

# Water management and heat integration in direct air capture systems

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Water plays a pivotal role in direct air capture technologies, impacting materials, regeneration processes and product streams. CO<sub>2</sub> removal methods, including absorption, adsorption and electrochemical techniques, encounter challenges associated with water, thus reducing their efficacy. Water fluxes into and out of aqueous solvents affect the concentration and overall capture performance. Solid adsorbents co-adsorb water in greater quantities than CO<sub>2</sub> and will require effective strategies to address the substantial energy penalty associated with water desorption each cycle. Water-management strategies are imperative for economic viability and minimizing the environmental impact, but the high energy intensity necessitates heat recovery techniques. Feed dehydration can be combined with strategic heat integration of process streams and standard recovery techniques for front-end water management. For back-end approaches, mechanical vapor compression is a viable solution for coupling heat integration with water management, and we highlight potential heat recovery benefits of three implementation methods. Further research into variable climate conditions and water quality impacts is essential for the success of direct air capture technologies.

Direct air capture (DAC) is a promising technological solution for mitigating the rising global average temperatures and associated consequences. Although various absorption, adsorption and electrochemical separation methods have been proposed for removing CO<sub>2</sub> from air, most struggle with the challenge of meeting cost targets<sup>1–3</sup>. These processes, though different in material structure, cycle design and unit configurations, encounter a common adversary that limits their economic viability—water. Water plays an integral role in every step of DAC. It is present in the air fed to the system (at concentrations that are one to two orders of magnitude higher than CO<sub>2</sub>), as a substantial component of absorption solvents, as a potential heating fluid for regeneration, and as a by-product of the carbon capture process. In these roles, water impacts productivity, energy requirements and material lifetime, collectively influencing the overall cost of the DAC process<sup>4</sup>. Effectively managing the challenges posed by water is critical for the success of DAC systems.

Water-management research has predominantly focused on engineering materials to mitigate water-related issues, such as reducing

solvent evaporation rates or developing hydrophobic adsorbents. However, these methods are often material-specific and limit the range of materials and processes that can be used. Many of the chemical properties that enable materials to interact with CO<sub>2</sub> also cause them to interact with water, making it challenging to achieve affinity for one but not the other. An alternate and more broadly applicable solution is to engineer the DAC system to manage water. Despite the potential high energy penalties associated with water management, coupling these strategies with heat integration can substantially lower the energy intensity and carbon footprint.

We first provide a brief overview of five DAC technologies, emphasizing the impacts of water on each to underscore the critical need for water management. Subsequently, we delve into five water-management strategies, including two front-end (that is, before the DAC unit) and three back-end (after the DAC unit) approaches. For each strategy, we highlight methods for heat integration and outline potential energy recovery ranges, offering a comprehensive perspective on the potential synergy between water management and heat recovery in DAC systems.

## Importance of water management in DAC technologies

### Temperature swing absorption

Temperature swing absorption (also known as scrubbing or stripping) is a well-established method for the cleanup of post-combustion flue gas, and its applicability for dilute CO<sub>2</sub> removal has been demonstrated as well<sup>5,6</sup>. The process begins with passing air over a solvent that has a high affinity for CO<sub>2</sub>. The solvent binds the CO<sub>2</sub>, and then the CO<sub>2</sub>-rich solvent is heated to release the captured CO<sub>2</sub> (Fig. 1a). Alkali hydroxides are commonly employed solvents in DAC processes because of their high affinity for CO<sub>2</sub> (with heats of CO<sub>2</sub> adsorption exceeding 100 kJ mol<sup>-1</sup>)<sup>7,8</sup>.

The type of alkali metal cation in the solvent determines the process configuration. For example, the reaction of calcium hydroxide with CO<sub>2</sub> yields a calcium carbonate precipitate, which can be filtered and calcined to produce calcium oxide, releasing CO<sub>2</sub> (ref. 8). The calcium oxide is then hydrated to revert to calcium hydroxide. Although the ability to filter the insoluble product facilitates regeneration, the low solubility of calcium hydroxide restricts the hydroxide concentration and amount of CO<sub>2</sub> removal achievable.

To overcome this limitation, solvents like potassium or sodium hydroxide, with higher solubilities, can be used. However, the resulting sodium/potassium carbonate is soluble, so causticization with calcium hydroxide is used to precipitate calcium carbonate, which can then be filtered and calcined. Although high binding strength is favorable for absorption, these processes have high regeneration energy penalties, particularly due to the energy-intensive calcination at temperatures above 700 °C, which is reported to require 180 kJ mol<sup>-1</sup> CO<sub>2</sub> (ref. 8).

Air humidity introduces additional issues. When air and solvent are in contact, the water content in each approaches equilibrium. Low air humidity prompts evaporation from the solvent, resulting in substantial water loss over time. Water evaporation will increase the solution molarity and consequently increase the CO<sub>2</sub> capture rate, and the reaction of CO<sub>2</sub> and alkali hydroxides generates water as a by-product, offsetting some water loss<sup>9</sup>. For air with a temperature of 21 °C and relative humidity (RH) of 69%, the net water consumption ranges from 4.7 to 6.6 t per tCO<sub>2</sub> (refs. 7,9), but this can reach 20–50 t per tCO<sub>2</sub> in hot and dry conditions<sup>10</sup>. High-molarity solutions have a lower vapor pressure and will therefore have less water evaporation. The solvent molarity can be used as a knob to tune evaporation rates based on the ambient conditions<sup>11</sup>. Conversely, high air humidity leads to water absorption into the solvent. The addition of water will reduce the solvent concentration, lower the CO<sub>2</sub> capture rate and increase the sensible heat required for desorption. Aqueous amine solvents are used less frequently for dilute CO<sub>2</sub> applications but will face similar challenges with humidity.

Ionic liquids have emerged as an alternate absorption-based DAC technology to address water volatility issues and enable structural design of the solvent. Although they have lower heats of adsorption (typically between –40 and –80 kJ mol<sup>-1</sup>), they face additional challenges including high viscosities and moderate cycle capacities for dilute CO<sub>2</sub> (ref. 12). Despite having no inherent water content, humidity in the feed can be problematic for ionic liquids. Absorption of water into the ionic liquid from humid air occurs at high relative humidities<sup>13</sup>. The impact of humidity on CO<sub>2</sub> capture performance varies depending on the specific ionic liquid's structure and functional groups, and humidity has been demonstrated to enhance capacity for some ionic liquids and reduce it for others<sup>14,15</sup>.

### Electrochemistry

Several absorption-based DAC processes leverage electrochemical methods, including electrophile displacement (for example, electrochemically mediated amine regeneration, EMAR), electrochemically mediated pH swings (for example, KOH scrubbing with bipolar membrane electrodialysis, BPMED) and redox-active compounds<sup>16–19</sup>. Electrophile displacement and electrochemically mediated pH swings utilize scrubbing for the absorption step, but then release CO<sub>2</sub>

electrochemically rather than with a thermal swing (Fig. 1b)<sup>19</sup>. Electrochemical regeneration addresses challenges associated with operating at higher temperatures, such as sorbent degradation and evaporation, while also allowing for the utilization of renewable energy sources<sup>18</sup>.

In EMAR, the CO<sub>2</sub>-rich amine solution is introduced into the anode compartment of an electrochemical cell with a metallic copper electrode<sup>19</sup>. On applying voltage, the electrode undergoes oxidation, releasing metal ions that bind to the amine and displace CO<sub>2</sub> (ref. 19). A condenser is then used to separate the gaseous CO<sub>2</sub> from the solution. BPMED utilizes a voltage across a series of ion-exchange and bipolar membranes to partition the CO<sub>2</sub>-rich alkali solvent into an acid and base<sup>20</sup>. CO<sub>2</sub>, in the form of carbonate/bicarbonate, moves to the acidic solution, where it is converted into CO<sub>2</sub> gas and exits the solution<sup>20</sup>.

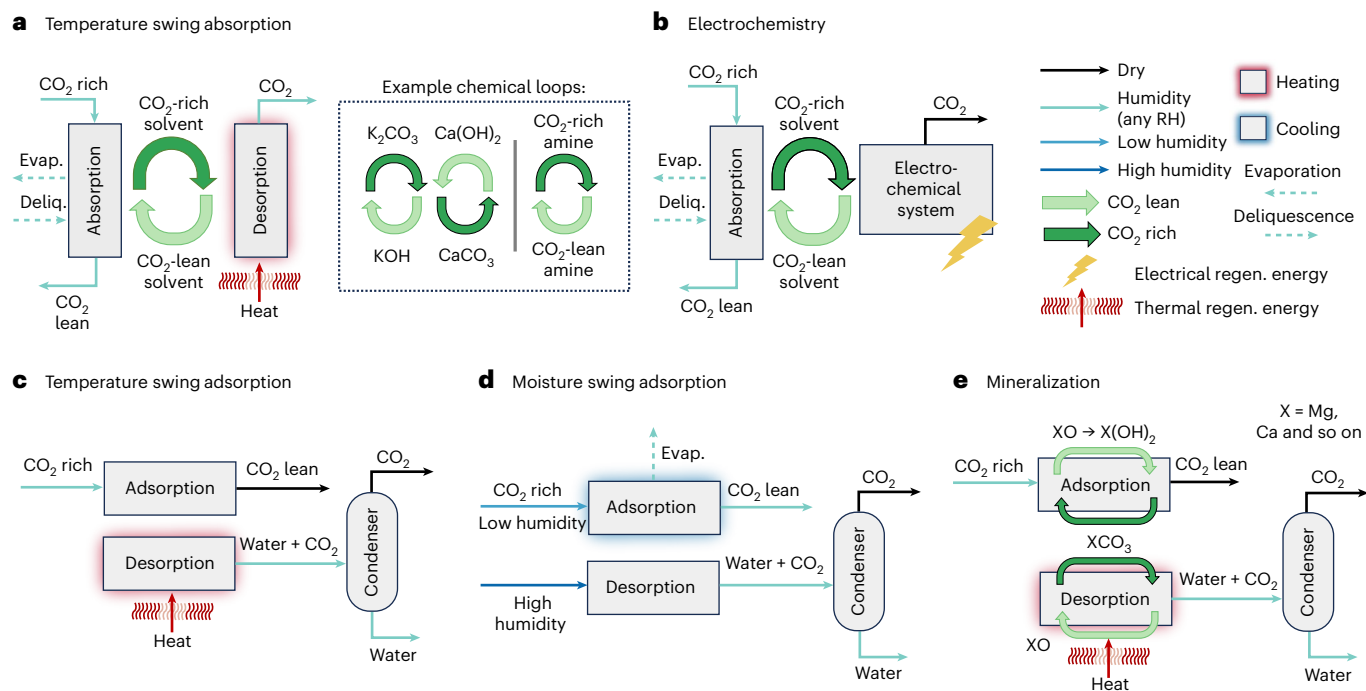
In the absorption unit, these electrochemical technologies face the same evaporation and deliquescence challenges discussed previously. The air humidity and solution volatility (dependent on solution properties and molarity) will again influence the amount of water flux. Conversely, changes in water concentration in the absorption unit can impact the molarity of the solution entering the electrochemical desorption unit, potentially negatively affecting performance. For example, the introduction of water can disrupt the structure of ionic liquids, impacting transport properties and reducing the electrochemical window<sup>13</sup>. The impact of humidity will need to be carefully considered in processes using the same solvent for both capture and electrochemical conversion, as humidity often enhances one side of the cycle while hindering the other.

CO<sub>2</sub> capture with redox-active compounds relies on cycles of electrochemical reduction and oxidation. During the reduction step, the compound is converted to a nucleophile that binds CO<sub>2</sub>, and subsequent oxidation of the compound releases the captured CO<sub>2</sub> (ref. 21). For example, 1-aminopyridinium nitrate, which is inactive for CO<sub>2</sub> in neutral aqueous solution, can be reduced to produce an electron-rich radical that captures CO<sub>2</sub> to form bicarbonate<sup>22</sup>. The bicarbonate solution is then oxidized to release CO<sub>2</sub> (ref. 22). Other examples of redox-active compounds include quinones and phenothiazines<sup>21,23</sup>. For some redox-active compounds, aqueous conditions are crucial for functionality because humidity stabilizes the radical species<sup>22</sup>. Evaporation in low-humidity environments could lead to instability and diminished performance of these compounds.

### Temperature swing adsorption

Solid adsorbent DAC technologies address solvent evaporation issues and reduce regeneration energy requirements. Similar to temperature swing absorption, the process involves directing air over a solid adsorbent contactor to adsorb CO<sub>2</sub>, followed by heating the adsorbent, either directly or indirectly, to release the CO<sub>2</sub> (Fig. 1c). Direct heating methods include steam heating, where steam offers the advantage of providing both temperature and concentration driving forces for desorption. Indirect heating requires either a contactor geometry that facilitates the flow of hot fluid (for example, hot water) adjacent to the sorbent or the use of resistance heating. Vacuum can be employed to remove oxygen from the bed before heating and enhance the concentration driving force during desorption, but the additional electrical energy required for this must be considered.

The impact of air humidity on solid adsorbents varies. Most DAC adsorbents have an affinity for both CO<sub>2</sub> and water, resulting in co-adsorption in humid air streams<sup>24</sup>. Typically, water uptake in solid adsorbents is much higher than CO<sub>2</sub> uptake (1 mol of CO<sub>2</sub> versus 30 mol of H<sub>2</sub>O is not uncommon) due to the low concentration of CO<sub>2</sub> in air compared to water (400 ppm versus 1–4%). Some materials exhibit cooperative adsorption, in which water enhances CO<sub>2</sub> uptake through new speciation or improved rates<sup>25</sup>. Amine-functionalized solid sorbents exemplify cooperative adsorption, where humidity enhances the CO<sub>2</sub> uptake by promoting bicarbonate formation with a 1:1 CO<sub>2</sub>:amine stoichiometry<sup>25</sup>. However, water can also impede CO<sub>2</sub>



**Fig. 1 | Types of DAC process, with water and heat inputs highlighted.** **a**, Temperature swing absorption with liquid solvents. **b**, Electrochemical regeneration of liquid solvents. **c**, Temperature swing adsorption. **d**, Moisture swing adsorption. **e**, Mineralization using alkali hydroxides. Evap., evaporation; Deliq., deliquescence; regen, regeneration.

uptake, as observed in metal–organic frameworks where CO<sub>2</sub> competes with H<sub>2</sub>O for sites. Liquid-phase water in the pores after capillary condensation at high RH can hinder CO<sub>2</sub> transport, and water can physically degrade the sorbent in some cases<sup>26</sup>. Water stability issues are especially prevalent in metal–organic frameworks because of their metal–ligand coordination bonds<sup>27,28</sup>.

Water not only affects productivity but also influences the energy requirements of the process. There is a substantial energy penalty associated with adsorbing and desorbing water each cycle, which raises the cost of DAC<sup>29</sup>. For example, at 30 °C and 50% RH, air contains about 50 times more H<sub>2</sub>O than CO<sub>2</sub>. With a CO<sub>2</sub>-to-H<sub>2</sub>O selectivity of 1.0, 50 moles of H<sub>2</sub>O adsorb for every 1 mole of CO<sub>2</sub>, requiring ~50 GJ per tCO<sub>2</sub> to desorb the water each cycle. Many adsorbents have CO<sub>2</sub>/H<sub>2</sub>O selectivities lower than 1.0, resulting in even higher energy penalties. The magnitude of the energy penalty will depend on the air humidity and temperature, which will influence the amount of water adsorption. However, it has been demonstrated that even at lower temperatures where the water concentration in the air is low, the latent heat for water desorption can still contribute substantially to the regeneration energy consumption<sup>30</sup>. For air at –20 °C and 70% RH, the latent heat required for water desorption constituted 50% of the total regeneration energy consumption, whereas the CO<sub>2</sub> latent heat contributed only 5% (ref. 30).

### Moisture swing adsorption

Moisture swing adsorption (MSA; Fig. 1d) utilizes water for regeneration instead of heat. The CO<sub>2</sub> affinity of MSA sorbents, predominantly amine-based ion-exchange resins, changes with varying RH<sup>31</sup>. A crucial step is pretreatment of the ion-exchange resin to replace the original anions with hydroxide or carbonate ions<sup>32</sup>. In low-humidity conditions (less than 20% RH), the resins adsorb CO<sub>2</sub>, forming bicarbonate. The subsequent introduction of a high-humidity stream (above 60% RH) facilitates the desorption of CO<sub>2</sub>. As the process cycles back to the low-humidity adsorption step, the water adsorbed during high-humidity desorption evaporates. The efficacy of MSA is strongly linked

to humidity, which serves as the driving force for its operation. Thus, it is clear that changes in air humidity and temperature will have a substantial impact on MSA performance.

### Mineralization

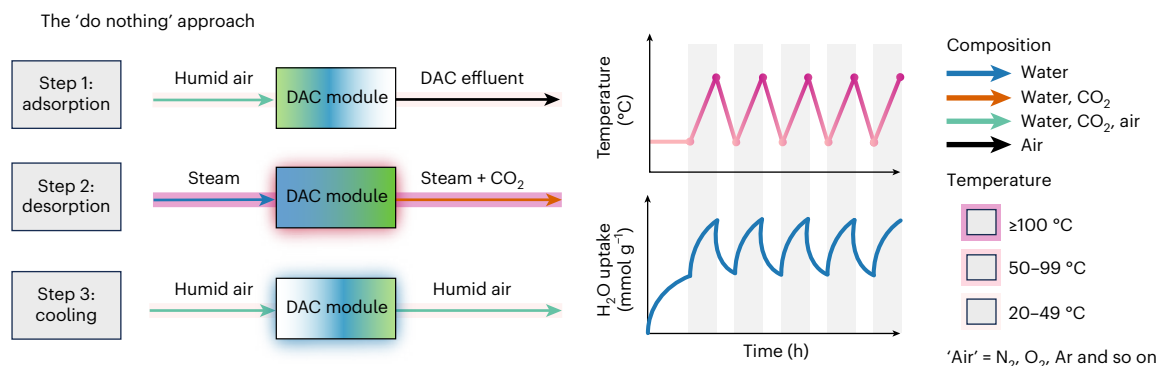
Carbon mineralization utilizes the conversion of oxides such as CaO or MgO into carbonates to capture CO<sub>2</sub> from the atmosphere (Fig. 1e)<sup>33,34</sup>. When distributed onto land or other surfaces, MgO reacts with water to form Mg(OH)<sub>2</sub>, and then with atmospheric CO<sub>2</sub> to form magnesite (MgCO<sub>3</sub>) and other Mg-carbonate minerals. The generated MgCO<sub>3</sub> is then calcined at temperatures ranging from 350 to 600 °C to release the CO<sub>2</sub> and produce solid MgO. This DAC technology eliminates blower costs, but there is still a notable energy cost for the regeneration process. In low-humidity environments where the conversion of MgO to Mg(OH)<sub>2</sub> is slower, the addition of extra water to the sorbent can expedite the process. The amount of extra water will probably depend on the air humidity. Akin to other solid adsorbents, some water is released along with the captured CO<sub>2</sub>, incurring an associated energy penalty<sup>33</sup>. The water is condensed to yield the CO<sub>2</sub> product.

### Strategies for water management with heat integration

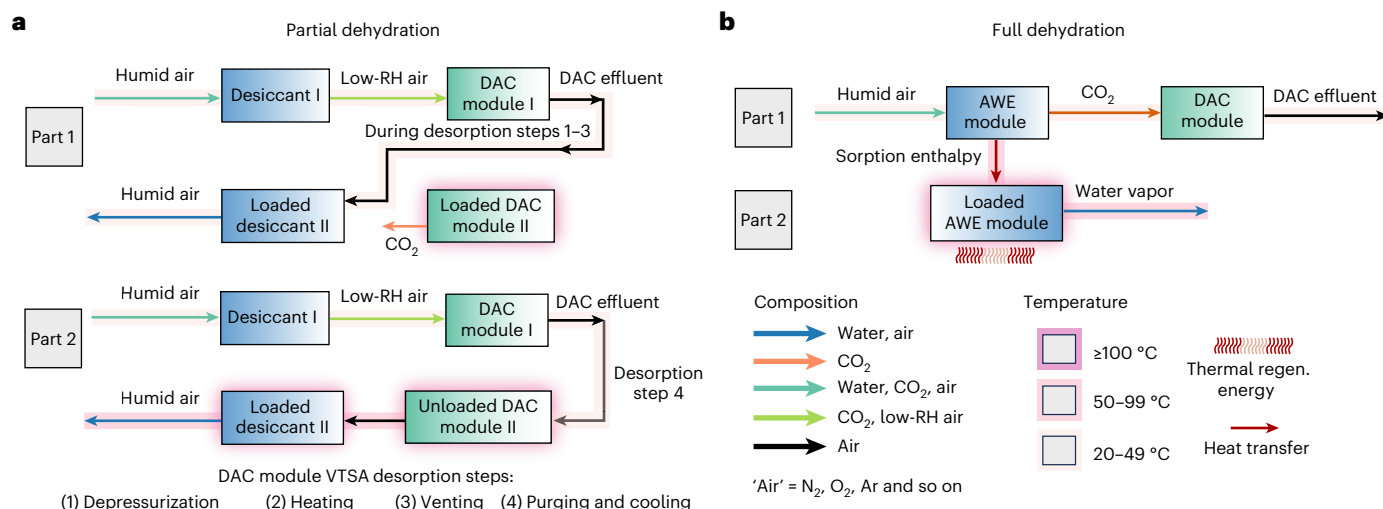
It is clear that all DAC technologies must contend with water. In this section we articulate several heat-integrated water-management strategies. Our focus is largely on solid adsorbent systems, but the strategies described can generally be applied to absorption and electrochemical methods.

#### The ‘do-nothing’ approach

We start by considering a scenario devoid of water management (Fig. 2), setting the stage for subsequent comparisons. In the adsorption step, both water and CO<sub>2</sub> adsorb onto the solid adsorbent from the humid air. For regeneration, steam is commonly employed, producing a CO<sub>2</sub>-rich stream that can be sent to a separator to condense the water and generate a high-purity CO<sub>2</sub> stream (as in Fig. 1c). Following



**Fig. 2 | Temperature swing adsorption with no water management.** Schematic illustrating the steps of a DAC process in which no water-management strategy is used. The DAC-module temperature and water-uptake cyclic profiles are shown on the right.



**Fig. 3 | Front-end engineering strategies for water management with heat integration.** **a**, Partial dehydration strategy. The desorption steps correspond to a vacuum-temperature swing adsorption (VTSA) process. **b**, Full dehydration strategy.

steam-induced CO<sub>2</sub> desorption, the system must be cooled before adsorption to prevent sorbent oxidation. Introducing a slight vacuum and decreasing the pressure in the module will cause the condensed water to evaporate. This process absorbs heat and rapidly cools the module<sup>35</sup>. The evaporated water is subsequently removed from the system using air and is typically exhausted to the environment.

Throughout the cycle of adsorption, desorption and evaporative cooling, the water loading on the module fluctuates. The steam used for regeneration is at a higher RH than the air feed, resulting in additional water adsorption onto the module (above the amount adsorbed during the CO<sub>2</sub> adsorption step). Conversely, during the evaporative cooling step, the water uptake reduces as the water evaporates. This cycle of water adsorption and desorption continues, but the total amount does not fall below the initial amount adsorbed onto the material. Although there is no energy penalty for this water swing, it introduces complexities in terms of process control and stability. Moreover, in this arrangement, the DAC system consumes water. The extent of water consumption depends on the feed temperature and humidity; higher humidity air reduces water evaporation from the bed during adsorption.

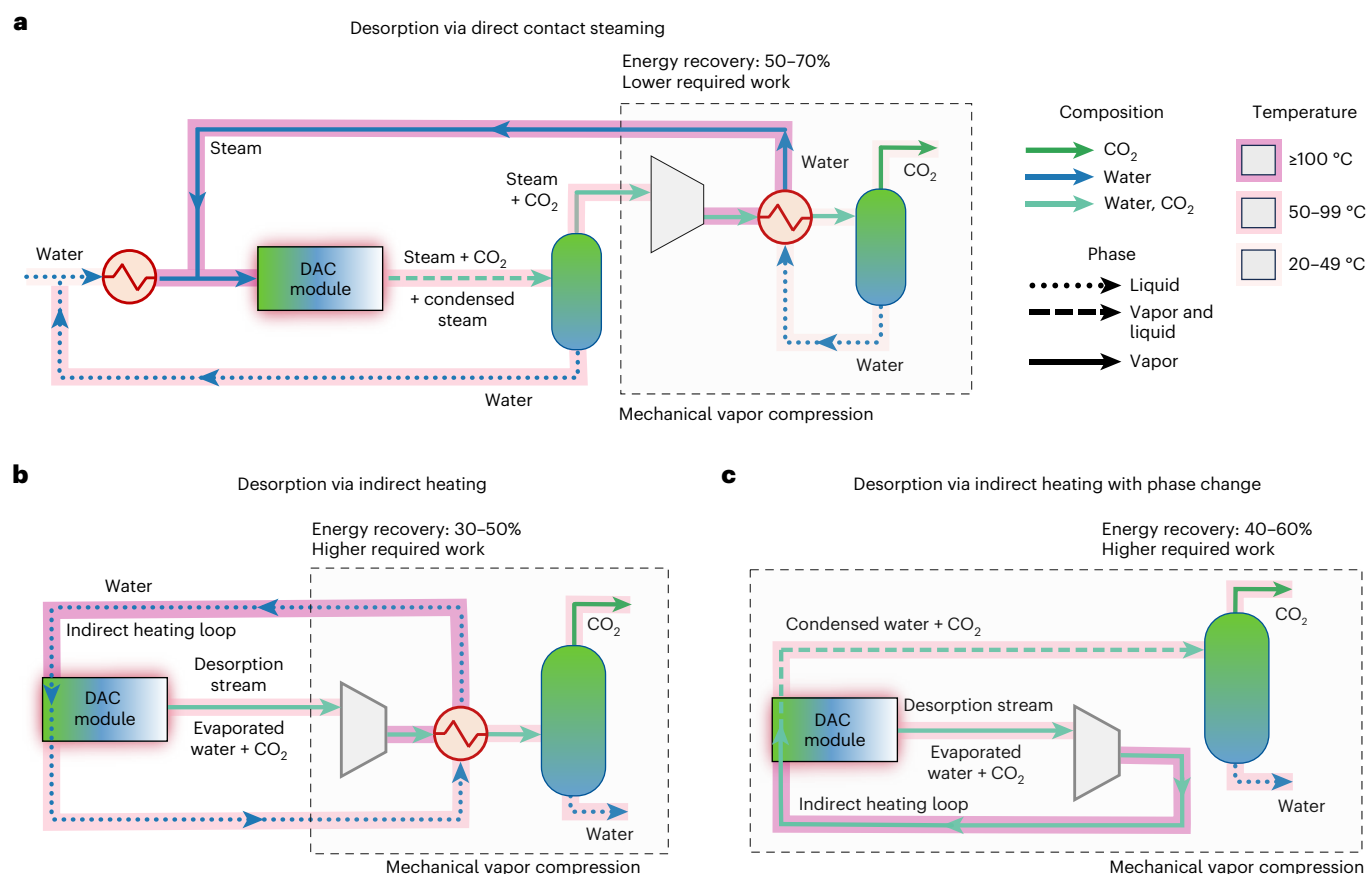
### Front-end approaches

Front-end approaches mitigate water-related challenges by selectively extracting water from the feed stream before it reaches the adsorbent bed. These dehydration methods are versatile and can be adapted for

a variety of DAC techniques. Dehydration is useful for sorbents whose performance is negatively impacted in humid feeds, either by competitive adsorption (for example, zeolites)<sup>30</sup> or structural degradation (for example, metal-organic frameworks)<sup>27,28</sup>.

Although refrigeration is indeed one dehydration technique, its prohibitive energy intensity renders it impractical for DAC applications. We instead focus on two dehydration approaches that can be integrated with heat recovery techniques to reduce energy demand. One proposed front-end approach is partial dehydration (Fig. 3a). In this method, a desiccant module precedes the DAC module, removing a substantial portion of the water before it reaches the adsorbent. Although removing water from a desiccant each cycle typically would be energetically expensive, strategic heat integration of other process streams can greatly reduce the energy demand and increase the feasibility of dehydration.

A notable example of the partial dehydration method, as proposed in ref. 36, involves two sets of desiccant and DAC modules. The air is directed to the first desiccant module to produce a less humid, CO<sub>2</sub>-rich stream, which is then fed to the first DAC module, resulting in a drier, CO<sub>2</sub>-lean stream. This CO<sub>2</sub>-lean stream can be used to regenerate the second, water-loaded desiccant module via concentration swing desorption. Additional heat may be necessary to augment the concentration driving force for drying the desiccant. It is important to note that the desiccant cannot achieve very low dew points, so there will still be some water in the stream entering the DAC module.



**Fig. 4 | Back-end engineering strategies for water management with heat integration. a,** Desorption strategy with direct-contact steaming. **b,** Desorption strategy with indirect heating. **c,** Desorption strategy with indirect heating and phase change of the heating fluid.

The CO<sub>2</sub>-lean stream can also be utilized for purging and cooling the second CO<sub>2</sub> capture module. The CO<sub>2</sub> capture module follows a typical vacuum-temperature swing adsorption cycle: (1) depressurization, (2) heating to desorb the CO<sub>2</sub>, (3) venting to release the CO<sub>2</sub> product and (4) purging and cooling. During the purging and cooling step, the CO<sub>2</sub>-lean stream removes and carries heat from the second CO<sub>2</sub> capture bed to the desiccant bed, contributing to regeneration of the desiccant. This effectively recovers the regeneration heat from the DAC module. This cyclical process continues, with the CO<sub>2</sub>-lean gas from the second set of modules being used for regeneration of the first set.

Full dehydration (Fig. 3b) employs a similar approach, but an atmospheric water extraction (AWE) bed is used in place of the desiccant. The AWE module ensures more complete water removal before contact with the CO<sub>2</sub> adsorbent and enables water-product generation. After saturation of the AWE module, heat is applied to generate the water product, requiring a substantial amount of energy. Heat integration, such as leveraging the sorption enthalpy from the exothermic adsorption step, can partially offset the energy needed for AWE module regeneration.

In both the partial and full dehydration scenarios, water management is enabled by using heat integration to supply regeneration heat to the dehydration beds. Standard heat recovery or heat-integration approaches, such as cross-exchangers, moving belts or beds, rotating beds and multi-fixed beds, can be applied for additional heat recovery<sup>37–39</sup>. For example, air-source heat pumps integrated with DAC processes have demonstrated substantial energy-consumption savings of 50 to 60% (ref. 40). Rotating and moving beds are another strong candidate for integrated heat recovery; they transfer heat from the sorbent leaving the regeneration section to the sorbent entering the regeneration section. However, there has been limited research on

the rotating-bed configuration for DAC, with existing work primarily focusing on point sources or non-CO<sub>2</sub> capture applications.

### Back-end approaches

Some sorbents exhibit enhanced performance in the presence of humidity, making it advantageous to retain at least some of the humidity in the front end of the system. In such cases, effective water management with heat integration becomes crucial to avoid the substantial energy penalty associated with cyclic adsorption and desorption of water. We propose three potentially viable back-end approaches here (Fig. 4), again focusing on temperature swing adsorption with solid adsorbents but with potential adaptability to aqueous systems or other processes.

All three approaches leverage mechanical vapor compression (MVC) for heat integration. During the CO<sub>2</sub> desorption step, energy is introduced into the DAC system as heat, and MVC can be employed to partially recover this input energy. The three main components are a compressor, a heat exchanger and a separator. The general procedure of MVC is as follows: (1) increase the pressure and temperature of a vapor stream using a compressor; (2) use the hot vapor stream from the compressor to heat a liquid stream via a heat exchanger (this can involve condensation of the hot vapor stream or evaporation of the liquid stream); (3) separate the vapor and liquid. MVC provides not only heat recovery but also water management, as water is condensed and separated from the CO<sub>2</sub> product.

The first back-end approach with integrated MVC involves desorption via direct-contact steaming (Fig. 4a), first proposed for DAC in a power-to-liquids, e-fuel plant (producing carbon-neutral jet fuel) in ref. 41. Steam is generated and utilized to heat the module and desorb CO<sub>2</sub> from the bed. Direct-contact steaming supplies more driving force for

desorption than indirect methods by providing both a temperature and concentration swing. It also reduces the regeneration energy by limiting water desorption from the bed. However, it is only applicable for materials with stability in hydrothermal conditions. After desorption, a stream comprising steam, condensed steam (water droplets) and CO<sub>2</sub> is obtained. The stream is sent to a separator to remove liquid-phase water and is then directed to a compressor to increase the temperature and pressure. The compressor requires mechanical work. The now hot, compressed vapor stream is then condensed in a heat exchanger to heat incoming water and convert it to steam. However, it is important to note that the vapor stream does not provide enough energy to produce steam in some systems, and additional energy input to the water stream may be required<sup>41</sup>. We expect this approach to recover 50–70% of the total desorption energy required (that is, latent heat of H<sub>2</sub>O, latent heat of CO<sub>2</sub>, and sensible heat).

Here, 'energy recovery' references the energy used with heat recovery to the required energy if there was no heat recovery. Energy recovery includes the thermal energy behind the compression work (using a Carnot efficiency conversion); heat recovery values would be higher because these do not include work in the energy used. The energy recovery ranges provided in Fig. 4 were estimated using a representative set of parameters and mass and energy balances to determine the energy that would be used with and without heat integration. For example, in the direct-steaming scenario, the energy required without heat integration includes the energy to produce the steam, and the energy used with integration includes the compression work (converted to heat) and any additional energy required for steam production if the heat provided by the integration is inadequate. The estimated ranges provide a comparison of approaches and loose guidelines for expected energy recoveries, but a more thorough analysis will be necessary using the specific parameters of a given technology.

The second approach uses indirect heating for desorption (Fig. 4b). Indirect heating relies on a temperature swing to desorb CO<sub>2</sub>, but it can be useful for materials with poor water stability or in locations without access to steam. In these systems, the DAC module is typically heated indirectly with hot water to desorb CO<sub>2</sub> and sorbed water. The exiting CO<sub>2</sub> and water vapor are compressed to increase the pressure and temperature. The hot CO<sub>2</sub> and water vapor stream can then be used to heat the water for desorption. It is likely that one compression/heat exchange step will not provide sufficient energy to reach the desired water temperature for desorption, and thus the stream will need to undergo a second (and potentially third) compression step before being used again to heat the water. The mechanical work of the additional compressors must be considered, and thus the energy recovery of this system will be lower than the direct-steaming system.

Finally, we consider a third approach that also uses indirect heating for desorption (Fig. 4c). Instead of an external water loop, the hot CO<sub>2</sub> and water-vapor stream is used for heating the module. Similar to the other two methods, the temperature and pressure of the desorbed water vapor and CO<sub>2</sub> stream are increased in a compressor. The stream is then sent back to the module, where the water vapor condenses to provide heat for desorption. The condensed water and CO<sub>2</sub> can then be easily separated. Additional cooling is required at the water–CO<sub>2</sub> separation step in all approaches. This heat-integration approach will have a higher energy recovery than one with an external water loop, as a result of avoiding the temperature of approach on a heat exchanger and higher heat transfer coefficient of condensing fluids. However, this approach still requires more work than direct steaming, and it also introduces the complexities of two-phase flow inside DAC-module heating systems.

## Challenges and potential

Water management is an integral part of successful DAC systems. Uncontrolled water adsorption and desorption will make process control and stability challenging and reduce the economic feasibility

of DAC systems. Water-management strategies exist and require effective integration with low-carbon heat to reduce their energy intensity and environmental impact. Five strategies for water management with heat integration have been discussed, and combinations of these strategies can also be used. In front-end approaches, water removal from the feed is made feasible by using heat integration to facilitate regeneration of the dehydration beds. Back-end approaches use heat integration to reduce the energy penalty associated with water—the back-end approach with direct-contact steaming and mechanical vapor compression is expected to provide the greatest energy recovery. The proposed strategies will need to be quantitatively assessed in the future to estimate the potential extent and additional cost of heat recovery. Even with effective heat integration, the capital costs of water-management systems must be considered carefully.

DAC will experience variable conditions (weather, seasonal, location), and this will need to be accounted for when water-management strategies are being developed and deployed<sup>42,43</sup>. Water sorption and evaporation will depend on the air temperature and humidity in all DAC technologies, and quantifying the magnitude of the water flux in variable conditions will be necessary in future work. Environmental conditions will also influence sorbent choice. For example, solid adsorbents with competitive water and CO<sub>2</sub> adsorption will be better suited for dry climates with less water sorption, whereas adsorbents with cooperative water and CO<sub>2</sub> adsorption will have better performance in climates that are more humid.

The water quality of the intake and outputs also needs to be considered. At the front end there can be atmospheric aerosols during adsorption or aerosolized metal ions from the steam system during desorption. Water can also be collected for product use at the back end, and more study is needed into the purity of water and any necessary post-treatments. Specifically for amine systems, the presence of amine by-products in the product water will need to be evaluated.

Finally, although there are clear paths forward for water management and heat integration in standard absorption and adsorption systems, the impacts of water on electrochemical systems are largely unknown, so more research is vital for the success of these systems. While innovating electrochemical systems, potential impacts on water management should be considered; modifications to sorbents intended to enhance cell energetics or oxygen stability may inadvertently affect other properties<sup>44</sup>. In summary, the next steps will be (1) to quantitatively evaluate strategies that combine water management with heat integration for various DAC technologies in variable environmental conditions, (2) to assess water-quality impacts on DAC processes and (3) to determine the impacts of water on electrochemical systems.

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## Author contributions

All authors contributed to discussions, analysis, and review and editing of the manuscript. R.P.L. contributed to conceptualization and visualization, M.J.R. to conceptualization and formal analysis, and H.E.H. to visualization, formal analysis and writing of the original draft.

## Competing interests

The authors declare no competing interests.

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