# Energy Efficient and Environmentally Responsible Desalination: Technological Progress and Brine Valorization Strategies

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## Abstract

Carbon dioxide removal (CDR) technology assist in emission reduction efforts in the case that $CO_2$ concentration increases. According to the Global Monitoring Laboratory at NOAA, monthly $CO_2$ levels globally averaged over 424 ppm in 2025, which represented excessive $CO_2$ in the atmosphere. Direct air capture (DAC) is one of the most popular of those technologies since it is capable of harvesting $CO_2$ without outsourcing sources, removing $CO_2$ that was previously released, and is geographically flexible. A historical overview of the last 20 years of DAC research is provided and the report considers critical analysis of the sorbent chemistry, regeneration methods, and systems engineering trends. Feasibility and comprehensive-cycle performance studies related to regeneration energy, water management, and infrastructure compatibility remained the most-important cost and scalability factors. Current roadmaps and comparative studies advocate regeneration-based system-level integration and optimisation. In addition, this study demonstrates that integrated carbon-removal facilities use heat and air-handling infrastructure as opposed to thermo-based capture devices. Distributed ventilation and conditioning (DAC) reduced additional air-handling penalties as well as improved indoor air quality.

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**Keywords:** Direct air capture, water management, regeneration energy, system integration, distributed carbon removal.

## 1. A Review on Progress Made in Direct Air Capture of CO

### 1.1 Background: Why did DAC become necessary?

The ease of point-source carbon capture inspired direct air capture (DAC), but hopeful industrial capture technology adoption cannot reduce emissions from diffuse industries like aviation, shipping, and distributed combustion or capture legacy $CO_2$ diffusion into the air. Climate mitigation initiatives involving considerable carbon dioxide removal (CDR) technology will be needed in the next decades to limit global warming to 1.5 o C (Persily, 2015).

DAC is supported by weather reports. More than 420 parts per million of atmospheric $CO_2$ are rising annually, according to sensors globally. Concentrations restrict DAC system design beyond climate change indicators. Since separation thermodynamics are insignificant at ultra-dilute partial pressures, selectivity, regeneration, and energy needs dictate system performance. DAC development should be judged by device performance under realistic air conditions and energy and cost curves, not merely feasibility

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### 1.2. 2000–2025: DAC feasibility to early implementation

DAC research consists of three overlapping phases with different technological aims and bottlenecks.

**Phase I (2000–2010):** Thermodynamics and industrial analogies. Initial direct air capture (DAC) experiments recorded ambient $CO_2$ using industrial carbonate looping or alkaline absorption. Initial studies indicated that DAC can be operated, however $CO_2$ regeneration and sorbent replacement are energy-intensive. Most systematic DAC technology reviews consider regeneration energy as the primary requirement. Carbonate looping cycles at 600–900 °C require high-quality heat sources (Erans et al., 2022; van der Spek, 2025). Given the major limitations of DAC—low $CO_2$ concentrations and enormous desorption energies—hybrid and lower-temperature regeneration technologies have been developed in recent decades.

**Phase II (2010-2018)** emphasizes low-temperature regeneration and sorbent advancements. Solid sorbents emerged, particularly amine-functionalized species, following the failure of direct air capture (DAC) research between 2010 and 2018. While these systems differ from high-temperature carbonate looping cycles in that they may renew at 80–120 °C, solid-sorbent DAC could potentially replace liquid alkaline systems for low-grade heat sources, such as district heating (geothermal) and industrial waste heat, in theory and practice. Material progression including amine grafting, impregnation, and support optimisation. All of these improvements further enhanced ambient $CO_2$ adsorption selectivity and kinetics. Regenerative solid sorbents that performed under less severe conditions led DAC to specialize in the area of process technologies, rather than thermodynamics, the most recent study indicated. Phase II reported systemic problems idealised trials ignored. High amine loading clogged pores, humid air co-adsorption of water, and oxidative and thermal sorbent degradation decreased performance. Subsequent studies in real air scenarios illustrated similar outcomes with minimal regeneration energy variability and effective operational capacity. For secondary synthesis research, the lower regeneration temperature did not reduce power consumption or cycle activity. This advanced DAC research. Phase II explored the advantages and disadvantages of material-oriented innovation of DAC. While humidity, lifetime, and cycling efficiency were measured, solid amine sorbents allowed for low-temperature regeneration and adaptable deployment. The guidelines selectively guided and conditioned post-2018 system integration and regeneration research priorities.

**Phase III** (≈2019–present) includes systems engineering, integration, and scaling-up limitations. Since 2018, direct air capture (DAC) research has transitioned from materials to systems engineering and scale-up realism. Nowadays priorities include complete cycle performance-based evaluation, techno-economic analysis harmonisation, and deployment bottleneck detection in the real condition of atmosphere and infrastructure. DAC systems have been investigated recently as an integrated process, such as regeneration energy, air handling, water management, and auxiliary power (as opposed to adsorption capacity or laboratory efficacies), and can be treated as different from one another. Not capture chemistry, comparative research and DACCS roadmaps identify regeneration energy, infrastructure availability, and system integration as DAC scaling challenges. Regeneration derives the majority of the energy for liquid and solid DAC systems, while compression and air handling increase cost and restrict throughput (Azarabadi & Lackner, 2019).

The results indicate that DAC is increasingly becoming a process and infrastructure design challenge but not one related to material optimisation. Phase III claims adsorption capacity is not predictive of performance. Increasing importance is given to equipment productivity, the lifetime of sorbent, regeneration energy per unit $CO_2$, and the working capacity of humid air. Erans et al. (2022) found that systems optimized for ideal or dry conditions often fail in capture regeneration cycles, calling for the application of harmonised assessment frameworks to track regeneration efforts. Low-carbon energy, storage, and $CO_2$ usage pathways and thermal or air-handling system compatibility take priority. For DAC to survive, investigators are exploring distributed architectures and aligning waste heat to regenerative processes, electrochemical cellular regeneration, and linking DAC infrastructure to the larger infrastructure to keep energy consumption under control.

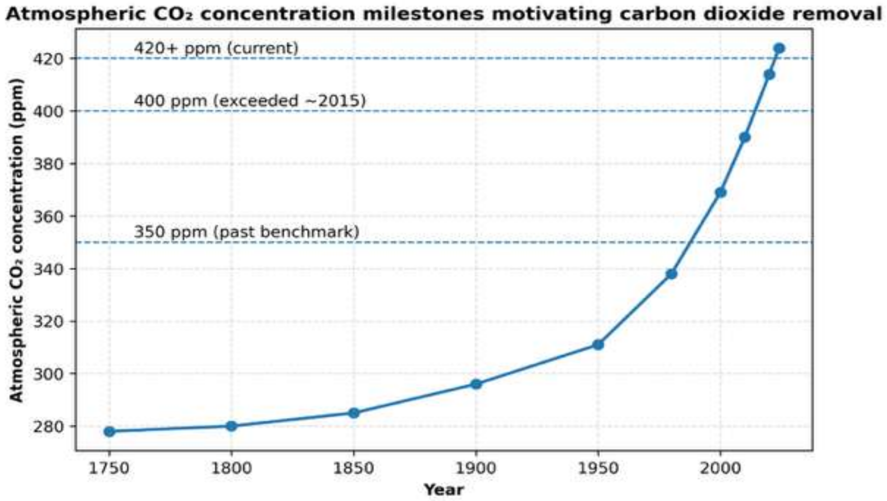

**Figure 1 Milestones in atmospheric $CO_2$ concentration since pre-industrial times**

Carbon dioxide concentration climbed from 278 parts per million in 1750 to more than 420 parts per million now, suggesting that a large-scale carbon dioxide removal technology (CDR) like direct air capture is needed and that emission reduction may not be enough. Figure 1 shows pre-industrial to modern $CO_2$ trends at 420 ppm. The persistent climb suggests emissions dominate the global carbon equilibrium after decades of mitigation. Most significantly, the portrayal indicates that cutting emissions won't return to 350 ppm since $CO_2$ will remain in the atmosphere. Carbon dioxide removal (CDR) is integral to climate stabilisation, not an alternative. A versatile CDR approach, DAC can help accumulate past $CO_2$ and remaining emissions independent of emission source location.

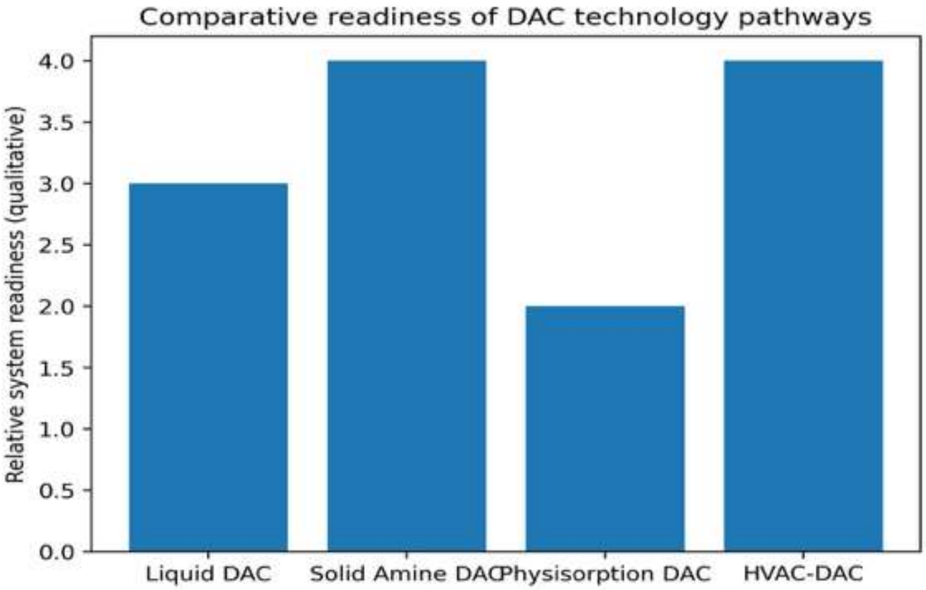

**Figure 2: Comparative DAC technology pathway readiness**

Figure 2 presents the evolution from chemical to infrastructure-integrated carbon-removal systems, prioritising CDR over DAC at $CO_2$ concentration milestones. Figure shows why solid amine DAC and HVAC-integrated DAC dominate deployment debates while physisorption-based DAC is still being studied. Solid amine DACs are future-ready due to their low-temperature regeneration and modular deployment. Physisorption-based DACs prepare employing humidity-sensitive infrastructure; and HVAC-DAC utilizes energy and air-handling infrastructure. This picture shows comparative analysis of commercial maturity for main DAC technology based on scalability, integration, and application experience; not just lab performance. Initial tests and chemical know-how demonstrate the simplicity of the liquid alkaline DAC, though centralised infrastructure and high-temperature regeneration restrain it. For solid amine DACs, modular deployment, early commercialisation, and low-temperature regeneration increase their growth. Both air humidity sensitivity and difficult validation make physisorption-based DACs unfeasible.

### 1.3 DAC "progress": capacity to full-cycle performance

In DAC research, realising that single-point adsorption measurements cannot quantify performance has improved methods. Full-cycle requirements, including working capacity between adsorption and regeneration, total regeneration energy (thermal and electrical), sensitivity to humidity and water co-adsorption, air controller pressure drop and kinetics, and sorbent over hundreds to thousands of cycles, are needed to assess DAC progress. This change to a holistic performance approach underpins modern DAC viability studies and is a key advancement of the profession (Sodiq et al., 2023).

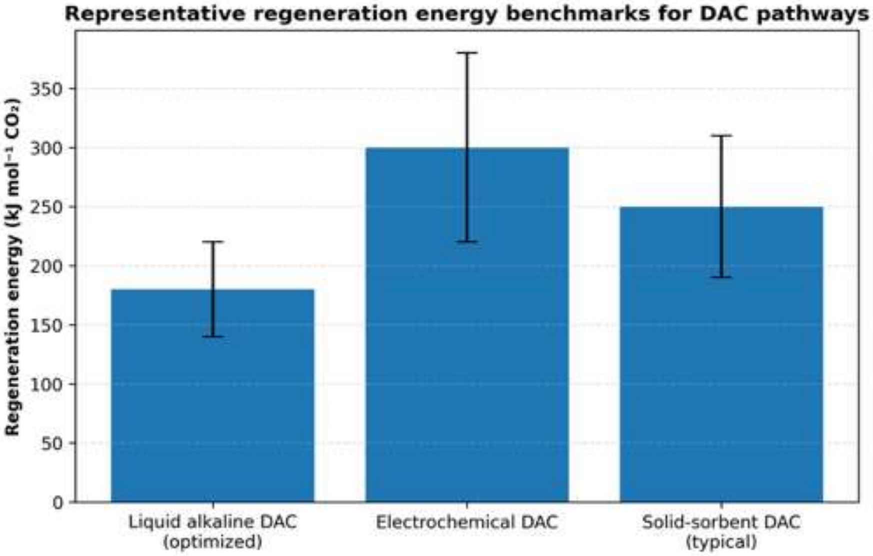

**Figure 3: Benchmarks for representative regeneration energy in DAC pathways**

Electrochemical, liquid optimum, and solid-sorbent typical regeneration energy criteria are shown in Figure 2. The simulation indicates that regeneration energy, not capture chemistry, drives system energy demand in all DAC scenarios, including the largest. The lowest mean regeneration energy was indicated for optimised liquid alkaline DAC, which suggested carbonate looping and causticization-facilitated optimisation. Solid-sorbent DAC devices are intermediate with wide regeneration energies. Amine-based sorbents have low intrinsic adsorption temperatures, but water co-adsorption and acceptable heat needs boost regeneration energy. The width of error bars shows that energy performance is affected by cycle management and system design as much as sorbent chemistry.

### 1.4. Water co-adsorption: why humidity management changed environmental sustainability

Direct air capture endangers atmospheric water vapour. Water content is many orders of magnitude larger than $CO_2$ in working settings, and humidity is always higher than ambient air. Water competes with $CO_2$ for porous, chemically active sorbent adsorption sites, modifies surface chemistry, and makes considerable latent and sensible heat losses during regeneration. Sodiq et al. (2023) imply water co-adsorption dominates DAC energy consumption and may overshadow $CO_2$ capture thermodynamics. Essential for the ecosystem. High energy use to desorb water, especially with carbon-rich electricity or regeneration heat, increases indirect emissions. Uncontrolled humidity in DAC systems boosts upstream energy demand, undermining climate mitigation. Humidity management is a technical optimisation problem and DAC need to achieve net-negative emissions.

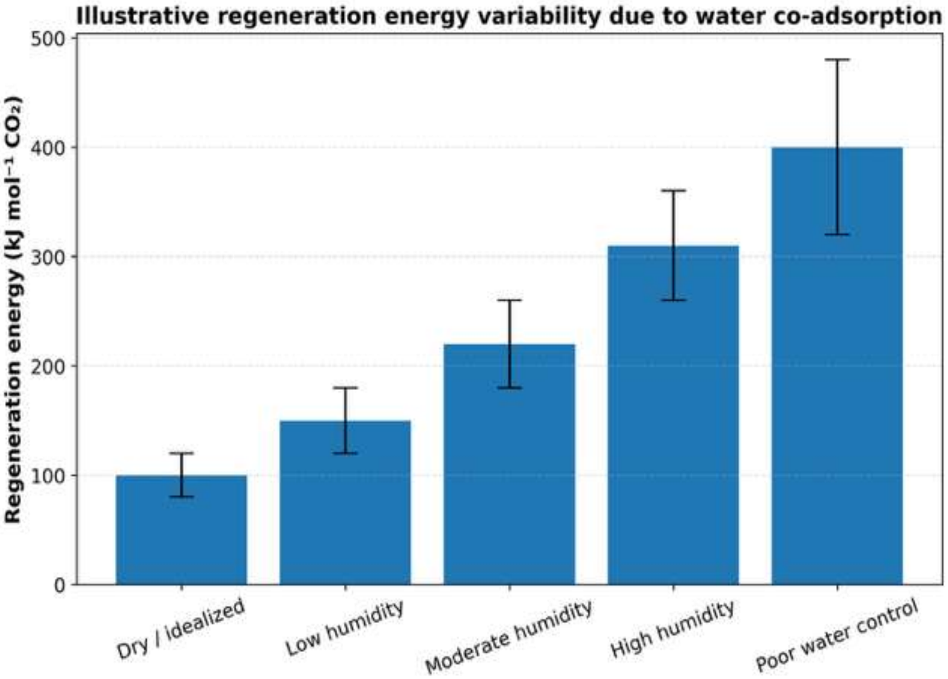

**Figure 4: Illustrative regeneration energy variability due to water co-adsorption (Wang et al., 2011)**

In Figure 3, the regeneration energy shift shows the penalty for water co-adsorption. Wang et al. (2011) recommended moisture swing adsorption for direct air capture to emphasise humidity. Water vapour modulates $CO_2$ collection and release without heating by modifying sorbent hydration, to varying degrees, according to their research. The water evaporation's latent heat raised temperatures and produced $CO_2$ in moist conditions, researchers concluded. It shows that a sorbent chemist cannot assess water control, displacement, or $CO_2$ capture-release cycle decoupling by indirectly but accurately predicting water absorption energy costs at different sorbent and system settings.

In moisture, humidity-resistant sorbents select $CO_2$, air-contact systems regulate water migration and condensation, while heat-free regeneration works for large quantities of co-adsorbed water. DAC's energy savings and environmental impact are improved through reducing life-cycle emissions and water-energy trade-offs.

### 1.5. Progress toward "leap improvements": integration over incremental material gains

Over the past two decades direct air capture (DAC) investigations have demonstrated that small sorbent features for example low heat of adsorption or improved equilibrium $CO_2$ capacity do not lower system-level energy demand or load. Material innovation still matters, but DAC performance has to do with system-scale constraints, such as air handling, regeneration energy, and water management; not adsorption chemistry. We formalise this realisation by looking at DAC system's total specific energy usage, $E_{DAC}$:

$$E_{DAC} = E_{air} + E_{reg} + E_{aux} \quad (1)$$

Where $E_{air}$ consists of contactor airflow energy, $E_{reg}$ is sorbent regeneration, and $E_{aux}$ is auxiliary electrical and control loads. Despite improved sorbents, freestanding DAC plants have high $E_{air}$ and $E_{reg}$ values and high energy intensity. Material-level adjustments reduce adsorption enthalpy or increase operational capacity to target $E_{reg}$. The substantial regeneration-energy variation in humid settings reveals that water co-adsorption dominates $E_{reg}$, decoupling system performance from sorbent qualities. $E_{DAC}$ reduction demands fundamental system boundary adjustments, not incremental sorbent improvements.

Integration restructures DAC: Integrating DAC into air-handling or thermal infrastructures alters energy balance:

$$E_{DAC}^{int} = \alpha E_{air} + \beta E_{reg} + E_{aux} \quad (2)$$

where $0 \leq \alpha \ll 1$represents the fraction of air-handling energy that is incremental (rather than already incurred for ventilation or process operation), and $0 \leq \beta \leq 1$represents the fraction of regeneration energy that must be supplied by new primary energy rather than recovered low-grade heat. In such configurations, leap improvements arise not from reducing adsorption energy by a few percent, but from driving $\alpha$and $\beta$toward zero through infrastructure coupling.

## 2. Review of the Emerging Trends in Direct Air Capture of $CO_2$

### 2.1 Materials discovery to system-oriented DAC research

In the last decade, direct air capture (DAC) research progressed from isolated material discovery to combined system optimisation. Between 2005 and 2015, the early studies of DAC literature focused on finding high-capacity sorbents capable of capturing $CO_2$ at extremely low partial pressures. In this materials-driven era, amine-functionalized solids and microporous frameworks improved, but only to a limited degree. A high equilibrium capacity does not guarantee low-cost or low-energy DAC performance in real-world climatic conditions with changing temperature and humidity.

### 2.2 Water and humidity tolerant sorbents

DAC studies are now investigating how water-$CO_2$ co-adsorption works. As air is humid, water vapour and $CO_2$ vie for adsorption sites in porous media. In physisorption systems, ultramicroporous framework configurations with electrostatic conditions restrict the water affinity and thus adsorb $CO_2$ preferentially. Likewise to full-cycle applications, temperature–vacuum swing adsorption (TVSA) cycles can dominate the thermal budget in regeneration with greater water. The present study is centred on amine efficiency (number of $CO_2$ molecules adsorbed per mole of amine) and stability of chemisorption systems, mostly amine solids, with cyclic oxidative and thermal cycling. Hence, regeneration stability and sorbent lifetime are equally important as capacity. The development of these DAC materials with water-tolerant sorbents, optimized amine loading, composite structures, and hierarchical porosity are being introduced. These solutions target humidity-related energy loss, pore blockage, and durability. The system-level benefits comprise lower regeneration energy, cyclic stability, mass transfer, pressure drop, increased adsorption–desorption cycles, and ambient air efficiency.

### 2.3 Regenerative techniques drive innovation

The fact that regeneration, and not capture, prevails as primary energy loss in the full cycle operation is the main direct air capture (DAC) advancement. Studies have demonstrated that the viability, feasibility, and environmental benefits of the system relied on energy consumption for recovering sorbent capacity rather than for reaching the $CO_2$ uptake in the correct atmosphere. Regeneration is the leading development of DAC system designs now. With it, consider gas-phase compression, water co-adsorption, sorbent heating, and intrinsic $CO_2$–sorbent binding enthalpy when calculating regeneration energy. DAC research aims to give birth to regeneration techniques which reduce desorption temperature, reduce material heating, or completely separate $CO_2$ release from total thermal input, all factors which routinely affect energy balance. Single-mode regeneration is now replaced by hybrid and non-thermal regeneration.

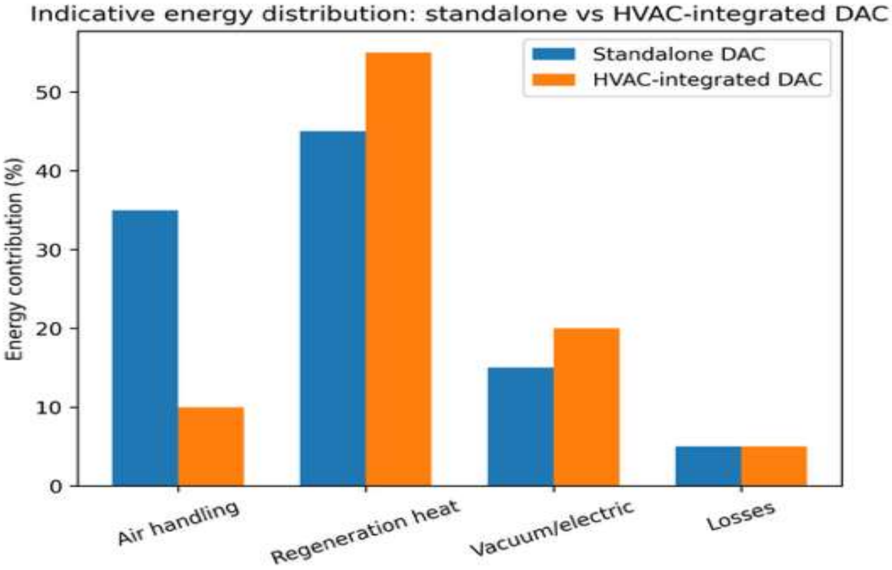

**Figure 5: Energy distribution: standalone vs HVAC-integrated DAC**

**Figure 4 depicts the transition from thermally dominated TSA cycles to hybrid and non-thermal regeneration methods. The figure shows how DAC regeneration innovation is shifting from bulk thermal heating to electrical, latent, or phase-change-driven mechanisms due to a wider focus on energy-quality optimisation rather than energy minimisation.**

### 2.4. Distributed DAC architectures, mobility, and modularisation

The direct air capture (DAC) systems has also trend is to modular systems. Given the constraints of capital intensity, site location, and the huge diversity of low-carbon energy and storage alternatives, DAC must redefine its strategies of scale. Recent DAC works emphasize scalability via replication, or more standardised units, rather than scaling via big setups. Centralised and modular DAC differ with respect to how total capture capacity $C_{tot}$ is achieved system-wise:

$$C_{tot} = N \cdot C_{unit} \qquad (3)$$

The number of DAC modules is N and capture capacity is $C_{unit}$. Because capacity increases linearly with deployed units, modular systems can grow incrementally and avoid the financial and technological hazards of large-scale first-of-a-kind facilities. Expansion of plants is required for expansion of centralised DAC systems as they expand capacity. Carbon Engineering's massive liquid alkaline absorption technologies need chemically sophisticated regeneration and central processing for scale. It requires a high-temperature regeneration unit, huge air contactors, and $CO_2$ compression and transportation plants to operate at high throughput. Though scaled better, these designs have huge entrance and sitting barriers. Comparisons demonstrate that centralised, modular DAC solutions are not better.

The system-level boundary components like the types of low-carbon energy sources used in this case, storage of $CO_2$, access paths, and infrastructure integration determine their significance. To formalise this, consider $C_{eff}$ effective capture cost:

$$C_{eff} = \frac{C_{cap} + C_{op}}{\dot{m}_{CO_2}} \qquad (4)$$

$C_{cap}$ and $C_{op}$ are represent capital and operational costs, while $m_{CO_2}$ reflects $CO_2$ collection rate. Standardisation and mass production can lower $C$caps in modular DAC systems, partially offsetting greater operational costs. Adding air-handling or heating infrastructure can reduce energy use. This system's reasoning has spurred interest in distributed DAC deployment when centralised infrastructure is unnecessary or impractical. DAC modules minimise most marginal energy and infrastructure needs for $CO_2$ capture when co-located with industrial waste heat sources, renewable electricity generation, or building ventilation systems. Such systems offer dynamic DAC capacity matching to local resource availability and emphasise mobility and adaptability.

### 2.5. Integration with current infrastructure as a key development in DAC

Direct air collection has been a significant feature of industrial and energy systems. The large cost that DAC requires and energy penalties associated with the management of air and regeneration are gradually being mitigated through synergistic integration rather than through standalone capture chemistry maximisation. DAC-enabled infrastructure types are described in literature. Unused waste heat from power and industrial plants can help enhance regeneration energy efficiency. These large-scale district heating and cooling networks will distribute or absorb regenerated heat and consume less energy.

**Each DAC integrates processes and flows energy without infrastructure. This search trend is consistent with low-carbon technology co-location and functional coupling in order to drive the acceleration of energy-systems engineering adoption and the reduction of capital costs. With DAC devices integrated into the hardware components of existing infrastructure without $CO_2$ capture, air movement, thermal cycling and plant power consumption can be reduced. Integrated infrastructure saves DAC energy and helps the environment. All air- or heat-transporting systems can be DAC, and that includes ventilation. DAC studies energy systems, industrial ecology, and urban infrastructure, outside chemical engineering.**

## 3. DAC Technology Evaluation and State-of-the-Art

### 3.1. DAC Tech Assessment Framework

Assessing direct air capture (DAC) devices by way of a multi-criteria, system-level approach goes beyond equilibrium sorbent capacity and single-point capture efficiency. DAC performance depends on several subsystems with 400-420 ppm $CO_2$ air. But chemical affinity is not limiting and carbon diffusion doesn't control the regime; sorbent-air contactor interaction, regeneration pathways, and energy infrastructure do. Increasingly, DAC research proves that a single parameter cannot determine performance and scale-up (Azarabadi and Lackner, 2019; Erans et al., 2022). The selectivity of capturing mechanisms, which limits DAC system thermodynamic and functional constraints for liquid or solid adsorption, reduces DAC systems in thermodynamic and functional constraints. Although the liquid solutions remain sensitive to humidity and material decay, liquid options are capable of capturing materials at the desired regeneration temperature and at a wide variety of air conditions even at different regeneration temperatures despite moisture limitation and degradation of materials, and have high regenerative properties, respectively using liquid solutions. DAC designs rely on low-carbon or waste heat sources based on energy intensity and regeneration. Regeneration energy is more economically and environmentally critical than adsorption capacity. In this environment, the water co-adsorption, coupled with the humidity, decreased the sensible and latent heat potential and regeneration energy.

To that end, DAC systems' long-term atmospheric performance and dry air performance will be assessed. The viability of the system depends on the air-contactor design, pressure-drop management and scalability, which can effectively carry out large volumes of air. But, at scale, a small pressure drop change is a big energy load so you need a lot of energy, and you get aerodynamic design and sorbent design. Consistency matters for career longevity. Cycling's temperature, humidity and even oxygen destroy material. Hybrid air capture achieved with the addition of chemisorption and physisorption to aqueous peptide absorption and carbonate crystal encapsulation. Custelcean et al. (2021) showed that glyoxal-bis-iminoguanidine can help crystallise bicarbonate in response to the $CO_2$ being absorbed by glycylglycine.

Carbonation results in intentionally low-solubility solid carbonate products that separate capture and desorption energetics from the bulk solvent regeneration, providing lower regeneration energy compared to relatively advanced solvent DAC methods. In this system, a hybrid peptide–crystallization mechanism exploits reactive phase change to process intensive heat regeneration into chemically-driven separation allowing for low-energy DAC without the thermal volatility.

### 3.2. Liquid Alkaline absorption systems

The most recent industrial DACs are liquid alkaline absorption systems. These employ aqueous NaOH or KOH solutions to extract $CO_2$ from ambient air and yield dissolved carbonate or bicarbonate ions. They are based on gas-liquid mass transfer and carbonate chemistry laws. Causticization and calcination yield high-purity streams of $CO_2$ that can be compressed, transported, stored, or utilized for regeneration. Alkaline liquid DAC is the ability to respond to the environment through chemical engineering. Alkaline solutions are unique in solid-sorbent systems because of their good capture efficiency with regard to ambient temperature and pressure, fast reaction kinetics, and no sensitivity to humidity. However, the primary task of liquid alkaline DAC in comparison to capture chemistry is the high-temperature carbonate breakdown for regenerative energy. Even high-temperature calcination processes at 600–900 °C require quite a bit of heat. Recent calculations indicate the minimum thermal energy to be 178 kJ $mol^{-1}$ $CO_2$. Pumping, solids, and gas compression require ample power (Keith et al., 2018). Liquid alkaline DAC can remove $CO_2$ steadily and predictably at very high regeneration temperatures owing to its chemical stability and scalability. Liquid alkaline DAC systems require large air liquid contactors to mass transfer at atmospheric $CO_2$ with a relatively high infrastructure and calcium carbonate loops. These are costs which are higher and less flexible when compared to solid-sorbent alternatives. Design focuses on the longevity and throughput and not on flexibility or mobility. Big, centralised, digital-to-analog converters require alkaline DAC, not a panacea.

Table 1 shows alkaline liquid DAC system performance and limitations with respect to the capture method, the regeneration condition, the scaling, the incorporation.

**Table 1: Assessment of liquid-based direct air capture technologies based on alkaline absorption**

| Attribute | Alkaline liquid DAC (NaOH/KOH) |
|---|---|
| Capture mechanism | Chemical absorption |
| Typical regeneration temperature | 600–900 °C |
| Regeneration energy | 178–390 kJ/mol $CO_2$ (thermal) |
| Humidity sensitivity | Low during capture; high during regeneration |
| Sorbent degradation | Low (chemically robust) |
| Scalability | High (centralized plants) |
| Modularity | Poor |
| Representative implementation | Carbon Engineering |
| Main limitation | High-temperature energy demand |

Sources: Keith et al. (2018); Sanz-Pérez et al. (2016); Sodiq et al. (2023).

### 3.3. Solid-sorbent DAC technologies

Solid-sorbent direct air capture (DAC) has been the focus of development and early commercialization of DAC systems. This is useful because they are capable of operating at moderate regeneration temperatures and with low-grade heat source solutions that reduce the regeneration energy intensity, a common DAC application problem. Liquid absorption methods require high-temperature carbonate breakdown, but solid-sorbent DAC systems collect and release $CO_2$ (Azarabadi & Lackner, 2019). The most common solid-sorbent DAC systems utilize chemisorption to adsorb $CO_2$ in air by using amine-containing chemicals. Microporous material may introduce humidity susceptibility for physisorption tests but low $CO_2$ selectivity at low dosages is limited.

Amine-based solid sorbents reduce regeneration temperature, resulting in adsorption and regeneration in one collection device which is advantageous in systems engineering. Water co-adsorption contributes significantly because air humidity causes the regeneration energy to increase and the latent and sensible heat to decrease. Volatilisation, chemical degradation, and amine oxidation reduce cycle life of the sorbent at elevated temperatures and oxygen. The high amine loadings can inhibit pores and mass transport, which can limit the capacity. Table 2 reperesents assessment of amine-based solid DAC.

**Table 2: Assessment of amine-based solid direct air capture (DAC) technologies**

| **Attribute** | **Amine-based solid DAC** |
|---|---|
| Capture mechanism | Chemisorption |
| Typical regeneration temperature | 80–120 °C |
| Regeneration energy | ~90–390 kJ/mol $CO_2$ |
| Humidity sensitivity | High |
| Sorbent degradation | Moderate (amine loss, oxidation) |
| Scalability | Moderate–high (modular) |
| Modularity | Excellent |
| Representative implementation | Climeworks |
| Main limitation | Water co-adsorption and sorbent stability |

Sources: Gebald et al. (2014); Beuttler et al. (2019); Erans et al. (2022).

### 3.4. Physisorption-based DAC: potential, limitations, and future research

Physisorption-based direct air capture (DAC) of $CO_2$ uses zeolites, activated carbons, and metal-organic frameworks' weak van der Waals and electrostatic interactions. These materials represent good DACs as well, owing to their high surface area, fast kinetics, and low intrinsic adsorption temperature. Physisorption, a low energy option for chemisorption, cycles rapidly and regenerates in low temperature medium. Physisorption materials are more effective than chemisorbents at absorbing $CO_2$ in dry, controlled labs and especially in low regeneration temperatures. Systems of MOF and zeolite have been extensively investigated for the enhancement of $CO_2$ selectivity through improved electrostatic fields, pore-size selectivity and functional pores. Physisorption materials are needed for low-$CO_2$ DAC structure-function studies. The application of these developments in the atmosphere is limited by water vapour competition.

In reality, physisorption materials preferentially favour water vapour orders of magnitude greater than $CO_2$. Pore-structures absorb the water, and generate latent and sensible heat to replace $CO_2$. Physisorption systems outperform chemisorption based systems in ideal conditions, but at practical conditions in the air these systems lose capacity, lowering cycle efficiency and environmental value. Thermal competition, which is difficult to decrease without modifications of sorbent's design or the way the system is operated, limits this, not material instability, as physisorbents are chemically inert and degradation-resistant. Hydrophobic or water-repelling nanoparticle pore materials, hybrid physisorption-chemisorption materials, and system-level approaches are being explored to decouple water management from $CO_2$ collection.

Table 3 represent the qualitative evaluation of physisorption-based DAC capture technologies.

**Table 3: Assessment of physisorption-based direct air capture (DAC) technologies**

| **Attribute** | **Physisorption-based DAC** |
|---|---|
| Capture mechanism | Physical adsorption |
| Typical regeneration temperature | Ambient to moderate |
| Intrinsic regeneration energy | Low |
| Effective regeneration energy | High under humid conditions |
| Sensitivity to humidity | Very high |
| Sorbent degradation | Low (chemically stable) |
| Scalability | Unproven |
| Modularity | High (in principle) |
| Representative materials | Zeolites, activated carbons, MOFs |
| Dominant limitation | Water competition |

**Sources: Kumar et al. (2015); Mukherjee et al. (2019); Sodiq et al. (2023).**

## 4. Complete Chemisorption vs Physisorption for Direct Air Capture

### 4.1 Scope and Intent

A collecting media is exposed to diluted ambient $CO_2$ in direct air capture. Theoretically and practically, physical and chemical methods of capture are rather distinct. Research into gas separation supports both systems but DAC needs continuous recycling and operation at ambient temperatures, constant water vapour, and a very low $CO_2$ partial pressure (400–430 ppm). In the earlier DAC literature, sorbents were defined by intrinsic heats of adsorption or equilibrium $CO_2$ capacity. Such results are inadequate to assess DAC viability based on the 10-year experience. Energy for regeneration and tolerance of humidity rely on system performance. This section illustrates the different chemisorption and physisorption processes and demonstrates how the physics of sorption impact operational robustness and regeneration energy for DAC.

### 4.2 Basic capture techniques

As a thermodynamic comparison of chemisorption- and physisorption-based $CO_2$ collecting, we can see how humidity, kinetics and regeneration penalties influence DAC performance. The sorbent regeneration energy and the $CO_2$ capture at low partial pressures for both systems depend on the shape and depth of the adsorption potential wells. Deeper potential wells retain stability but require more regeneration energy in diluted conditions.

### 4.3 Humid/water co-adsorption

DAC chemisorption and physisorption for water vapour are not much the same. Adsorption is highly competitive the water vapour in the air is two to three orders of magnitude higher than that of $CO_2$. There are two chemisorption functions of water. Moisture assists bicarbonate and amine in absorbance of $CO_2$. Co-adsorbed water desorption requires more sensible and latent heat, which is an increasing factor on regeneration energy. The ruggedness and humidity control of chemisorption devices enables engineers to develop in situ regeneration protocols.There are not many physisorptions that are able to co-adsorb water. Water fills pores, then selects adsorption sites, resulting in reduced $CO_2$ uptake. Water outperforms $CO_2$ desorption, balancing physisorption's low-energy regeneration. DACs based on physisorption can have a greater renewal rate than chemisorption in humid environments but their adsorption temperature is inherently lower.

### 4.4 Movement and mass transfer

No obstacles to bond forming speed physisorption over chemisorption. This boosts dry lab cycling and minimizes pressure loss. The water adsorption prevents the diffusion of $CO_2$ into micropores in ambient humidity, which negates kinetic benefits. Due to active site diffusion and reaction restrictions, amine-functionalized chemisorption systems exhibit reduced inherent kinetics. It uses amine loading, air-contactors, and hierarchical pores to speed cycles. Most importantly, chemisorption kinetics are consistent with relative humidity while physisorption decreases rapidly.

### 4.5 Renewables

Intrinsic adsorption energy vs. effective regeneration energy is vital to DAC assessment. Effective regeneration energy includes water desorption and sorbent matrix heating as well as vacuum pumping, and auxiliary losses, while intrinsic adsorption energy measures $CO_2$–sorbent interaction.

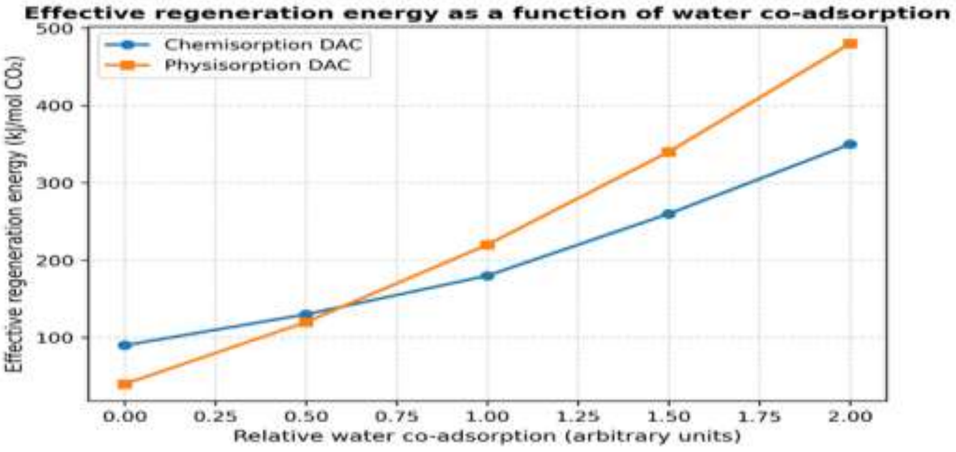

**Figure5: Effective regeneration energy for chemisorption and physisorption DAC systems with water co-adsorption.**

Figure 5 shows regeneration energy from chemisorption and physisorption is affected by water co-adsorption. Chemisorption systems have higher regeneration energies due to improved $CO_2$ binding, although gains with water loading are modest. Low water concentrations give physisorption systems high regeneration energy, but co-adsorbed water concentrations multiply it quickly. In humid areas, water desorption costs energy.

In humid environments, water removal boosts low-adsorption-energy physisorption system regeneration. Lower adsorption energies and slower regeneration energy increase with humidity lower system-level effective energy demand in chemisorption systems. DACs that chemisorb influence deployments.

### 4.6 Durable

Long-term cyclic stability determines DAC's viability. Time deactivates, volatilises, and oxidises chemical sorption systems, notably amine-based ones. With regulated regeneration, most systems last hundreds to thousands of cycles below 120 °C.

Although physically stable, wet air limits CO2 working capacity, rendering physisorbent redundant. Chemisorption's maternal conduct from material deterioration improves because durability without function is not DAC practical.

## 5. Direct Air Capture of $CO_2$: Alternative Regeneration Strategies

### 5.1. Regenerations require DAC energy

Sorbent regeneration is the primary energy-consumption, economic, and scalability factor in direct air capture (DAC). Though it is very hard to adsorb air at 400–420 ppm $CO_2$, $CO_2$ escape and sorbent turnover requires 10 times higher thermal energy than separations. Recent DAC roadmaps and overhead comparing studies have shown that regeneration remains the main barrier to large-scale deployment (Realmonte et al., 2019; Erans, 2022). From a system perspective, regeneration solutions must satisfy five requirements simultaneously:

1. Small-scale energy use (kJ/mol $CO_2$).
2. Ambient humidity air appropriateness.
3. Purity for $CO_2$ storage/use.
4. Low long-cycle sorbent degradation.
5. Low-carbon energy compatible.

DAC research explores multiple regeneration approaches because none satisfy all five criteria. PSA, VSA, PVSA and $CO_2$ pressure-generated PSA, VSA, PVSA. DAC cannot have the capacity to be used for industrial gas separation by pressure swing adsorption PSA. PSA is depressurized after pressurising the supplied gas for adsorption. According to Sumida et al. (2012), compressing ambient air in the DAC to cause increase in $CO_2$ partial pressure imposes high electrical energy costs. PSA is very expensive for ultra-dilute conditions, and therefore most of the designs of modern DAC systems are not based on it (Sanz-Pérez et al., 2016).

The vacuum swing adsorption (VSA) technique, essentially adsorbing at atmospheric pressure and desorbing at vacuum, does not require feed compression. DACs based on VSA are interesting, yet deep vacuum (0.4 mbar) desorption is necessary, limiting further scalability and energy consumption (Zhu et al., 2021). PVSA (a PSA-VSA hybrid) suffers from compression and vacuum inefficiencies. PVSA is less economical for DAC than temperature based regeneration.

### 5.2 TSA/TVSA temperature-based regeneration

Temperature swing adsorption is the most well-studied regeneration strategy for chemisorption-based DAC systems; particularly solid amine sorbents. TSA reverses the $CO_2$-active site interaction by heating the sorbent at 80-120 °C (usually for solid amines) (Choi et al., 2011; Sanz-Pérez et al., 2016). TSA has advantages, such as low-grade heat compatibility. Easy to use. Do not use deep vacuums. But TSA has drawbacks:

Desorbed $CO_2$ is commonly diluted with purge gas. Amine oxidation increases with increased temps. Water desorption markedly increases regeneration energy. These obstacles give rise to hybrid regeneration strategies.

TVSA helps to improve $CO_2$ purity and desorption with mild heating and vacuum. To a great extent, TVSA is used for regeneration in solid-sorbent DAC research and construction (Wurzbacher et al., 2011; Elfving, 2017). One obvious drawback of TVSA is that it uses vacuum to bring $CO_2$ purity into a higher range. However, this method increases electricity use and reduces productivity. Mild vacuum with air or inert purge surpasses vacuum-only TVSA under 100 °C (Elfving et al., 2021).

### 5.3. Steam- and moisture-mediated regeneration

Steam-assisted regeneration catalyses desorption with latent heat of condensation. Steam-assisted TVSA heats and releases $CO_2$. A high-purity $CO_2$ stream results from condensation (Bos et al., 2019). Steam regeneration has drawbacks despite its thermodynamic appeal:

- Amine leaching in polymer-supported sorbents was observed.
- Enhanced system complexity
- Challenges in water management.

However, steam-assisted regeneration is appealing where water and low-carbon steam are abundant. One fundamentally separate regeneration method in direct air capture (DAC) is moisture swing adsorption (MSA), which replaces the thermodynamic driver of humidity with thermal regeneration. MSA systems preferentially remove $CO_2$ by ion-exchange or carbonate-forming processes in dry settings and release it in humid situations. The latent heat of water evaporation powers this regeneration process rather than perceptible heat from the sorbent or solvent matrix (Wang et al., 2011). This approach uses regulated hydration-dehydration cycles instead of heat management. Recognition that water phase transition dominates regeneration work explains MSA's energy basis:

$$E_{\mathrm{reg}}^{\mathrm{MSA}} \approx \Delta H_{\mathrm{vap}}^{\mathrm{H_2O}} \cdot n_{\mathrm{H_2O}} \qquad (5)$$

where $\Delta H_{\mathrm{vap}}^{\mathrm{H_2O}}$ is the latent heat of vaporization of water and $n_{\mathrm{H_2O}}$ is the number of water molecules involved in the hydration–dehydration cycle per mole of $CO_2$ released.

By system integration, MSA will produce low-to-moderate purity $CO_2$ streams, perfect for distribution routes that do not require compression or purification to pipeline quality. Even little amounts of ambient $CO_2$ enrichment benefit algae farming, indoor air quality, and agricultural greenhouses (Wang et al., 2011; Bos et al., 2019). As a regeneration-focused solution, MSA is better suited to specialised end applications than a DAC solution. Climate is a major drawback of MSA. Since $CO_2$ capture uses dry air, repeated exposure to high humidity affects adsorption capacity and cycle efficacy. Under high relative humidity or seasonal variations, uncontrolled hydration permanently saturates the sorbent, preventing $CO_2$ release (Shi et al., 2018). MSA's climate sensitivity makes it less successful than other regeneration procedures, which can endure more air conditions.

### 5.4. Electrochemical regeneration pathways: heat-decoupled $CO_2$ release

Electrochemical regeneration is a research focus to separate $CO_2$ emissions from bulk thermal heating. These devices desorb $CO_2$ from functionalised sorbents or alkaline solutions using electrical energy to induce ionic gradients, pH shifts, or electrochemical processes (Shu et al., 2020; Kim, 2021). The energy-quality pathway of electrochemical DAC is very different from thermal regeneration because electrical work is instantaneously transferred to separation work.

Electrochemical regeneration is practical because it works at temperatures near to ambient temperature, hence regeneration energy may be described in electrical terms:

$$E_{\mathrm{reg}}^{\mathrm{elec}} = \frac{W_{\mathrm{elec}}}{\eta_{\mathrm{elec}}} \qquad (6)$$

where $W_{\mathrm{elec}}$ is the electrical work required to drive $CO_2$ release and $\eta_{\mathrm{elec}}$ is the overall electrochemical efficiency. In low-carbon electricity, this approach offers the potential for high energy efficiency and compatibility with a renewable energy system.

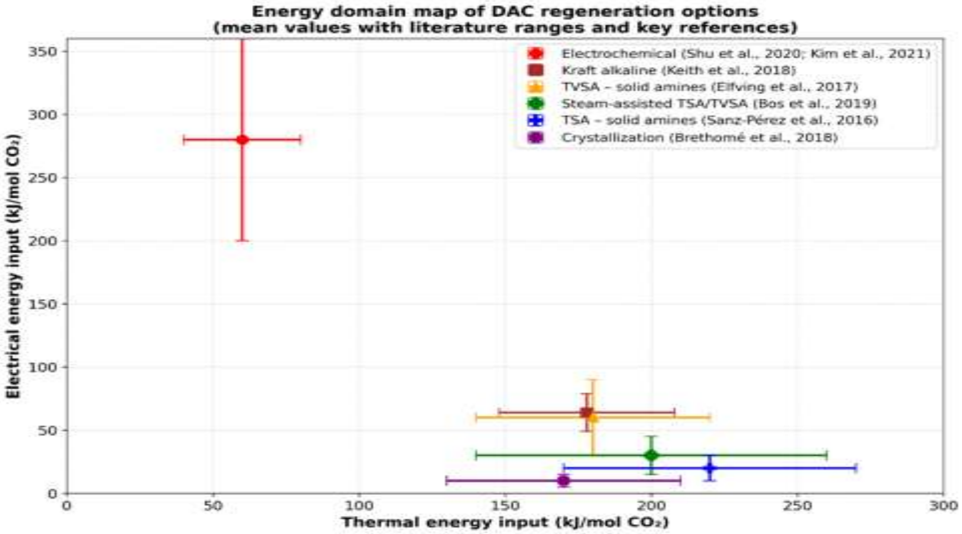

**Figure 6: Representative DAC regeneration energy domain map**

The relative inputs of thermal and electrical energy for potential energy sources, such as direct air capture (DAC) regeneration, are shown in Figure 6. Shu et al. (2020) used a hydrogen-recycling electrochemical system (HRES) to renew spent alkaline absorbents, which is relevant to electrochemical DAC regeneration. Unlike temperature-swing regeneration, the device uses an electrochemically driven pH gradient to construct contiguous acidic and alkaline compartments for $CO_2$ desorption at low pH and NaOH production at high pH. Most crucially, this process regenerates solvents and releases high-purity $CO_2$ (>95%) without substantial thermal heating.

### 5.5. Crystallization-based regeneration: phase-change separation

DAC regeneration based on crystallization is a unique concept. These systems, by capturing $CO_2$ in solution, promote detaching carbonates (and breaking the solid carbonate crystals down) without heating the solvent volume (Brethomé et al., 2018; Custelcean et al., 2019), enabling separation. It significantly reduces the regeneration temperature thanks to phase separation rather than bulk thermal cycling. Crystallization-based DAC regenerates energy from local phase transitions and moderate heating (60-120 °C), making it suitable for low-grade sources of waste heat. By preventing amine-based system-specific degradation processes like oxidative loss and volatilisation, crystallisation provides greater long-term chemical stability. Scalability and complexity limit the scope of crystallization-based DAC. These systems work mainly in batch or semi-batch modes and inherent crystal formation and dissolution dynamics introduce design restrictions. This approach is only early stage due to reactor design, continuous operation, and uncertainties in deployment at scale. The following table compares TVSA, electrochemical regeneration, and crystallization-based technologies, according to temperature regime, energy domain, maturity, and scalability, to evaluate advanced regeneration pathways.

**Table 4: Comparison of advanced regeneration pathways**

| Regeneration pathway | Typical temperature | Energy domain | Maturity | Scalability |
|---|---|---|---|---|
| TVSA (solid amines) | 80–120 °C | Thermal + electrical | High | Moderate–high |
| Electrochemical | ~25–60 °C | Electrical | Low–moderate | Uncertain |
| Crystallization | 60–120 °C | Thermal | Low–moderate | Limited |

Sources: Brethomé et al. (2018); Shu et al. (2020); Erans et al. (2022).

## 6. Conceptual shift: from standalone DAC plants to distributed air-contacting infrastructure

Reducing the dependency on standalone DAC units, and instead establishing distributed air-contacting plants. Conventional direct air capture (DAC) systems are constrained through air-handling energy costs. DAC standalone plants primarily consume energy as the result of air flow through contactors to buffer pressure, not $CO_2$ expulsion (Keith et al., 2018; Erans et al., 2022). As a result, the application of air-handling infrastructure as a DAC platform has also been popular in the literature (Shi et al., 2018). HVAC systems are common and continuous air-contacting systems, particularly in cities. In this perspective, DAC is a distributed, infrastructure-integrated negative emissions solution, not a single-use, centralised industrial activity. Indoor air quality, $CO_2$ exposure, and HVAC systems as carbon-control interfaces.

In the past, indoor air quality (IAQ) studies have used $CO_2$ as a proxy for ventilation adequacy rather than a primary contaminant. Expanding studies in the epidemiological and building-science literature associate high $CO_2$ concentrations indoors with adverse health, comfort, and cognitive consequences, such as headache, fatigue, poor decision-making, and worsened respiratory symptoms (Seppänen et al., 1999; Erdmann et al., 2002; Jung et al., 2009). Although indoor $CO_2$ exposure is measured by ventilation restrictions, such as compliance with the rules, the impacts are shown to persist in heavy use environments that exceed 1000 ppm, such as workplaces, schools, and institutions (Ferreira & Cardoso, 2014). This research shows that growing outdoor $CO_2$ concentrations are limiting ventilation-based internal $CO_2$ control. Almost all typical $CO_2$ outside ventilation rules (including ASHRAE) assume external $CO_2$ values of ~350 ppm. Today's climate, where background $CO_2$ levels exceed 420 ppm, even well-designed ventilation systems face challenges sustaining indoor levels below historical averages (Persily, 2015).

This results in structural imbalances: increasing ventilation rates to accommodate external $CO_2$ generates more costly energy penalties, which is of particular concern in warm or damp climates subject to cooling and dehumidification loads, whose effects in building energy use are felt. So we now see indoor $CO_2$ as a control variable limited only by thermodynamics, for economic reasons, and not a ventilation one. As it raises the amount of latent heat removed which in turn contributes to sensible cooling load and fan energy, relaxing the airflow by itself has become infeasible. According to the IAQ literature, the importance of comprehensive indoor $CO_2$ regulation over ventilation rate control has received increasing attention. Therefore, direct air capture (DAC) with air conditioning components (DAC) from the HVAC is a scientific answer and not a new idea (Shi et al., 2018).

From an engineering perspective, HVAC systems are among the largest continuous energy users in the built environment because of air flow, sensible heat exchange, and latent heat removal. And most importantly, these energy penalties are required for temperature and humidity regulation, whether DAC is present or not.

By combining air processing and thermal conditioning capacities with DAC, HVAC-integrated DAC can reduce the energy needed for capturing carbon dioxide, and these effects are reinforced by this finding. HVAC systems already disperse massive quantities of air, whereas standalone DAC equipment needs to create airflow to capture.

By embedding DAC modules within HVAC airflow routes, $CO_2$ capture can share fans, ducting, cooling, control, and thermal exchange surfaces with HVAC systems. This means that DAC is an accretional load on an energy flow (thermodynamics), not a separation technique (thermal mechanics). This distinction is critical: HVAC-powered DACs utilize energy-justified airflow, but freestanding DACs need to manufacture airflow by design. Since some sorbents are sensitive to humidity, latent heat is kept by HVAC dehumidification, thus influencing the performance of DAC. Capture of $CO_2$ during HVAC dehumidification reduces water co-adsorption penalty in conventional DAC regeneration energy.

This duality has motivated a quantitatively energetic survey on HVAC-based DAC as follows—explaining why it closely tracks system-level DAC optimisation trends.

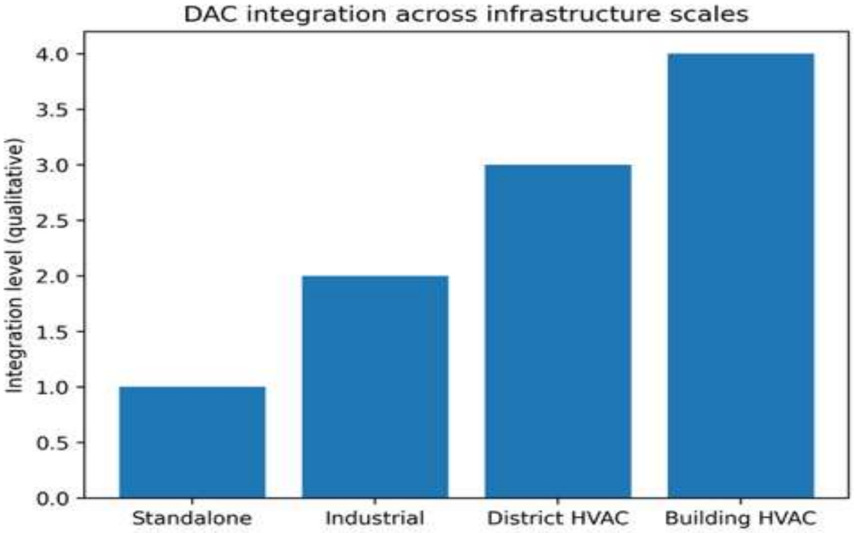

**Figure 7: Compare freestanding direct air capture (DAC) air-handling needs with HVAC-integrated DAC designs, demonstrating reduced fan energy when $CO_2$ collection is integrated into existing ventilation systems.**

Figure 7 compares HVAC-integrated DAC air-handling requirements to freestanding DAC systems. Because big fans must draw ambient air through capture contactors solely, isolated DAC plants have a high incremental fan energy penalty that scales directly with capture capacity. However, HVAC-integrated DACs contain capture modules in AC and ventilation airflows. Thus, airflow formation is mostly avoided and sorbent regeneration becomes the main energy demand.

### 6.2. HVAC–DAC integration architectures

In the literature, integrated approaches relating to HVAC operations, regeneration mechanism, and capture site placement have been described or suggested. Supply-air capture integration installs the direct air capture (DAC) module into the fresh air intake of the HVAC system before conditioned air flows into the occupied space. This approach minimises $CO_2$ content at the ventilation point, partially decarbonising ambient outdoor air and delivering it through to the occupied interior space. The primary advantage is that $CO_2$ can be controlled on the scene and in advance of time. Since capture is performed at outdoor $CO_2$ concentrations of 420 ppm, the supply-air design ensures indoor air quality for different occupant occupancy levels while preventing above-average concentrations of inside $CO_2$ from occurring. It aligns with the systems-based operational logic of HVAC systems that emphasise fresh-air treatment instead of thermal conditioning and distribution. Since the DAC module is placed in the main ventilation airways, aerodynamic restrictions are required. The sorbent module raises the pressure drop rate and fan energy consumption, thus potentially cancelling the energy savings found in HVAC-based DACs. The requirement for low-resistance sorbents to capture supply air (e.g., coated monoliths or structured contactors) minimises pressure drop.

Safety and compatibility also limit choice of materials in this arrangement, especially those for the same purpose. Sorbents can benefit from working at low (usually below 100 °C) regeneration temperatures, have little off-gassing, and are mechanically sound to maintain mechanical integrity as long as air flows steadily through the materials. The low-temperature regeneration process of supply-air DAC, solid sorbent-immobilized amines and other forms of suitable material are preferred (Gall et al., 2016; Hu et al., 2017).

On the whole, supply–air capture integration is a preventive HVAC–DAC approach resulting in cleaner indoor air and removal of $CO_2$. Its efficacy will be directly related to the trade-off between capture efficiency, pressure drop control and safety of the sorbent in the occupied building.

**Figure 8: Conceptual schematic of HVAC-based DAC supply-air capture integration.**

A DAC sorbent module partially eliminates $CO_2$ from ambient outdoor air before it enters the HVAC supply duct and is cooled and delivered to indoor rooms. In sorbent regeneration, low-grade heat (below 100 °C) produces $CO_2$ for storage or usage. DAC module design is sensitive to minimal pressure drop and material safety because it operates directly in the principal ventilation air stream. Instead, $CO_2$ capture units can be mounted in exhaust or return-air ducts, where passengers breathe greater CO2 (800–2000 ppm). This boosts separation and thermodynamic driving force (Zhao et al., 2019). Capture in return air generally concerns interior $CO_2$ rather than net atmospheric recovery unless the $CO_2$ may be used or stored. Hybrid systems maximise net $CO_2$ reduction and IAQ with supply- and exhaust-air capture. Though more sophisticated, these systems are versatile and require greater control.

### 6.3. Infrastructure-Coupled HVAC-DAC: Petrochemical and Desalination System Integration

Unlike conventional direct air capture (DAC), dedicated energy and air-handling facilities raise operational costs and system complexity. By contrast, there is a new operational model for HVAC-integrated DAC that embeds $CO_2$ capture into air-cycle and heat-management systems. This is particularly relevant in the Gulf Cooperation Council (GCC), coastal industrial belt, and desalination cluster, where the energy-water-industrial nexus is dominated by large-scale petrochemical and desalination plants. Petrochemical and desalination plants have large waste-heat streams, huge auxiliary air-handling capacity, and continuous operation, all of which are suitable for DAC based on their heating, ventilation, and air conditioning (HVAC) performance. Waste heat is rejected by petrochemical plant compressors, reformers, distillation columns, and utility systems. Such rejection occurs approximately in the range of 60–120 °C, which is appropriate for low-temperature regeneration of DAC but not power production. Multi-effect distillation (MED) and hybrid MED–TVC units reject large volumes of low-grade heat via condensers and cooling circuits, much in the same sense as large electrically powered desalination plants like SWRO, which utilize extensive HVAC systems to sustain equipment rooms, control areas, and worker environments.

Commercial-level HVAC systems mostly work at 5-10 $h^{-1}$ air change rates by airflow and capture capacity studies (Dittmeyer et al., 2019). Airflow rates for high-rise office buildings of $1.4 \times 10^5$ $m^3$ are between 0.7 and 1.4 million $m^3$ $h^{-1}$. Combined with the installation of an HVAC airflow module, DAC can dramatically reduce energy needs, particularly for capturing $CO_2$ in such buildings. Air movement is imposed—a high energy cost for freestanding DAC plants, designed to satisfy ventilation and workplace safety standards. The rest of the energy use is determined by sorbent regeneration, which can be linked to petrochemical waste heat or desalination. In this study, both low-grade waste heat availability and the regeneration heat requirement of the system are used to evaluate HVAC-integrated DAC for industrial establishments. An uncomplicated energy coupling criterion is as follows:

$$\dot{Q}_{waste} \geq \dot{m}_{CO_2} \cdot \Delta H_{reg} \qquad (7)$$

where $\dot{Q}_{waste}$is the recoverable low-grade waste heat from petrochemical or desalination processes, $\dot{m}_{CO_2}$is the rate of $CO_2$ captured through HVAC-integrated DAC, and $\Delta H_{reg}$is the effective regeneration enthalpy per unit mass of $CO_2$.

When regeneration need can be met by heat normally rejected to the environment, HVAC-based DAC will be energetically appealing. Asymmetry is a design concept. This is very useful in petrochemicals. Hydrogen, ethylene cracking, and refinery hydrotreating generate steady low-grade heat. Air coolers or cooling water cool such heat. Even a tiny quantity of this heat diverted to DAC regeneration can permit continuous $CO_2$ capture without increasing primary fuel use. Since $CO_2$is already a process stream in petrochemical plants, compression or downstream usage systems are easier to integrate.

Desalination facilities complement integration. Thermal desalination systems work naturally with DAC regeneration, unlike electrically driven facilities, which are generally near power stations and industrial centers that create recoverable waste heat. Desalination plants employ mega HVAC systems to regulate humidity, corrosion, and worker comfort and provide ready-built air-contacting infrastructure for DAC. In water-stressed places, DAC and desalination facilities lower the water-energy nexus, reducing $CO_2$ emissions and improving business sustainability.

DAC/HVAC-based petrochemical and desalination plants outperform energy coupling operationally and spatially. DAC modules can be placed between buildings and control rooms and in utility spaces, eliminating the requirement for huge centralised contactors. This versatility allows progressive scale-up during plant expansions or retrofits and reduces capital risk. $CO_2$ removal directly on ventilation air improves occupant air quality and helps remove $CO_2$ from the atmosphere by removing $CO_2$-rich local concentrations.

Successful integration demands good system design. HVAC airflow rates, pressure-drop limits, and regeneration schedules should match industrial operations to avoid safety-related ventilation issues. In coastal desalination, seasonal temperature and humidity fluctuations should be considered in sorbent selection and management. The amount to which energy and money should be channelled toward core industrial processes (including fuel and water manufacturing) and non-essential carbon purification, especially for accounting and legal procedures, is unclear.

HVAC paired with desalination and petrochemical plants makes DAC a system-level opportunity, not a standalone solution. Using low-grade heat fluxes and air-handling devices, this strategy moves DAC deployment from energy-dupolar, customised plants to embedded carbon removal in the industrial ecosystem. Integration puts DAC in equities with businesses that have the volume, persistence, and plumbing to have a significant climate impact while decreasing effective energy usage. The following sections discuss sorbent compatibility, regeneration performance, and aerodynamic performance, which will determine integration.

HVAC systems in large commercial and institutional buildings typically have air change rates of 5-10 $h^{-1}$, varying on use, occupancy, and ventilation rules (Dittmeyer et al., 2019). In an average high-rise office building with a closed air volume of $1.4 \times 10^5$ $m^3$, the air change rates equal the overall ventilation air flow rates of $0.7\text{-}1.4 \times 10^6$ $m^3$ $h^{-1}$. Modern office towers, hospitals, and vast commercial complexes have airflow magnitudes, especially in hot locations where constant ventilation is needed.

Calculating the rate at which $CO_2$ enters the building ventilation system with a $CO_2$ concentration of 420 ppm outdoors, which is similar to the world today, will reveal this. The $CO_2$ capture potential of a large building is 0.4-1.0 t $CO_2$ $h^{-1}$ with a conservative capture efficiency of 40-60% from a DAC unit in the HVAC system, accounting for humidity, sorbent saturation, and regeneration limits. This estimate matches the quantitative characteristics described earlier in this analysis and other DAC integration studies (Dittmeyer et al., 2019; Sodiq, 2023). Table 6 shows the indicative number of HVAC-based DAC capture possibilities for a big office building and its implications to summarise the key considerations leading this assessment.

**Table 6: Indicative HVAC–DAC capture potential (office building scale)**

| Parameter | Typical value |
|---|---|
| Air volume | $1.4 \times 10^5$ $m^3$ |
| Air changes per hour | 5–10 |
| Airflow rate | $0.7\text{–}1.4 \times 10^6$ $m^3$ $h^{-1}$ |
| Outdoor $CO_2$ | 420 ppm |
| Assumed capture efficiency | 40–60% |
| $CO_2$ captured | 0.4–1.0 t $h^{-1}$ |

Derived from Dittmeyer et al. (2019); Sodiq et al. (2023).

Despite the discontinuous building-scale estimate given in Table 6, the link between airflow and capture capacity is continuous (scalable). For a representative set of building sizes and operating conditions, Figure 9 illustrates the link between anticipated $CO_2$ capture potential and HVAC airflow rate.

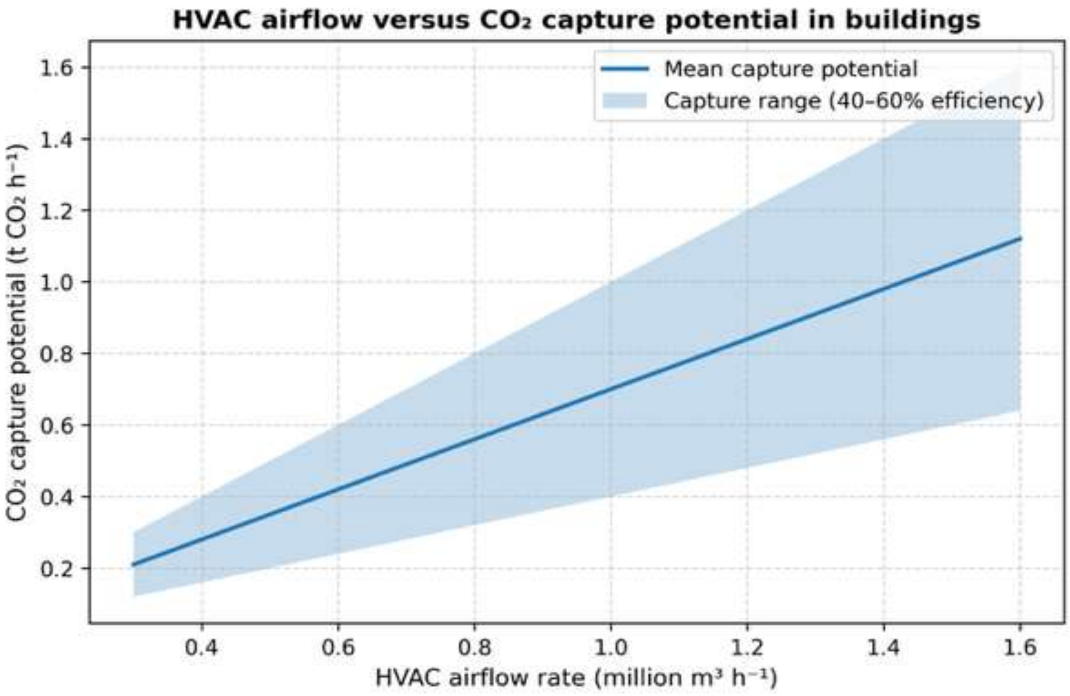

**Figure 9: Potential CO2 collection capacity for building-integrated direct air capture (DAC) systems in relation to HVAC airflow rate**

While the solid line represents the average ability for capture prediction, the highlighted region is a practical operating range, which corresponds with a capture efficiency of about 40–60%. This range includes changes in ambient humidity, regeneration capacity, sorbent performance as well as system integration constraints. The graphic above shows the real-world scalability of the HVAC–based DAC, which essentially states that the higher the ventilation rate, the higher the possibility for $CO_2$ capture, without the need for special air-handling equipment. Table 6 and Figure 9 together present that HVAC-based DAC can achieve a non-trivial $CO_2$ removal rate at the single building level given reasonable assumptions. This is immediately apparent when we bring the cumulative capture potential of HVAC systems into consideration with dense metropolitan building stocks, in order to realise the distributed platform of elimination for atmospheric $CO_2$.

### 6.4. Sorbent selection constraints for HVAC deployment

When direct air capture (DAC) is incorporated into heating, ventilation, and air conditioning (HVAC) systems as opposed to being installed separately or inside an industrial DAC installation, the sorbent selection requirements are also stricter. In contrast to the industrial system, HVAC-controlled DAC is utilised in occupied buildings, where occupant safety, compliance with occupied air standards, and continuous operating robustness are unavoidable limitations. As a result, sorbents must meet extremely strict mechanical, aerodynamic, and health standards in addition to $CO_2$ capture performance requirements.

The pressure drop over the sorbent module, which directly impacts the fan power needed by HVAC systems, is one of the most significant energy and airflow constraints. The extra electrical power required to overcome this pressure decrease can be expressed as follows:

$$P_{fan} = \frac{\Delta P \cdot Q}{\eta_{fan}}$$

where $\Delta P$is the pressure drop across the DAC module, Qis the volumetric airflow rate, and $\eta_{fan}$is the fan efficiency. The high airflow rates characteristic of HVAC operation, even slight increases in pressure drop can result in significant increases in energy use at the building scale. To prevent high fan energy penalties, sorbents must be arranged in mechanically stable, low-resistance forms (e.g., monoliths, structured beds, or coated surfaces).

Low regeneration temperature is a prerequisite for HVAC deployment in addition to aerodynamic concerns. Because they exceed the temperature limits of HVAC components and pose safety hazards, sorbents that require regeneration temperatures above about 100 °C are typically incompatible with building systems. Chemical safety is also crucial; sorbents should have low volatility, insignificant off-gassing, and resistance to degradation products that could impair indoor air quality over time.

These limitations immediately rule out a number of high-capacity sorbents that are frequently suggested for industrial DAC, such as those that require regeneration at high temperatures and those that use liquid alkaline solutions. Rather, the literature focuses on a more limited class of options that strike a compromise between capture performance, safety, and operational compatibility. The most established choice is low-volatility solid amines immobilized on stable supports; they offer low-temperature regeneration and proven DAC performance, but long-term degradation remains a concern. Because of their structural stability, moisture tolerance, and non-toxicity, inorganic sorbents, such as carbon nitrides, have become attractive substitutes. As long as solvent residues, metal leaching, and mechanical fragility are adequately addressed, metal–organic frameworks (MOFs) produced by environmentally friendly methods have attracted interest for HVAC applications (Kumar et al., 2020).

### 6.5. Implications for energy and system integration

The primary advantage of HVAC-integrated direct air capture (DAC) is avoiding unnecessary air-handling energy, which is one of the primary operational costs of freestanding DAC systems. In conventional DAC plants, massive fans are required to circulate large volumes of ambient air through specialised contactors, which means that air movement rather than $CO_2$ separation itself contributes for a considerable amount of overall energy demand (Keith et al., 2018). In contrast, HVAC-based DAC makes use of the air's existing circulation and thermal conditioning to satisfy indoor ventilation and comfort requirements. As a result, the primary causes of the higher energy burden related to DAC integration are sorbent regeneration and modest increases in fan power brought on by the additional pressure drop over the capture modules. This change in energy consumption has important system-level implications. By isolating DAC performance from specialised air-handling equipment, HVAC-integrated solutions shift the major energy focus from airflow generation to regeneration efficiency. Therefore, improvements in sorbent regeneration techniques, such as lowering regeneration temperature, removing water co-adsorption penalties, or synchronising regeneration with present thermal loads, are the most effective levers for raising total system efficiency. Figure 10 illustrates this distinction by comparing the energy flow distribution in standalone DAC systems and HVAC-integrated DAC solutions.

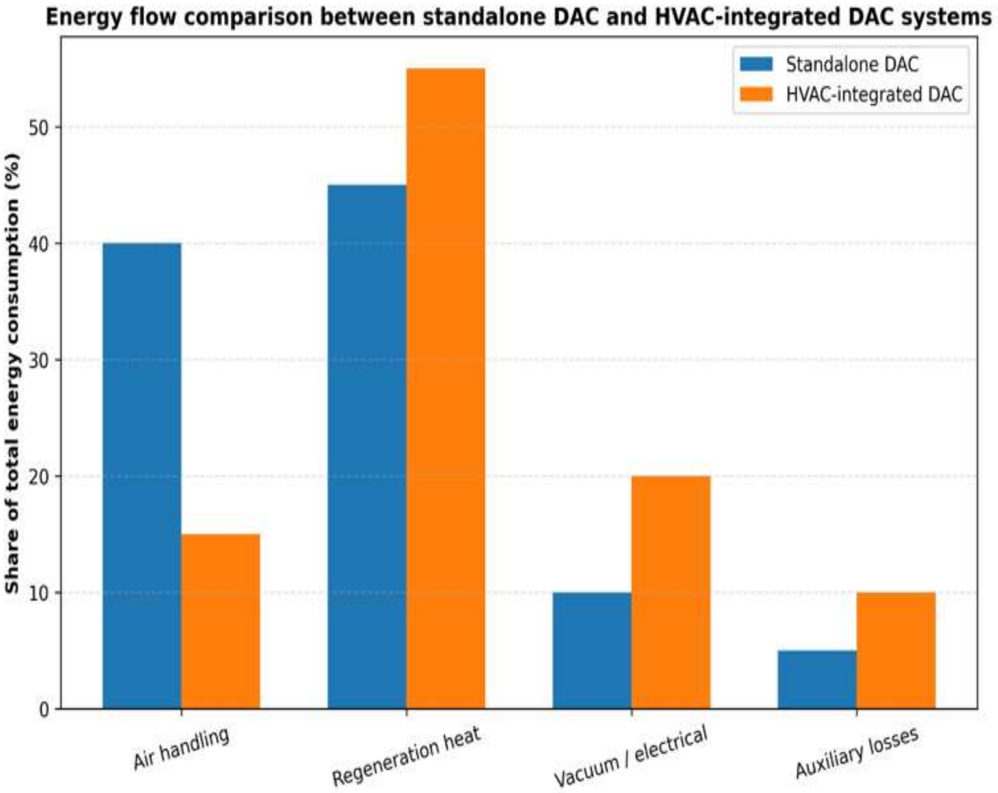

**Figure 10: Comparison of energy flow between HVAC-integrated direct air capture (DAC) arrangements and freestanding DAC systems**

A significant amount of the total energy consumption of standalone DAC systems is attributed to the air handling required to treat huge volumes of ambient air. HVAC-integrated DAC, on the other hand, greatly reduces incremental air-handling energy and moves the primary energy demand toward sorbent regeneration by making use of pre-existing ventilation flows. This presentation shows how HVAC-based DAC can boost overall system efficiency while utilising existing infrastructure. Although there are obvious energy benefits to this integration, there are also major operational and control issues. Regeneration cycles should be properly synchronised with changes in HVAC load to prevent compromising indoor air quality or thermal comfort. Adaptive control techniques are needed because seasonal variations in humidity might affect sorbent performance and regeneration rate. Strict reliability and safety requirements are also necessary for continuous operation in occupied buildings in order to guarantee continuous ventilation performance. The problems need be resolved in order to transform the anticipated advantages of HVAC-integrated DAC into a successful and reliable deployment.

### 6.6. Research gaps, limitations, and system-level consequences

Although it presents a viable method of lowering the effective energy and infrastructure cost of collecting CO2 from the atmosphere, the conceptual and experimental direct air capture (DAC) based on HVAC is not yet economically viable. Before this approach can be widely implemented, a number of important problems need to be addressed. The most important of these is the sorbents' long-term resilience to the continuous running of HAV systems, which subject the material to repeated cycles of regeneration in addition to changes in humidity, oxygen, and particulate matter levels. It has not been determined whether HVAC-based DAC is feasible, especially in terms of long-term stability.

Strong life-cycle evaluation methods that, when integrated into building systems, can verify net-negative performance are also crucial. This would entail figuring out where the CO2 is eventually stored or used, as well as taking into account the extra energy needed for regeneration, control needs, and maintenance effects. HVAC-based DAC presents a unique economic problem since it is difficult to distinguish between the costs and benefits of improving indoor air quality and removing carbon emissions, especially in regulatory and policy environments where both services are subject to distinct incentive frameworks.

Despite these drawbacks, the discussion in this section shows that HVAC-integrated DAC represents a significant change in the possible design and implementation of DAC systems. Based on the existing thermal and air-handling infrastructure, HVAC systems transform buildings into passive energy receivers and active parts of distributed carbon removal systems. Combining these two goals—improving indoor air quality and simultaneously reducing atmospheric CO2—offers a scalable substitute for mega-centralized initiatives. Developments in sorbent safety, regeneration efficiency, and regulatory alignment will ultimately determine the success of HVAC-based DAC. This supports the review's general finding that system-level integration—rather than component optimization—will determine the viability of direct air capture systems in the future.

## 7. Conclusion

This systematic and comprehensive survey of direct air capture (DAC) technology has detailed sorption approaches, regeneration, novel technologies, emerging applications, current developments, and innovative adaptations with existing HVAC systems of DAC technologies. The conversation overall shows that DAC is a theoretical concept and an early industrial technology in its infancy and sheds some light on some of the infrastructure, energy and financial obstacles to its wide application. Previously, DAC research focused on thermodynamic feasibility and industrial counterparts, particularly those in liquid-absorbing systems with alkali salts. These devices demonstrated ideal capture performance at the need for large energy and capital investments at high-temperature regeneration. Following developments in solid sorbent technologies, especially amine-functionalized materials, future modular DAC architectures can now be regenerated at much lower temperature. This report shows that even though improved sorbent chemistry and air-contactor design, lower adsorption capacity by itself does not directly reduce system-level energy consumption and costs. Thermal, vacuum-assisted, moisture-mediated, electrochemical, and crystallization regeneration options all are costly compared to the low thermodynamic work required for $CO_2$ extraction from air. Water co-adsorption resulted to be a strong predictor of the efficient regeneration energy, frequently superseding the CO2 adsorption heat that arises from its intrinsic nature. This gives us an understanding of why chemisorption dominates DAC practice today, even though the binding enthalpy is greater due to it being able to accurately capture in humid-ambient regions and have a constant regeneration performance at the system scale. The comparison of chemisorption and physisorption could serve to shed more light on why physisorption-based DAC has not been exploited in the industry. Despite the low intrinsic adsorption energies and rapid kinetics of physisorbent systems, their extensive humidity susceptibility prevents working capacity as well as increases regeneration energy requirement in real operating conditions.

Applications: The introduction of physisorption-based DACs for use in future is to explore the concept of developing new, specifically special classes of materials having hyper-selectivity to CO2 and very impervious to water vapour.

The key finding of the review is that DAC performance is as much about integration as it is about isolation. One great example of so many of the paradigm shifts, for example, to consider buildings as distributed air-contacting infrastructures that can remove carbon from air rather than only deliver it as carbon footprint, is the novel idea of HVAC-integrated DAC. HVAC systems utilize energy to dehumidify and condition immense quantities of air. A practical approach to improving the indoor air quality is to reduce the additional energy to facilitate the cleaning, as this is one of the most critical elements of operating costs of standalone DAC systems and often can be ameliorated with the addition of DAC capacity to a fixed hardware base. The HVAC-DAC concept is another socio-technical angle of DAC implementation. Unlike other centralized, distant facilities in DAC, HVAC-systems perform in close proximity to end users, which provides two benefits: higher occupant productivity and health with reduced indoor CO2 and increased atmospheric CO2 capture at scale. HVAC-inspired DAC, and centralised geological storage facilities and DAC plants could turn cities into drivers of negative-emissions initiatives if it were to spread across high urban density.

Nevertheless, there remain significant risks to consider before HVAC-DAC emerges as a reality rather than a vision. Tight sorbent stability and safety requirements are met, pressure dips are minimised, regeneration synchronised with HVAC duty cycles, and heavy-duty life-cycle costs are considered in order for net-negative performance to achieve a healthy level. In order to address these problems, legislators, building scientists, materials chemists, and chemical engineers have to cross discipline lines. A number of future options for DAC will be determined by five avenues:

1. System-level optimisation, which is prioritising regeneration efficiency, integration with air handling and humidity management over the measurement of individual materials.
2. Low-quality electrical energy and heat services like waste heat, geothermal, district energy, and renewable energy.
3. Scenarios for distributed deployment, like town HVAC systems and modular DAC systems.
4. Stable water-insoluble sorbents that are able to react with oxygen and humidity when exposed more than once.
5. Policy and evaluation frameworks that are based on the recognition of co-benefits such as improved indoor air quality and infrastructure carbon sequestration.

In conclusion, DAC is unlikely to become one, all-encompassing solution to climate change. Instead it will be a portfolio of technology with centralised industrialization integrated to distributed and infrastructure based approaches like HVAC-DAC. Through this systems paradigm adopting, DAC will become a scalable part of an efficient urban and industrial system, and an energy efficient niche technology.

## References

1. Azarabadi, H., & Lackner, K. S. (2019). A sorbent-focused techno-economic analysis of direct air capture. Applied Energy, 250, 959–975. https://doi.org/10.1016/j.apenergy.2019.04.012
2. Beuttler, C., Charles, L., & Wurzbacher, J. (2019). The role of direct air capture in mitigation of anthropogenic greenhouse gas emissions. Frontiers in Climate, 1, 10. https://doi.org/10.3389/fclim.2019.00010
3. Bos, M. J., Pietersen, S., & Brilman, D. W. F. (2019). Production of high purity $CO_2$ from air using solid amine sorbents. Chemical Engineering Science: X, 2, 100020. https://doi.org/10.1016/j.cesx.2019.100020
4. Custelcean, R., Garrabrant, K. A., Agullo, P., & Williams, N. J. (2021). Direct air capture of $CO_2$ with aqueous peptides and crystalline guanidines. Cell Reports Physical Science, 2(4), 100385. https://doi.org/10.1016/j.xcrp.2021.100385
5. Dittmeyer, R., Klumpp, M., Kant, P., & Ozin, G. (2019). Crowd oil not crude oil. Nature Communications, 10(1), 1818. https://doi.org/10.1038/s41467-019-09685-x
6. Erans, M., Sanz-Pérez, E. S., Hanak, D. P., Clulow, Z., Reiner, D. M., & Mutch, G. A. (2022). Direct air capture: Process technology, techno-economic and socio-political challenges. Energy & Environmental Science, 15(4), 1360–1405. https://doi.org/10.1039/D1EE03523A
7. Gutknecht, V., Snæbjörnsdóttir, S. Ó., Sigfússon, B., Aradóttir, E. S., & Charles, L. (2018). Creating a carbon dioxide removal solution by combining rapid mineralization of $CO_2$ with direct air capture. Energy Procedia, 146, 129–134. https://doi.org/10.1016/j.egypro.2018.07.017
8. Jung, K.-S., Kim, N.-S., Lee, J.-D., Hwangbo, Y., Son, B.-S., & Lee, B.-K. (2011). The association of subjective symptoms of students and indoor air quality in private academic facilities. Epidemiology, 22, S45–S46. https://doi.org/10.1097/01.ede.0000391800.92289.ce
9. Keith, D. W., Holmes, G., St. Angelo, D., & Heidel, K. (2018). A Process for Capturing $CO_2$ from the Atmosphere. Joule, 2(8), 1573–1594. https://doi.org/10.1016/j.joule.2018.05.006
10. Kim, S., Choi, M., Kang, J. S., Joo, H., Park, B. H., Sung, Y.-E., & Yoon, J. (2021). Electrochemical recovery of LiOH from used $CO_2$ adsorbents. Catalysis Today, 359, 83–89. https://doi.org/10.1016/j.cattod.2019.06.056
11. Kumar, A., Madden, D. G., Lusi, M., Chen, K., Daniels, E. A., Curtin, T., Perry, J. J., & Zaworotko, M. J. (2015). Direct air capture of $CO_2$ by physisorbent materials. Angewandte Chemie International Edition, 54(48), 14372–14377. https://doi.org/10.1002/anie.201506952
12. McQueen, N., Psarras, P., Pilorgé, H., Liguori, S., He, J., Yuan, M., Woodall, C. M., Kian, K., Pierpoint, L., Jurewicz, J., Lucas, J. M., Jacobson, R., Deich, N., & Wilcox, J. (2020). Cost analysis of direct air capture and sequestration coupled to low-carbon thermal energy in the United States. Environmental Science & Technology, 54(12), 7542–7551. https://doi.org/10.1021/acs.est.0c00476

13. Mukherjee, S., Sikdar, N., O'Nolan, D., Franz, D. M., Gascón, V., Kumar, A., Kumar, N., Scott, H. S., Madden, D. G., Kruger, P. E., Space, B., & Zaworotko, M. J. (2019). Trace $CO_2$ capture by an ultramicroporous physisorbent with low water affinity. Science Advances, 5(11), eaax9171. https://doi.org/10.1126/sciadv.aax9171
14. Persily, A. (2015). Challenges in developing ventilation and indoor air quality standards: The story of ASHRAE Standard 62. Building and Environment, 91, 61–69. https://doi.org/10.1016/j.buildenv.2015.02.026
15. Realmonte, G., Drouet, L., Gambhir, A., Glynn, J., Hawkes, A., Köberle, A. C., & Tavoni, M. (2019). An inter-model assessment of the role of direct air capture in deep mitigation pathways. Nature Communications, 10(1), 3277. https://doi.org/10.1038/s41467-019-10842-5
16. Sanz-Pérez, E. S., Murdock, C. R., Didas, S. A., & Jones, C. W. (2016). Direct Capture of $CO_2$ from Ambient Air. Chemical Reviews, 116(19), 11840–11876. https://doi.org/10.1021/acs.chemrev.6b00173
17. Shi, X., Ming, H., Shakkottai, S., Xie, L., & Yao, J. (2019). Nonintrusive load monitoring in residential households with low-resolution data. Applied Energy, 252, 113283. https://doi.org/10.1016/j.apenergy.2019.05.086
18. Shi, X., Xiao, H., Liao, X., Armstrong, M., Chen, X., & Lackner, K. S. (2018). Humidity effect on ion behaviors of moisture-driven $CO_2$ sorbents. The Journal of Chemical Physics, 149(16), 164708. https://doi.org/10.1063/1.5027105
19. Shu, Q., Legrand, L., Kuntke, P., Tedesco, M., & Hamelers, H. V. M. (2020). Electrochemical regeneration of spent alkaline absorbent from direct air capture. Environmental Science & Technology, 54(14), 8990–8998. https://doi.org/10.1021/acs.est.0c01977
20. Sodiq, A., Abdullatif, Y., Aissa, B., Ostovar, A., Nassar, N., El-Naas, M., & Amhamed, A. (2023). A review on progress made in direct air capture of $CO_2$. Environmental Technology & Innovation, 29, 102991. https://doi.org/10.1016/j.eti.2022.102991
21. Van Der Spek, M., Bardow, A., Baum, C. M., Bolongaro, V., Dufour-Décieux, V., Esch, C., Fritz, L., Garcia, S., Hamann, C., Hondeborg, D., Kiani, A., Lueck, S., Patel, S. K., Peh, S. B., Pisciotta, M., Psarras, P., Repke, T., Sáenz-Cavazos, P. A., Schulte, I., … Minx, J. C. (2025). An ecosystem of carbon dioxide removal reviews – part 1: Direct air $CO_2$ capture and storage. Energy & Environmental Science, 18(22), 9713–9785. https://doi.org/10.1039/D5EE01732G
22. Wang, T., Lackner, K. S., & Wright, A. (2011). Moisture swing sorbent for carbon dioxide capture from ambient air. Environmental Science & Technology, 45(15), 6670–6675. https://doi.org/10.1021/es201180v