₂ with

Table 1

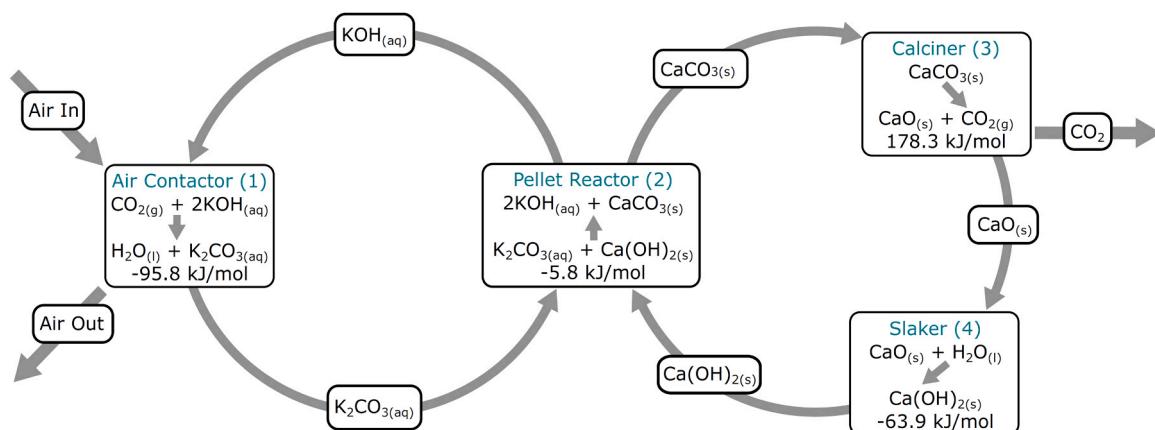
Information on commercial DAC companies (before 2020).

	Carbon Engineering[34,49, 50]	Climeworks[51]	Global Thermostat[50, 52]	Infiniterree[53]	Carbon Collect[54]
Start year	2009	2009	2010	2017	2018
Capture method	KOH solvent	Amine-based sorbent	Amine-modified monolith	Ion-exchange sorbent	Ion-exchange sorbent
CO ₂ capture capacity (t-CO ₂ /year)	1500 (Squamish, Canada)	4000 (Hellisheiði, Iceland)	1000 (Huntsville, United States)	100	Lab scale
Regeneration method	Oxy-fuel combustion	Temperature and vacuum swing	Temperature and vacuum swing	Moisture swing	Moisture swing
Regeneration temperature (°C)	900	100	85–95	Ambient	Ambient
Estimated cost (\$/t-CO ₂)	168–232	600–800	—	—	—
Future cost (\$/t-CO ₂)	126–170	200 by 2030 100 by 2050	—	—	—
Remarks	Carbon Engineering plans to build a 1 Mt/year plant by 2024 and use its captured CO ₂ in Occidental Petroleum's enhanced oil recovery operations.	Climeworks is building its newest and largest DAC plant with a planned nominal CO ₂ capture capacity of 36,000 t-CO ₂ /year in 2024. Climeworks' ambitious scale-up plan is megaton capacity by 2030 and gigaton capacity by 2050.	Global Thermostat had a 10-year contract to supply Coke with 20,000 tons per year of captured CO ₂	The Infiniterree moisture swing system (which requires dry air conditions) provides enhanced reductions of CO ₂ for a more competitive price than current combustible methods.	Carbon Collect's technology applies the latest research of Dr. Lackner's group at Arizona State University[22,55,56]. These moisture swing systems are a thousand times more efficient than natural trees.

Table 2

Information on commercial DAC companies (after 2020).

	Heirloom[57]	Mission Zero[58]	Hydrocell[59]	Susteon[60]	Noya[61]	Skytree[62]
Start year	2020	2020	2020	2020	2021	2022
Capture method	Carbon mineralization	Electrochemical separation	Amine-functionalized sorbent	Alkali-based sorbent	Monoliths	Amine-functionalized sorbent
CO ₂ capture capacity (t-CO ₂ /year)	—	—	1.39 in 2020	—	—	7.3 in 2022
Remarks	Heirloom plans to remove CO ₂ emissions at the gigaton scale by 2035.	The Mission Zero plant (technology readiness level 6) is expected to be operational by mid-2023.	The Hydrocell DAC system will produce sustainable fossil fuel-free hydrocarbon fuels.	Susteon is developing a DAC at low costs using an alkali-based sorbent supported by renewable energy sources.	Noya is attempting to retrofit 2 million existing cooling towers to DAC modules.	Skytree's DAC units continuously generate and deliver enriched CO ₂ to the indoor farm on site without the need to burn fossil fuels.

**Fig. 2.** Schematic illustration of the Carbon Engineering liquid solvent DAC process.
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sorbents.

Sabatino et al. [70,71] studied a novel process exclusively based on electric regeneration in which the hydroxide solvent regeneration and CO₂ recovery are performed via bipolar membrane electrodialysis (BPMED), as shown in Fig. 4. The results showed that the regeneration

process could require as little as 5.36 GJ/t-CO₂ when employing a relatively low current density of 150 A/m². However, the regeneration energy demand can reach up to 21.75 GJ/t-CO₂ when employing a high current density of 1000 A/m² [71]. Furthermore, the techno-economic analysis showed a very high total capture cost of \$773/t-CO₂, which is

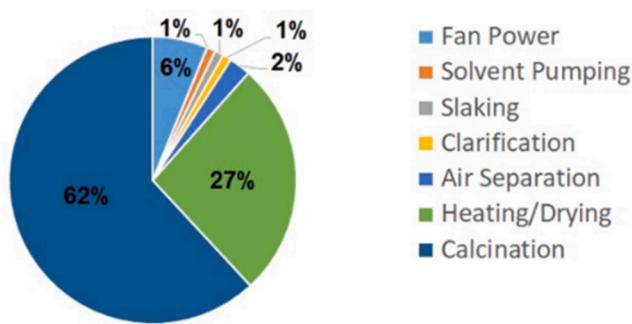


Fig. 3. Estimated total energy requirements for a liquid solvent [66].

approximately three times higher than that found from previous research [34]. This high capture cost is mainly from the very high costs of current bipolar and ion-exchange membranes and electricity usage. Nevertheless, the BPMED regeneration method could become commercially scalable when abundant renewable energy sources are more affordable and improved membranes become available. Sabatino et al. [72] also stated that the relatively lower current density provides an energy- and cost-efficient membrane operation. In this scenario, a 10-fold membrane price reduction would result in a minimum energy demand of 12 GJ/t-CO₂, which corresponds to a total process cost of \$367/t-CO₂.

Studies have examined the increase in CO₂ desorption by nanofluids, which have a high potential for increasing CO₂ desorption because of their fast kinetics and thermal and oxidative stability. The uniformly dispersed nanoparticles that have high thermal conductivity can greatly enhance the effective thermal conductivity of the nanofluids [73,74]. Lee et al. [75] reported that CO₂ regeneration improvement for SiO₂ nanoparticle concentrations of 0.005, 0.01, 0.03, and 0.05 vol% were 3.6%, 11.8%, -4.9%, and -7.2%, respectively. For Al₂O₃ nanoparticles, the CO₂ regeneration improvement was -2.8%, -11.2%, -12.6%, and -14.7% for the same concentrations. The regeneration

improvement with the Al₂O₃ nanoparticles was lower because the reaction between CO₂ and the Al₂O₃ surface promotes the formation of both adsorbed bicarbonate and carbonate species, and the Al₂O₃ has a high surface potential according to the variation in pH, so CO₂ is easily captured by the Al₂O₃ nanoparticles. Lee et al. [76] added SiO₂ and Al₂O₃ nanoparticles to methanol to improve CO₂ regeneration. The regeneration rate of the SiO₂ with methanol nanofluid increased by 22% after the fifth cycle.

Aqueous amino acids (e.g., sarcosine, glycine) and CO₂ absorption have been combined in laboratory-scale DAC processes [27,69]. The results of these studies indicated a regeneration temperature of 60–120 °C. Custelcean et al. [27,69,77–79] investigated an aqueous-phase CO₂ absorption and crystalline-phase regeneration method at very low temperatures (60–120 °C) that can be supported by concentrated solar heat. The study described the development of a novel, energy-efficient pathway to DAC based on the crystallization of hydrogen-bonded bis(iminoguanidines) (BIGs). The aqueous amino acid salts (e.g., potassium glycinate, potassium sarcosinate) were used to capture atmospheric CO₂, and then the CO₂ saturated solutions were reacted with a guanidine compound to crystallize and regenerate the amino acid sorbent as an insoluble carbonate salt. Finally, CO₂ regeneration of the carbonate crystals was achieved by heating at 60–120 °C. This low-temperature, crystallization-based regeneration process allows the aqueous amino acid sorbents to use low-grade heat sources (232 °C and lower) such as solar or waste heat, thereby minimizing the energy demand. The BIG compounds did not degrade after 1 week of heating at 120 °C because they are chemically and thermally stable at low temperatures [69]. The detailed information on each BIG regeneration process is listed in Table 3. Glyoxal-bis(iminoguanidinium) (GBIG) efficiently captured CO₂, but it proved insufficient for DAC because the exposure of an aqueous GBIG solution to air can lead to crystallization of the hydrated free ligand [77], thereby reducing the overall capture performance. For the pyridine-bis(iminoguanidine) (PyBIG) ligand, 66% of the measured enthalpy of regeneration was wasted on water desorption; therefore, crystal engineering of the anhydrous BIG carbonate crystals would significantly reduce the energy associated with

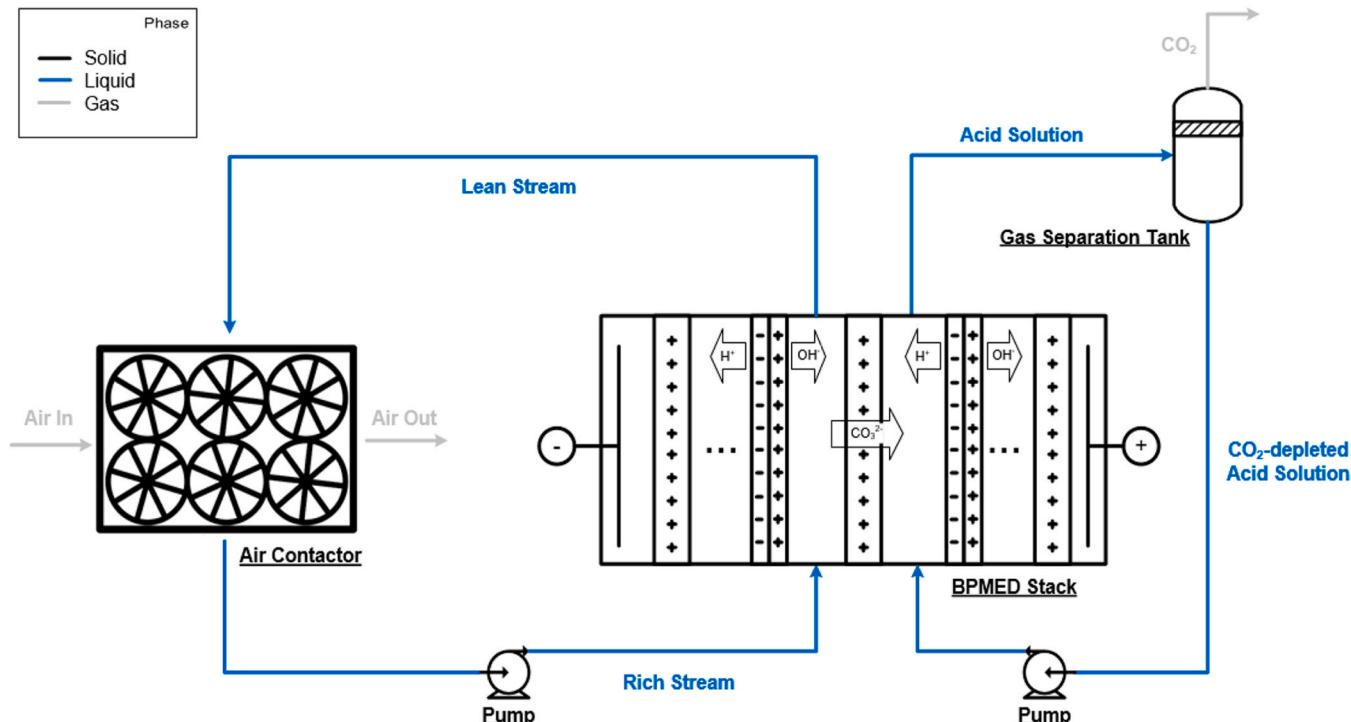


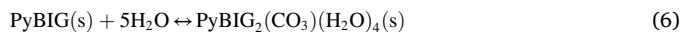
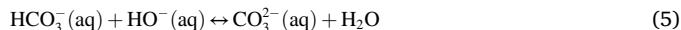
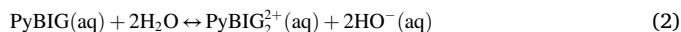
Fig. 4. Schematic representation of the proposed wet scrubbing–BPMED DAC process.

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Table 3
Regeneration information on liquid solvent DAC systems.

Reference	[66]	[34]	[71]	[77–79]	[80]	[81]	[72]
Solvent material	NaOH	KOH	KOH	Aqueous amino acid	Nanoparticle organic hybrid	Redox active amine	KOH
Regeneration method	Oxy-combustion	Oxy-combustion	BPMED	Temperature swing desorption	Temperature swing desorption	Oxidation	BPMED
Regeneration temperature (°C)	900	900	Ambient	Na-Gly: 100 PyBIG: 120 m-BBIG: 60–120 GBIG: 120 MGBIG-1: 80–120 MGBIG-2: 80–120 DABIG: 80–120	120	Ambient	Ambient
Regeneration energy (GJ/t-CO ₂)	5.3 (Thermal)	5.98 (Thermal)	5.36 (Electric)	Na-Gly: 5.75 PyBIG: 6.54 m-BBIG: 8.18 GBIG: 3.43 MGBIG-1: 8.13 MGBIG-2: 7.34 DABIG: 9.59 (Thermal) Concentrated solar	—	2.29 (Electric)	23.04 (Electric)
Energy source for regeneration	Natural gas	Natural gas	Electricity	—	Electricity	Electricity	Electricity
Remarks	Regeneration energy consumption includes CaCO ₃ heating and drying, calcining, heat recovery that is 64.1% of total energy consumption	This work is first economic analysis of DAC with commercial-scale 1 Mt CO ₂ /year, resulting in leveled costs of \$94–\$232/t-CO ₂ from the atmosphere.	The estimated CO ₂ capture cost is \$773/t-CO ₂ , which is more than three times higher than the cost estimated by Carbon Engineering [34], mainly because of the high costs of bipolar and ion-exchange membranes.	CO ₂ capture capacities (mmol/g) are as follows: PyBIG: 2.6 GBIG: 6.1 MGBIG-1: 2.1 MGBIG-2: 3.5 DABIG: 2.4	The process was stable over 20 cycles of CO ₂ capture (50 °C) and regeneration (120 °C) temperature swing. CO ₂ capture capacity (mmol/g): 3.1 at 15 vol % CO ₂ and 1.7 at 400 ppm.	The system demonstrated a reversible electrochemical capture and release of CO ₂ with electron utilization during CO ₂ release of up to 1.25 mol-CO ₂ per mole-electron with constant capacity (0.4 mmol/ml).	The regeneration energy demand, is 96–97% of the total energy demand that includes CO ₂ compression, air ventilation and pumping.

the regeneration process [78]. The CO₂ capture using PyBIG from the ambient air proceeds according to Eqs. (1) to (6), and the CO₂ can be released by heating the carbonate crystals PyBIG₂(CO₃)(H₂O)₄(s) at relatively mild temperatures of 80–120 °C [69].



Nanoparticle organic hybrid materials (NOHMs) based on amines significantly reduced the energy needed for solvent regeneration [82]. The regeneration of NOHMs or NOHM-based fluids is different from conventional processes owing to the reduced water content in the solvents [83]. Therefore, the energy required for solvent regeneration can be largely reduced by the enhanced CO₂ desorption kinetics with negligible vapor pressure and high thermal stability [84,85]. Rim et al. [80] developed solvent-impregnated polymers (SIPs) based on an easily scalable encapsulation technique to improve the CO₂ capture kinetics of water-lean viscous solvents. The NOHMs functionalized with polyethylenimine were integrated into a shell material and UV-cured to make gas-permeable solid sorbents (NPEI-SIPs). The CO₂ loading of the NPEI-SIPs was maintained over 20 cycles with a drop of only approximately 2.6% at low regeneration temperatures of 100 °C and 120 °C. These findings indicate that the NPEI-SIPs can be applied to DAC systems. The NOHMs also enable flexible design of CO₂ capture reactors by combining the advantages of liquid solvents and solid adsorbents.

Electrochemically mediated amine regeneration (EMAR) has been used as an alternative to the conventional heat-swing regeneration of post-combustion CO₂ capture [86]. The EMAR system consumed about 52.5 kJ/mol CO₂, which is approximately 30% of the electrical energy used by a commercial 550 MW power plant. In a related work, Diederichsen et al. [87] advanced a concept for a solvent-free, continuous CO₂ capture method using liquid quinones that potentially enable a large capture area with desorption occurring at a single-point location with minimal water usage. They optimized a proposed redox-active liquid solvent for a flowing system by mixing the liquid quinone with low-volatility glymes that exhibit high CO₂ capacities and active molecule concentrations. The experiments showed that the separation energy, which was around 1.1 GJ/t-CO₂, could be obtained from a cell voltage of –1 V and a release voltage of –0.5 V (assuming 1 electron

per CO₂ process). The results revealed that electrochemically mediated carbon capture is a promising technology that potentially eliminates costly pressure and temperature fluctuations in carbon capture systems by using an applied potential to separate CO₂ from feed gas. Recently, Seo et al. [81,88] investigated an electrochemical carbon capture application of DAC using a redox-active amine. They reported a robust electrochemical redox-active amine system that exhibited high electron utilization of 0.78 mol CO₂/mol electrons and a total energy demand of 2.3–2.8 GJ/t-CO₂ for the DAC application. Furthermore, the electrochemical redox cycle introduced a continuous and stable CO₂ separation approach without the energy-intensive thermal regeneration process.

4. Regeneration methods for solid sorbent DAC

Many modern atmospheric CO₂ capture processes use solid sorbents. Fig. 5 illustrates the commercial DAC plant configuration developed by Climeworks [10]. Climeworks uses TVSA that requires near-vacuum conditions during desorption. In general, solid-supported amines have lower energy demands for CO₂ desorption and temperature compared with liquid solvent DAC regeneration processes [18]. However, they also tend to have slow sorption kinetics, and their optimum performance requires maintaining a high structural integrity throughout multiple cycles and preventing water condensation in the pores. Solid sorbents also tend to degrade over time, especially when the material is repeatedly exposed to open air during heating and cooling cycles [89,90]. Comparison of different regeneration options for solid sorbent materials has typically been limited to pure CO₂ production, thereby limiting the process options to methods such as TVSA [39,43,91] and steam stripping [90]. Table 4 features operational information on solid sorbent DAC systems.

Numerical modeling has been used to examine the effectiveness of TVSA DAC using two metal-organic frameworks (MOFs) [40,43]. These frameworks—MIL-101(Cr)-PEI-800 and mmn-Mg₂(dobpdc)—have experimentally demonstrated film growth on monolith structures. The regeneration energy requirements were 9.68 GJ/t-CO₂ for MIL-101(Cr)-PEI-800 and 4.75 GJ/t-CO₂ for mmn-Mg₂(dobpdc). These energies were 92.4% and 86.7% of the total energy demand, respectively. The regeneration energy sources were sensible heat to the adsorbent, monolithic wall sensible heat, CO₂ desorption, and energy from uncondensed steam that exits the monolith channel during desorption. Because the wall was so thick, the monolithic wall sensible heat was the major regeneration energy demand. However, decreasing the wall thickness reduces the structural stability and results in lower CO₂ capture capacity. In summary, the results showed that the thicker adsorbent films and thinner monolithic walls can exponentially reduce the regeneration energy demand during the desorption process.

The Climeworks DAC plants in Hinwil and Hellishei, Iceland, already

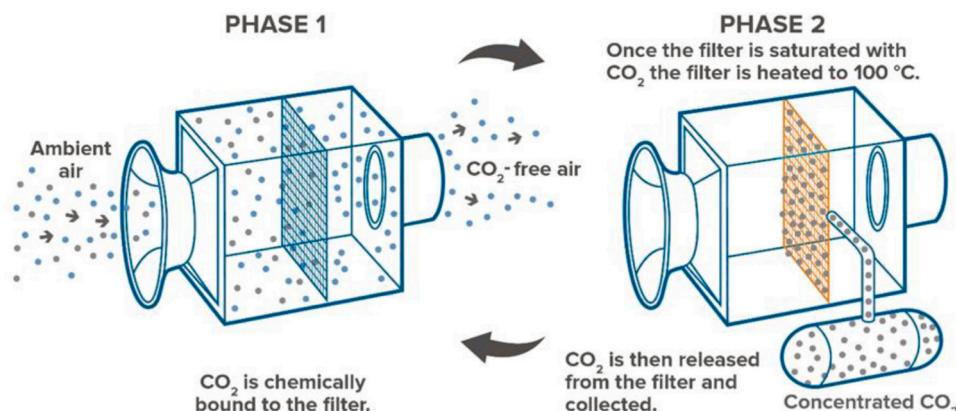


Fig. 5. Schematic illustration of adsorption and regeneration in the Climeworks DAC system.
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Table 4
Operational information on solid sorbent DAC systems.

Reference	[40,43]	[91]	[42]	[92]	[93]	[94]
Sorbent material	Amine-loaded MOFs MIL-101(Cr) and nmen-Mg ₂	Amine-based 1065)	Amine (Lewatit VP OC 1065)	Amine-functionalized (Cr)	Amine-functionalized MIL-101 SI-AEATPMS, APDES-NFC-FD	Amine (Lewatit VP OC 1065)
Regeneration method	TVSA	TVSA	TVSA	TSA	SI-AEATPMS: 6.76 (Thermal) APDES-NFC-FD: 5.04 (Thermal)	Microwave
Regeneration temperature (°C)	100	100	60–100	25–60	—	70–120
Regeneration energy (GJ/t-CO ₂)	MIL-101(Cr): 8.16 (Thermal) 0.8 (Electric) nmen-Mg ₂ : 4.25 (Thermal) 0.73 (Electric)	Waste heat: 10.0 (Thermal) 0.7 (Electric) Heat pump: 3.95 (Thermal) 0.7 (Electric)	8.34 (Thermal) 0.8 (Electric)	6.9 at 60 °C, 10 at 100 °C (Thermal) TVSA with mild vacuum 500 mbar Heating circulator	—	25 (Electric)
Heat source for regeneration	Hot steam	Waste heat/heat pump	—	—	—	Microwave heating
Remarks	The regeneration energy is considered by the blower, adsorbent sensible heat, monolith wall sensible heat, heat for CO ₂ desorption, vacuum pump, and heat of uncondensed steam.	Regeneration thermal energy demand is considered 84% of total energy demand based on the previous reported TVSA process [40,43]. The electric energy demand includes blower and vacuum pump.	Regeneration thermal energy demand is considered 84% of total energy demand based on the previous reported TVSA process [40,43]. The electric energy demand includes blower and vacuum pump.	Productivity: 0.042–0.168 kg-CO ₂ /kg _{adsorbent} -day for 90% working capacity at 60 °C, 0.089–0.161 kg-CO ₂ /kg _{adsorbent} -day for 99% working capacity at 100 °C	The results showed that the 30 wt% TEPA-impregnated MIL-101(Cr) can be effectively regenerated with excellent stability at 25 °C even under humid conditions. 0.367 mol/kg and 0.771 mol/kg.	SI-AEATPMS and APDES-NFC-FD are chemisorbents showed working capacity, respectively, 1.05–1.52 kg CO ₂ /day

produce zero emissions; according to life cycle assessments, their respective carbon capture efficiencies are 85.4% and 93.1% [91]. According to Climeworks, the estimated heat supply was 11.9 GJ/t-CO₂ from waste heat or 4.7 GJ/t-CO₂ from the electricity supply for the heat pump. Waste heat from no-cost operations likely made up the heat source. Only when waste heat is available or when the heat pump uses a low carbon footprint electricity source is the DAC plant's negative carbon footprint (from cradle to gate boundary) possible. Young et al. [42] focused on the effect of humidity on CO₂ adsorption and explained how it affects solid sorbent DAC adsorption–desorption cycles. They analyzed the TVSA process by employing commercially available amine-functionalized sorbents (Lewatit VP OC 1065). According to an isotherm co-adsorption model, humidity played an important role on the heat of adsorption of the adsorbed species and the minimum specific work equivalent of the TVSA process was 2.49 GJ/t-CO₂ at 95.2% CO₂ purity. The specific work equivalent of the Climeworks process is 4.55 GJ/t-CO₂. Elfving et al. [92] experimentally compared the regeneration energy demands for different methods such as temperature swing adsorption (TSA) and TVSA for DAC. All other studied regeneration methods, except TVSA without purge flow, obtained more than 85% regeneration at 60 °C. The lowest regeneration energy demand of 4.2 GJ/t-CO₂ was obtained from isobaric TSA at 60 °C. Coupling TSA with a mild vacuum improved the desorption rate and increased the working capacity from 0.47 to 0.51 mmol CO₂/g sorbent, requiring 7.5 GJ/t-CO₂ for regeneration. TVSA regeneration without purge flow had a working capacity of only 0.39 mmol CO₂/g sorbent and a regeneration energy demand of 8.6 GJ/t-CO₂ at 100 °C. From their results, Elfving et al. recommended that the TVSA with purge flow should be used as a viable regeneration option for DAC.

Studies have been conducted to improve the CO₂ capacity and weather resistance of amine-based sorbents. Rim et al. [93] showed that the CO₂ adsorption capacity of 30 wt% TEPA-impregnated MIL-101(Cr) dramatically increased from 0.39 mmol CO₂/g sorbent at ambient conditions (25 °C) to 1.12 mmol CO₂/g sorbent at –20 °C. The authors concluded that this increase was due to the enhanced weak chemisorption. The sorbents also remained stable for 15 adsorption–desorption cycles with a 0.72 mmol CO₂/g sorbent working capacity at very low temperatures (–20 °C adsorption to 25 °C desorption). The results suggest that the sub-ambient DAC performance of the sorbents is improved even more in humid environments and has stable and promising CO₂ working capacities over multiple humid temperature swing cycles. These findings indicate that properly constructed DAC sorbents can function at very low temperatures in a weak chemisorption mode even at high humidity. Moreover, using the small temperature changes made possible by this weak chemisorption activity can result in energy savings. Leonzio et al. [39] examined amine-functionalized sorbents in which chemisorbents were considered and, using a mathematical model, compared where capture capacity, energy consumption, and cost were used as key performance indicators. For the regeneration energy demand compared with that of MOFs, the amine-based sorbents exhibited lower values of 6.77 GJ/t-CO₂ for SI-AEATPMS ([N-(2-aminoethyl)-3-aminopropyl] trimethoxysilane grafted on silica gel) and 5.04 GJ/t-CO₂ for APDES-NFC-FD (3-amino-propylmethyldiethoxysilane on nanofibrillated cellulose).

Schagen et al. examined the development of a fully electric regenerator for the microwave-based desorption of CO₂ from unaltered commercial sorbents [94]. The results showed that faster sorbent heating and desorption is possible by using microwave heating instead of conventional heating. Furthermore, microwave heating improved the thermal conductivity of the sorbent, which assists the desorption rate during the desorption process. The regeneration energy demand was approximately 25 GJ/t-CO₂ for batch desorption and 25–50 GJ/t-CO₂ for the continuous process, and the energy losses ranged from 35% to 70%. Schagen et al. [94] concluded that microwave regeneration could be improved by preventing hot spots in the reactor and by using near-vacuum conditions to produce pure CO₂. Overall, microwave

desorption showed promise for enhancing the productivity and energy efficiency of sorbent-based DAC.

In the regeneration process of liquid solvent or solid sorbent, thermal regeneration requires the input of heat or electricity. The effectiveness of an energy source is determined by the amount of total energy that can be recovered as work. This study utilized a motor efficiency of 75% to convert electrical energy to an equivalent work output [95,96]. To convert thermal energy to work, Eq. 7 based on the Carnot efficiency was used, with an isentropic efficiency of 75% applied to represent a hypothetical turbine undertaking the conversion [97,98].

$$W_S^{eq} = \eta_{isen} \bullet \left(1 - \frac{T_L}{T_H} \right) \bullet Q_{th} \quad (7)$$

The resulting equivalent shaft work, W_S^{eq} is calculated using the temperature (T_L) at which the thermal energy is used down to (usually ambient temperature), the source temperature of thermal energy (T_H), the thermal energy requirement (Q_{th}), and isentropic efficiency (η_{isen}). Here we used 75% for the isentropic efficiency. This approach enables a reasonable comparison between different regeneration processes and the ability to sum thermal or electric energy inputs to obtain the work equivalent energy requirement. It is also acceptable to report separate energy requirement values for thermal and electrical energy. Fig. 6 shows the work equivalent regeneration energy demands of different DACs using liquid solvent or solid sorbent.

5. Potential technologies for efficient regeneration

The energy demands of different regeneration technologies are shown in Fig. 6. The regeneration process typically relies on temperature swings to release CO₂ by using conventional oxy-combustion or an air heater and electrical heater under ambient to near-vacuum conditions. Various technologies could be used to efficiently regenerate CO₂-saturated solid sorbents or liquid solvents. This section reviews different CO₂ desorption technologies for enhanced sorbent and solvent regeneration.

5.1. Magnetic nanoparticles

Along with conventional resistance heating, heating mechanisms such as microwave heating and magnetic heating have been explored. For instance, magnetic heating methods that use magnetic nanoparticles (MNPs) have been investigated in MOF-based materials [99–102]. MNPs generate heat under alternating magnetic fields [103], which has been widely studied in MNP hyperthermia for cancer therapy. The fundamental mechanisms for this magnetic heating include the hysteresis loop mechanism, Néel relaxation, Brownian motion, particle-particle interactions, or some combination of these mechanisms [104]. When MNPs are exposed to an alternating magnetic field, they generate heat and increase the surrounding temperature. In contrast to traditional heating methods (e.g., electric heating rods [105], heating tapes and jackets [106], oil baths [107]), magnetic heating can generate rapid, uniform heating of the entire system. Moreover, magnetic heating can overcome the drawback of most sorbent materials' low thermal conductivity. The heat transfer efficiency of these MNPs is expected to be higher than most sorbent materials because MNPs are typically well dispersed in the matrix and act as a nano-heater that generates heat for regeneration [108]. Magnetic field-responsive materials include MNPs such as Fe₃O₄ [102,109–112], MgFe₂O₄ [100,113], and NiO₂ [82,114]. The specific adsorption rate, which is the measure of the heating efficiency of MNPs [115], provides a reliable estimate of the thermal performance of the MNP system. To use magnetic heating for sorbent regeneration, MNPs must be incorporated in the sorbent system. MNPs can be introduced through directly blending MNPs with sorbents [111] and during sorbent synthesis (e.g., magnetic framework composites [MFCs] [99,116–118]).

Li et al. [99,113,116,117] reported that rapidly heating magnetic particles delivers local temperature increases to the otherwise thermally insulating MOF material, and in optimized conditions, heating the magnetic particles releases all adsorbed gas within minutes. In these studies, MFCs were synthesized by introducing MNPs during the preparation of the MOFs. Li et al. found that exposing the MFCs to an alternating magnetic field triggered the release of most of the adsorbed CO₂ from the MFCs, as illustrated in Fig. 7. The corresponding efficiency

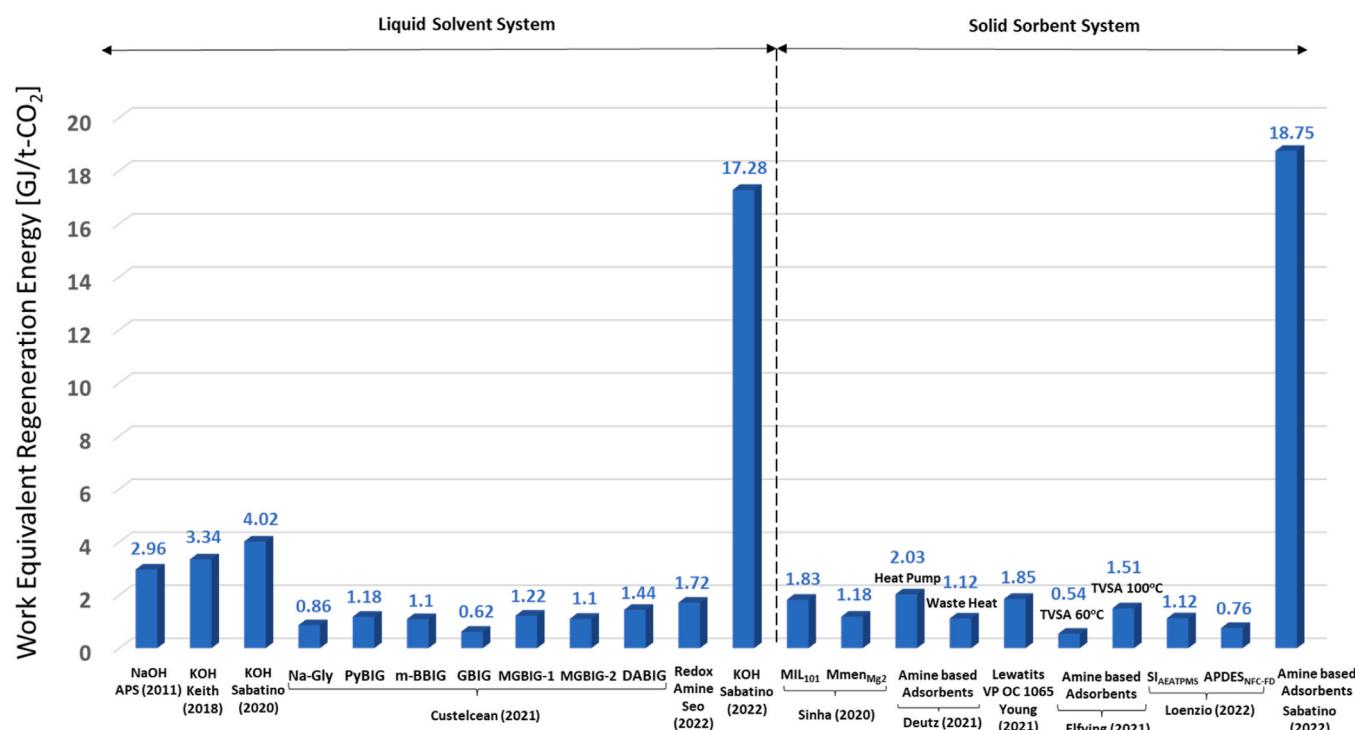


Fig. 6. Work equivalent regeneration energy demand for liquid solvent and solid sorbent DAC systems.

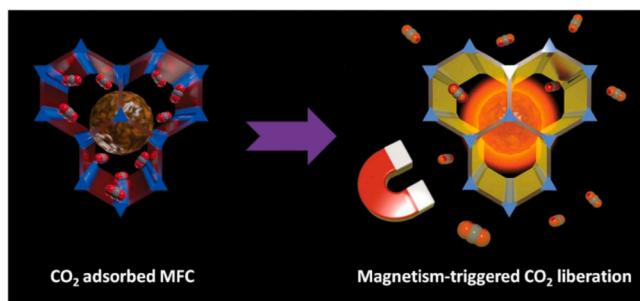


Fig. 7. Schematic illustration of CO₂ liberation from MFCs triggered by the application of an external alternating magnetic field.

Figure reproduced from Li et al. [99] with permission. Copyright © 2016 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

of releasing CO₂ from MFCs with Fe₃O₄ nanoparticles was significantly increased up to 56.2% at 0.35 bar within 23 min, 54.5% at 0.61 bar within 20 min, and 49.5% at 0.97 bar within 18 min, all at an applied magnetic field strength of 81 mT [119].

Sadiq et al. [100,101] used MFCs synthesized from ferrimagnetic MgFe₂O₄ and MOF UiO-66 in a magnetic induction swing adsorption process for CO₂ capture and release. The heat generation capability of the magnetic content of the composite ensured a rapid temperature swing that provided CO₂ removal efficiencies of 82% at 21 mT, 96% at 32 mT, and 100% at 42 mT. Additionally, Sadiq et al. reported that the MFC with the Mg-MOF-74 system was tailored to deliver a very low energy cost of 1.29 GJ/t CO₂, which is 45% below commercially deployed materials and allows for a productivity as high as 3.13 kg CO₂/h-kg of adsorbent [120].

Gholami et al. [111] investigated the magnetic heating of MNPs for zeolite–MNP composites. Zeolite 13X and Fe₃O₄ were used in composites with differing amounts of Fe₃O₄ (13X-IO20 and 13X-IO10). The results showed that the CO₂ mass adsorption capacity decreased as the Fe₃O₄ content increased. However, the heating capacity and desorption rate increased as the Fe₃O₄ content increased. With 20 wt% loading of Fe₃O₄, the specific adsorption rate reached 149.7 W/g for an applied current of 171.0 A. Furthermore, the maximum desorption rate was 461.4 mg/g-min for 13X-IO20 when the applied current was 171.0 A. The average desorption rate (95% desorption) reached 103.0 mg/g-min for 13X-IO20 at an applied current of 171.0 A, which is one order of magnitude higher than the previously reported values. The study also reported that regeneration could be achieved within minutes. However, the cyclic adsorption–desorption behavior and energy consumption were not reported, so the energy efficiency and stability of the composite materials under multiple adsorption–desorption cycles are unknown.

In magnetic nanofluids [121,122], MNPs are dispersed in a fluid for sorbent regeneration. The enhanced movement of MNPs induced by an external magnetic field increases the local velocity around the particles; therefore, the absorption–desorption performance improves. However, current studies mainly focus on enhancing the CO₂ capture performance [121], and studies on CO₂ desorption are limited. Komati et al. [122] reported an 92.8% of enhancement of the mass transfer coefficient for a volume fraction of the fluid at approximately 50 wt% N-methyl-diethanolamine, and an Fe₃O₄ volume fraction of approximately 0.39%.

MNP-based heating mechanisms are versatile in sorbent regeneration. However, not all the absorbed gas can be easily released to efficiently regenerate MOF adsorbents. This incomplete release increases the energy demands for the desorption process or significantly lowers the working capacities at the given amount of gas adsorbed [116]. Therefore, further examination of this field are needed to explore the potential to lower DAC energy requirements.

5.2. Microwave

Microwave irradiation has been suggested as an alternative method to overcome solvent regeneration in CO₂ removal [123]. A comparison of the conventional and microwave heating processes is shown in Fig. 8 [123]. Microwave heating, as displayed in Fig. 8(b), is similar to conventional heating as illustrated in Fig. 8(a), but microwave heating consumes less energy because it can heat a material directly without heating the reactor walls. The direct heating from microwaves occurs by energizing the molecules within the solvent via ionic conduction, dipole rotation, or interfacial polarization [124,125]. However, the ability of a dipole moment to adsorb and convert the microwave energy into heat can significantly affect its process performance [126]. Various studies have suggested that in terms of CO₂ desorption, microwave is four times faster than conventional methods [123,127].

The use of microwaves for the water regeneration of zeolite 13X sorbents was first proposed by Roussy et al. [128]. In their study, the zeolite pellets were irradiated in a silica tube. Their findings indicated that the zeolite exhibited continuous and reversible dehydration–rehydration behavior over a wide range of elevated temperatures. Molga et al. [129] tested many processes of desorption and found that microwave heating was faster and more efficient than other heating methods. They found that annular or fluidized beds are the favored reactor types because of the limited penetration depth of microwave radiation. Another study [125] reported that microwave heating decreased CO₂ desorption time by at least 50% compared with conventional heating as a consequence of the rapid heat rates induced by microwave irradiation. Furthermore, they estimated that the microwave desorption process required an energy input of approximately 16–19 kJ/mol, which was approximately half the calculated energy required for conventional thermal desorption (41.5 kJ/mol).

Bougie et al. [130] investigated the microwave regeneration of nonaqueous monoethanolamine (MEA) solutions to reduce the energy consumption during the CO₂ capture process. The solvents used for the experiments were a mixture of ethylene glycol and 1-propanol, diethylene glycol monoethyl ether, and N-methylformamide. MEA (20–70 wt %) solutions in different solvents were studied in a single CO₂ absorption–desorption step. A magnetron operating at 2.45 GHz with a maximum output power of 1.2 kW was used to produce the microwaves. The best results came from the diethylene glycol monoethyl ether solutions, especially the ones with the low MEA concentrations (20–40 wt %). These solutions exhibited the lowest energy consumption and relatively good CO₂ cyclic capacities. Furthermore, the solution containing 20 wt% MEA reduced the energy consumption by 78% compared with the standard 30 wt% MEA aqueous solution.

Li et al. [131] compared microwave irradiation and heat conduction for the energy consumption and regeneration efficiency of CO₂

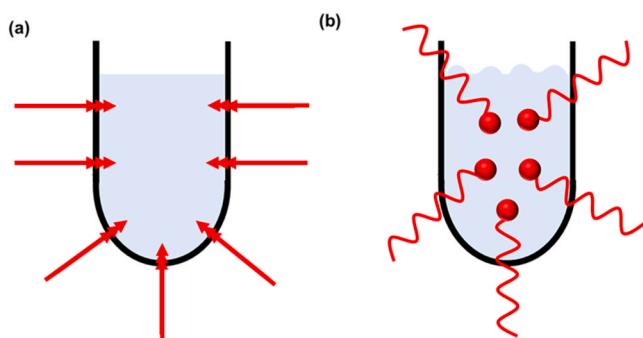


Fig. 8. Illustration of the heat induction process for (a) conventional heating and (b) microwave heating. The red arrows denote heat conduction, and wavy lines denote microwave energy. The red spheres represent the solvent molecules.

Figure adapted from Pauzi et al. [123].

regeneration of MEA and triethylenetetramine (TETA) solutions. They found that compared with conductive heating, microwave heating performed better based on regeneration temperature, energy requirements, CO₂ recovery, and the rates of heating and desorption. For a microwave regeneration of 30 wt% TETA/1,4-butanediol solution, energy consumption was 69% lower and CO₂ recover was 260% higher compared with a 30 wt% MEA aqueous solution regenerated by conductive heating. For the TETA/poly(ethylene glycol) 200 solution, the energy consumption was 76% lower and CO₂ recovery was 270% higher compared with a 30 wt% MEA aqueous solution regenerated by conductive heating.

Schagen et al. [94] presented an all-electric regenerator developed for the desorption of commercial amine-functionalized sorbents using a radial-flow microwave desorber, and the results demonstrated quick sorbent heating and fast desorption. Productivities of up to 1.5 kg CO₂/kg sorbent were demonstrated, with a high regeneration energy demand of 25 GJ/t-CO₂. The productivity was significantly higher compared with traditional TVSA desorption. The process can be further improved by creating an even more homogeneous electric field for enhanced productivity and energy efficiency of sorbent-based DAC systems. Cherbański [129] and Meloni et al. [132] demonstrated that the geometry of the desorber is crucial to its performance for microwave desorption. The geometry is important because it largely determines the amount of radiation that reaches the microwave generator. These studies indicated that fluidized bed adsorbers performed better than fixed bed adsorbers because of the homogenous temperature distribution but still struggled to overcome the short heat penetration depth. Compared with conventional TSA, the microwave desorption was faster and more energy efficient, with an efficiency of up to 75%.

Before moving on, it is important to note that microwave heating still has technical challenges with regards to scaling up the technology. For instance, it has been suggested that some microwave adsorbers would create problems at the commercial scale such as localized heating, thermal runaway effects, non-homogenous heating, cost and availability of large scale reaction rigs, and material/process handling issues [133, 134]. However, a recent study by Thomas-Hillman et al. [135] showed that microwave heating could be used to synthesize sub-micron [Al₂(OH)₂(C₁₆O₈H₆)₂]·(H₂O)₆ MOF with a resultant CO₂ capacity of 8.8 mmol/g at 273 K and 1.0 bar and 99.77% lower reaction time as compared to current conventional solvothermal methods. The authors

concluded that such a short timescale offers conditions favorable for scaling up the microwave heating technology. Despite this promising result, however, more work is needed to better determine the scalability of microwave heating technology for CO₂ adsorption.

5.3. Ultrasound

Ultrasound is generally defined as sound waves with frequencies above the range of human hearing, which ranges from approximately 2 to 18 MHz [136]. Ultrasound has been used in numerous applications for process improvement, such as cleaning [137,138], drying [139,140], and composite fabrication [141,142]. The main mechanism to improve performance is cavitation, which is a series of formation and subsequent collapse of bubbles in a liquid media, as illustrated in Fig. 9. The positive and negative pressure waves, which are generated by a high-frequency mechanical vibrating device, propagate through the solution. Micrometer-sized bubbles are formed and grown until they reach resonance size. When a vapor bubble implodes, a jet of liquid solution is pulled to the center [143]. The speed of the liquid jet attributed to the implosion can reach up to 400 km/h [144]. The collapse of the bubbles creates extremely high temperatures and pressures. Through the combination of these effects, ultrasound can effectively intensify or accelerate chemical reactions.

The CO₂ stripping or regeneration phase occurs when the captured CO₂ is stripped from the liquid absorbent. Ultrasonic-assisted desorption experiments have been performed in batch systems and continuous-flow devices to accelerate CO₂ desorption. Fig. 10 shows ultrasound-assisted CO₂ stripping from amine solutions conducted by Ying et al. [146]. When the ultrasound was applied in the chamber, many bubbles were produced, and the cavitation process began. The ultrasound helps remove CO₂ from the liquid solvent. In contrast to typical thermal desorption methods, by using ultrasound, CO₂ can be degassed at low temperatures (60–80 °C) [147,148]. Liu et al. [149] investigated the enhancement of CO₂ desorption from an N-methyldiethanolamine-rich solution and Ying et al. found that the CO₂ desorption rate was significantly enhanced by ultrasound; it almost doubled at low temperature, mainly because the bubble growth rate increased significantly owing to rectified diffusion and bubble coalescence. Ying et al. [146,150] demonstrated that an ultrasound-assisted method exhibited a regeneration rate three times higher than heating alone. Furthermore, they

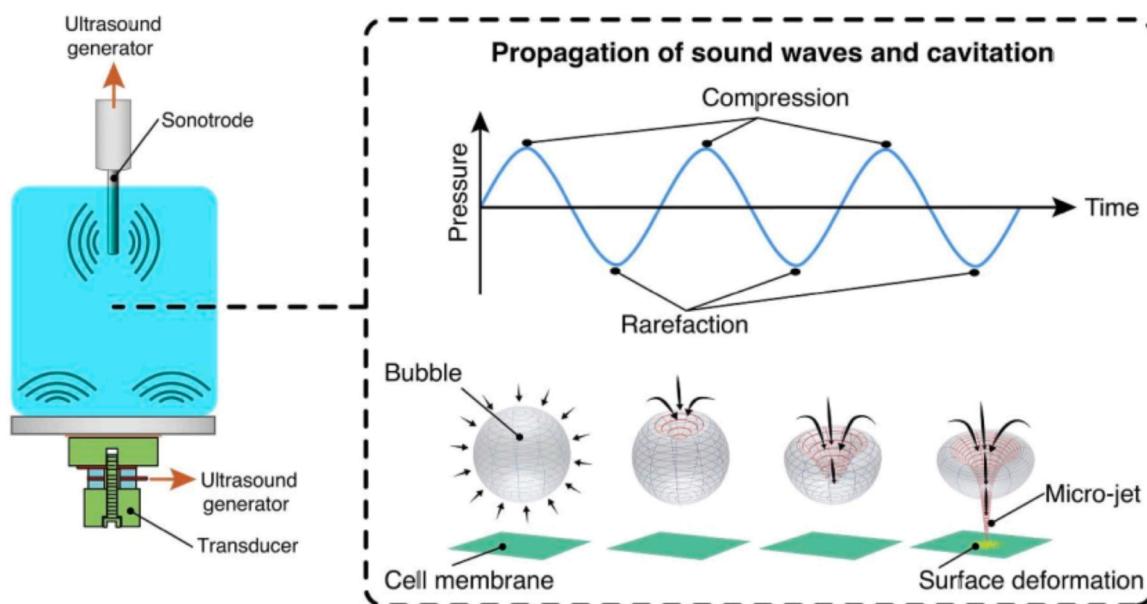


Fig. 9. Illustration of an acoustic cavitation process and an imploding cavity in a liquid irradiated with ultrasound. Figure reproduced from ref [145] with permission. Copyright © 2020 Elsevier Ltd.



① Before the ultrasound is switched on a small amount of bubbles is generated at the heating coil.
② Start ultrasound, needle valve (8) opens as the pressure starts increasing, CO₂ is released, cavitation bubbles are growing

Fig. 10. Ultrasound-assisted CO₂ stripping from amine solutions.

Panels 1 and 2 reproduced from Ying et al. [146] with permission. Copyright © 2018 Elsevier Ltd.

reported a 19% cost reduction using this method, as well as a low lean amine solution of 0.2 mol CO₂/mol MEA. Ultrasound-assisted stripping can enhance reactivity and mass transfer through cavitation. Schueler and Yang [151] reported that the activation energy for the surface diffusion was decreased owing to localized heating and high-pressure shock waves. Therefore, this technology has great potential to reduce capital cost by intensifying absorbent regeneration. Tanaka and Okawa [152–155] used ultrasound to desorb CO₂ from aqueous solutions of MEA at a very low temperature of 25 °C. However, they found that desorbing CO₂ using ultrasound for a pH > 8.2 was difficult because CO₂

mainly exists as HCO₃ and not as aqueous CO₂. They also found that decreasing the concentration of MEA solutions increased the rate of CO₂ desorption.

Until recently, the central difficulty has been the successful transition of scientific discoveries of ultrasound technology from laboratory settings to practical industrial applications. This challenge arises due to the limitations of traditional ultrasonic technology, which hinder the process of scaling up without sacrificing quality. This issue arises because the need to increase scale requires a reduction in the intensity of ultrasonic waves, impacting the process's effectiveness. Nevertheless, a

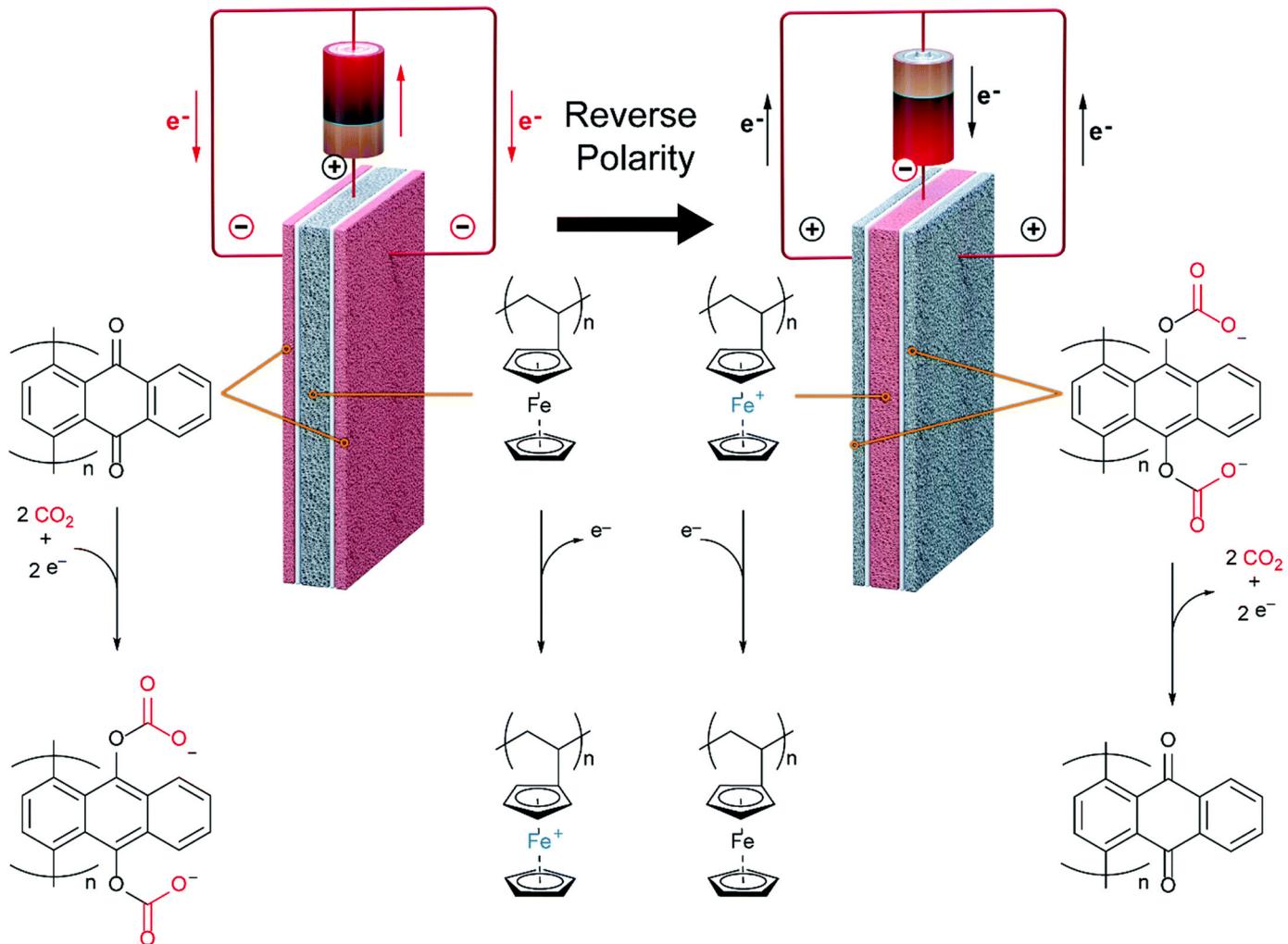


Fig. 11. Electroswing mechanism for CO₂ capture. Figure reproduced from Voskian et al. [157] under CC BY-NC 3.0.

recent study [156] has identified a potential solution through the adoption of barbell horn ultrasonic technology (BHUT). This innovative approach enables the creation of large-scale industrial machinery that employs powerful ultrasonic waves. The study demonstrates the feasibility of achieving over a 50-fold increase in scale when moving from controlled laboratory conditions to real-world industrial use, all while maintaining the quality of the final output. Consequently, this advancement positions high-amplitude ultrasonic processing as a viable and cost-effective alternative that can compete with expensive methods across various industries.

5.4. Electric swing

Multiple studies have been performed that use electrochemistry to promote the capture and regeneration cycle in an electro-swing approach, which may have applications for DAC. Electro-swing technology uses electrical energy to reduce a quinone into a radical anion or dianion to capture CO₂, as shown in Fig. 11.

Gubler et al. [158] reviewed research advances in electrochemical methods of CO₂ separation such as those involving specific energy consumption and faradaic efficiency. Liquid electrolyte solutions are the most thoroughly explored electrochemical approach for CO₂ capture. Zhao et al. [38] used a novel hybrid monolith as an adsorbent using a combined vacuum and electric swing adsorption technique. This method relied on rapid Joule heating of the adsorbent to liberate adsorbed CO₂. The combined process provided a CO₂ purity of 33% and recovery of 72% for a brief electrification time of 30 s at a mild desorption pressure of 10 kPa. Lillia et al. [159] employed a hybrid process of temperature-electric swing adsorption (T/ESA), in which they tested activated carbon and zeolite 13X materials. The net electric efficiency of a natural gas combined cycle using an MEA absorption process (49.9%) was significantly higher than that of the T/ESA process (35.3%). This significantly higher efficiency is because of the high energy penalty of T/ESA owing to the electric consumption required for the heating and fast cooling of the adsorbent.

Hatton et al. [157] demonstrated CO₂ capture in a cell from inlet streams of CO₂ (concentrations ranging from 0.6% to 10%) at a constant CO₂ capacity with a faradaic efficiency of 90% and energy consumption of 0.91–2.04 GJ/t-CO₂. Additionally, the cells showed exceptional durability over more than 7000 cycles of capture and release of CO₂. The study noted that the reduced form of quinone is highly sensitive to oxygen and not practical for separation of CO₂ from gas mixtures containing significant amounts of oxygen, such as air. Therefore, further tests will be necessary to determine the long-term stability of the device. Wang and Hatton [86,160–165] investigated an EMAR process, which is an alternative pathway to the conventional high-thermal swing configurations [166]. Hatton et al. identified electrochemical kinetics and efficiencies and performed process-level energetic calculations. They found that an isothermal EMAR process requires about 1.18 GJ/t-CO₂, and the net energy demand can be reduced to 0.84 GJ/t-CO₂ with the available waste heat. Furthermore, they found that the advanced process designs, process optimization, and identification of improved solvents may further decrease the energy demand of the regeneration process. Although the results reported in several studies [81,86,159,157, 160–166] focused on higher concentrations of CO₂, future investigations could have implications for DAC of CO₂. However, these studies would require improvements in capacity and kinetics for the dilute feeds with CO₂ concentrations about 300 times lower than in flue gas. Therefore, to determine whether the electro-swing materials under investigation are applicable to DAC, they need to be tested under dilute CO₂ conditions.

6. Summary and outlook

Developing and deploying energy-efficient and cost-effective DAC systems is essential to effectively reduce global CO₂ emissions. However, most DAC systems require energy-intensive regeneration processes.

Although improvement of DAC system sorbents and processes continues, limitations exist, particularly in developing a viable regeneration process. Additionally, the trade-off between a strong capture agent and the required regeneration energy is critical for both liquid and solid DAC systems. Still, limited reliable data are presented in the current literature and documentation in academia and industry. Novel material development and a deep understanding of desorption mechanisms and their energy requirements are needed to move toward commercial-scale deployment of DAC systems.

Recently, solid sorbent and liquid solvent DAC technologies have been investigated to produce systems that can efficiently regenerate sorbents saturated with CO₂. For liquid solvent DAC, novel regeneration approaches were recently examined, including a CO₂-loaded solution crystallization using guanidine compounds [27,69,77–79]; BPMED [70–72]; and electrochemical redox cycling [81]. Although conventional regeneration methods require high-temperature oxy-combustion using natural gas, these methods are still competitive in terms of regeneration energy demand (4.5–6 GJ/t-CO₂) compared with newer approaches [34,66]. For solid sorbent DAC, researchers have primarily focused on testing solid sorbent materials such as MOFs [39,43,93,167] and amine-functionalized sorbents [39,42,91,92,94] to improve CO₂ capacity, manufacturing scale-up, and regeneration energy consumption. This review indicates that work equivalent regeneration energy demand (supported by either the electric grid or fossil fuel combustion) ranges from 0.54 to 18.75 GJ/t-CO₂ for solid sorbent DAC systems and 0.62–17.28 GJ/t-CO₂ for liquid solvent DAC systems. As previously discussed, various potential methodologies can efficiently regenerate the CO₂-saturated sorbents via MNPs [99,100,109,110,112,114,118], microwave [94,125–129,131,132], ultrasound [41,146,150,152–155], and electric swing [38,159]. Although most of the research works are still based on experiments conducted at the laboratory level for the processes of regeneration, researchers are actively striving to enhance the efficiency of DAC systems, particularly in the aspect of regeneration. Currently positioned at "technology readiness level" 6, which indicates that DAC is in the phase of large-scale prototyping and not yet ready for full commercial use. However, this also signifies a chance to enhance performance and lower costs by learning from the initial stages of the technology's development [168].

Furthermore, research on novel materials and processes for DAC technologies is increasing, along with the need to investigate and understand the economic costs and life cycle emissions associated with different DAC systems. Research and development are likely to continue to advance solid sorbent and liquid solvent DAC technologies via techno-economic analysis [43,63,72,86,167] and life cycle assessments [37,91, 169]. To perform meaningful life cycle assessment and techno-economic analysis studies, transparent and available data on pilots to commercial-scale DAC systems are required. To achieve better performance, DAC technologies require low-carbon energy sources such as renewables, hydropower, geothermal, and nuclear, which are often geologically limited [9,10,26,91,170]. Additionally, DAC systems need to be close to CO₂ transportation infrastructure and CO₂ sink options because additional CO₂ emissions are created during CO₂ transportation [18,171]. Finally, emerging challenges relate to climate impacts on DAC technologies because their operation is potentially located in regions that can exhibit a wide range of temperatures and humidity conditions. For liquid DAC systems, the overall energy demand decreases from 11.1 to 8.3 GJ/t-CO₂ as the CO₂ capture rate increases from 40% to 85%, and high capture rates can only be achieved in hot and humid climate conditions because of the absorption kinetics [172]. In contrast, solid DAC systems have notable lower capture costs in cold and humid conditions where the temperature is a major factor [93,173,174], but only when abundant renewable energy is available [170]. Therefore, solid sorbent and liquid solvent DAC technologies need to be further developed so that they can help accomplish the goal of net-zero emissions by 2050.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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