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# Perspective on distributed direct air capture: what, why, and how?



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Direct air capture (DAC) is widely considered as a critical negative emission technology to not only mitigate but reverse global climate change. While commercially expanding, its efficiency is limited by energy-intensive sorbent regeneration. Here, we highlight distributed DAC as a complement to centralized systems, analyzing the regeneration energy demands and carbon footprints of various sorbents. A comprehensive evaluation of distributed DAC's impact is crucial for maximizing its potential.

According to the Paris Agreement, the mitigation of climate change aims to hold the temperature rise below 2 °C, ideally 1.5 °C, by the end of this century<sup>1</sup>. Carbon neutrality is targeted by the mid-century through the reduction in greenhouse gas emissions, and negative emission technology (NET) plays a vital role in mitigation efforts. To meet climate goals while sustaining economic growth, NET is recommended to remove approximately 10 Gt of CO<sub>2</sub> per year by mid-century, increasing to 20 Gt CO<sub>2</sub> per year globally by the century's end<sup>1</sup>. Considering the annual industrial growth rate of around 20%<sup>2</sup>, the current use of non-carbon technologies and flue gas capture process can only slow the increase in atmospheric CO<sub>2</sub> concentration. The urgency to deploy more carbon NET cannot be overemphasized<sup>3</sup>.

Direct air capture (DAC) is one of the critical NETs, with a noticeable deployment progress in recent years. DAC is broadly defined as the direct extraction of CO<sub>2</sub> from ambient air<sup>4</sup>. It generally involves two steps: capture and regeneration. In the contactor, CO<sub>2</sub> is extracted from ambient air by chemically bonding with the sorbents. The air, now depleted of CO<sub>2</sub>, leaves the carbonated sorbents. Once a sufficient loading capacity is reached, the saturated sorbents must be regenerated, predominantly by elevated temperature. The extracted atmospheric CO<sub>2</sub> can be either sequestered geologically<sup>5</sup>, reused in other industries such as enhanced oil recovery<sup>6</sup>, or converted to valuable chemicals<sup>7</sup>. (Fig. 1a) One prominent advantage of DAC is its efficient use of land compared to photosynthesis. Modern DAC plants require 0.4 – 66 km<sup>2</sup> land for each ton of captured CO<sub>2</sub>, much smaller than 862 km<sup>2</sup> required for the afforestation and reforestation to capture a similar amount of CO<sub>2</sub><sup>8</sup>. From a long-term perspective, as we decarbonize fossil fuel-driven industry, capturing CO<sub>2</sub> through DAC will play a crucial role in achieving net-zero emissions.

As of 2023, twenty-seven DAC plants have been commissioned worldwide, and 130 DAC facilities are under development, according to the International Energy Agency<sup>9,10</sup>. Given the urgency of climate change mitigation, upscaling current DAC technologies is essential for gigaton-scale CO<sub>2</sub> capture, with a target of 20 Gt CO<sub>2</sub> per year by 2100 to meet net-

zero emission<sup>1</sup>. Currently, global carbon capture capacity stands at 0.049 Gt per year<sup>11</sup>, while DAC contributes only 0.01 Mt annually<sup>9</sup>. Scaling DAC alone presents significant challenges in meeting these capture targets. Table 1 summarizes three major DAC technology providers and their projects as of 2022.

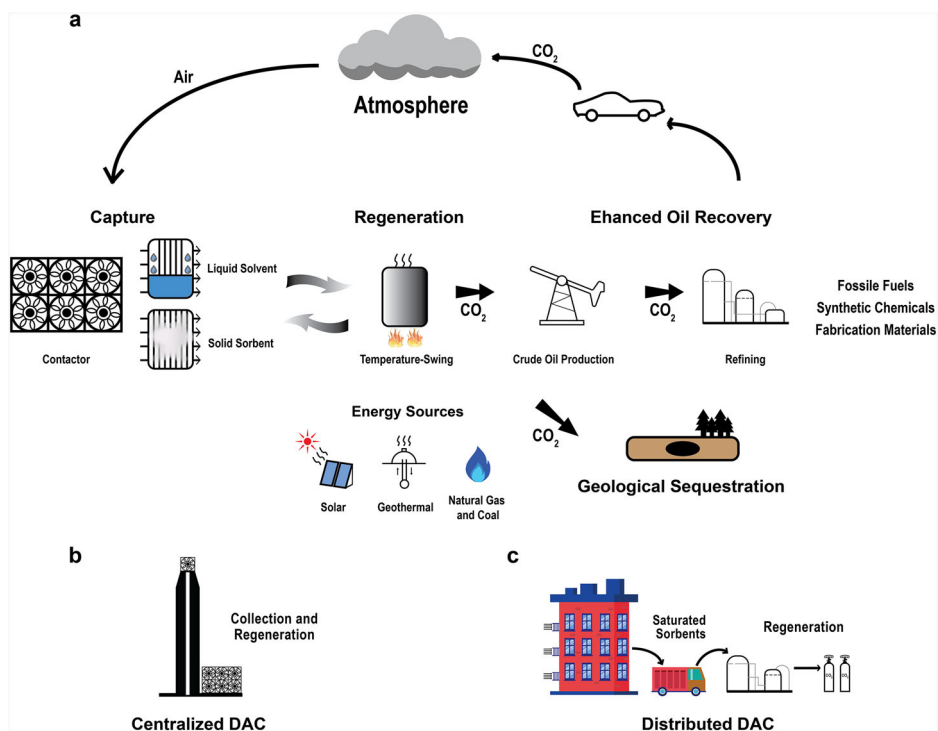
## Centralized versus distributed DAC

Although atmospheric CO<sub>2</sub> is ubiquitous and mostly uniform, current DAC deployment is nonetheless location-selective and has yet to achieve the full potential of its carbon removal. Why is this the case? To make a DAC plant carbon-negative and financially sustainable, the location must have vast and cheap land, renewable energy sources, and preferably nearby sequestration or conversion sites. To understand this bottleneck, we first break down each component of current DAC plants.

In centralized DAC systems, considerable infrastructure is typically required for CO<sub>2</sub> capture, compression, and storage or utilization. Large air contactors are often stacked together, with electric fans drawing ambient air into the reactors. Sorbents with strong chemical affinity capture and react with the dilute CO<sub>2</sub> in the air. Once saturated, these sorbents are directly regenerated in a central regeneration facility for subsequent capture cycles. (Fig. 1b)

Low-temperature DAC sorbent relies on two primary sorption mechanisms: physisorption and chemisorption. Physisorption involves the physical trapping of CO<sub>2</sub> within the pores of solid sorbents without chemical reactions, whereas chemisorption involves the reaction of CO<sub>2</sub> with basic sites functionalized on solid materials called adsorbent<sup>12</sup>. Alternatively, CO<sub>2</sub> can be chemically absorbed into liquid sorbents, such as aqueous bases absorbent like NaOH and Ca(OH)<sub>2</sub>. Physisorbents, such as unmodified zeolites and metal-organic frameworks (MOFs), generally exhibit poorer performance in capturing CO<sub>2</sub> compared to chemisorbents<sup>13</sup>. But excellent tunability and crystallinity of MOFs enable efficient kinetic separations of gases. Chemisorbents, on the other hand, are more effective due to their strong chemical bonding with dilute CO<sub>2</sub> from air<sup>13</sup>. Therefore, this discussion will

**Fig. 1 | Schematic diagram of direct air capture (DAC) plants for CO<sub>2</sub> capture, regeneration, and reuse.** **a** DAC plants incorporate both centralized and distributed designs for flexible deployment. Ambient air is drawn into the system via fans, where CO<sub>2</sub> is captured using either liquid or solid sorbents. Once captured, the CO<sub>2</sub> is released through thermal regeneration of the sorbents powered by various energy sources. The captured CO<sub>2</sub> can subsequently be sequestered or utilized as a raw material in industrial applications. **b** Schematic of centralized DAC design. **c** Schematic of distributed DAC design.



**Table 1 | Overview of three represented DAC technology providers and their projects**

| Company            | Location                  | Sorbent Type | Approximate Capture Capacity (tCO <sub>2</sub> yr <sup>-1</sup> ) | Thermal Energy Source | Market Application  |
|--------------------|---------------------------|--------------|-------------------------------------------------------------------|-----------------------|---------------------|
| Climeworks         | Iceland                   | Solid        | 4000                                                              | Geothermal            | Utilization Storage |
| Carbon Engineering | U.S. (Under construction) | Liquid       | 1,000,000                                                         | Natural Gas           | Utilization         |
| Global Thermostat  | U.S. (Under construction) | Solid        | 4000                                                              | Natural Gas           | Utilization         |

It includes only one DAC project from each company as of 2022. Data sourced from Abatable, 2023<sup>36</sup>; iScience, 2022<sup>17</sup>.

focus on chemisorbents, due to their critical role in enabling efficient DAC processes.

There are three factors to be evaluated when deploying DAC: cost, resource demand, and carbon footprint. First, for DAC to be economically viable, the costs must be reduced to below \$100 per ton of CO<sub>2</sub><sup>1</sup>, making it competitive with other NETs like bioenergy with carbon capture and sequestration (BECCS). However, the current DAC has the costs as high as \$600 per ton of CO<sub>2</sub>, so it is not among the NETs ready for large-scale deployment<sup>1</sup>. Second, the availability of energy sources and materials is critical for scaling up. Locations with existing supply chains for metals, hydroxides, calcium carbonate are advantageous for producing DAC sorbents. Energy sources and freshwater are also essential for the regeneration process. Lastly, the carbon footprint of DAC operations should not be overlooked. The selection of energy sources and sorbents can significantly impact the carbon emissions generated during operation. These three factors will be the focus of discussions in the following sections.

### Thermodynamic consideration of DAC sorbent regeneration

Significant progress has been made so far in advancing the DAC capacity and selectivity. However, CO<sub>2</sub> capture is only the first step in the DAC cycle, and the regeneration process should not be underestimated. Because of the low concentration of CO<sub>2</sub> in ambient air, the thermodynamic driving force must be sufficiently strong to ensure high capacity. As we reverse the adsorption into desorption, the same large amount of free energy (or enthalpy for a pure thermal process) is needed. Such energy requirement is a major factor that needs to be rationally engineered to realize carbon-

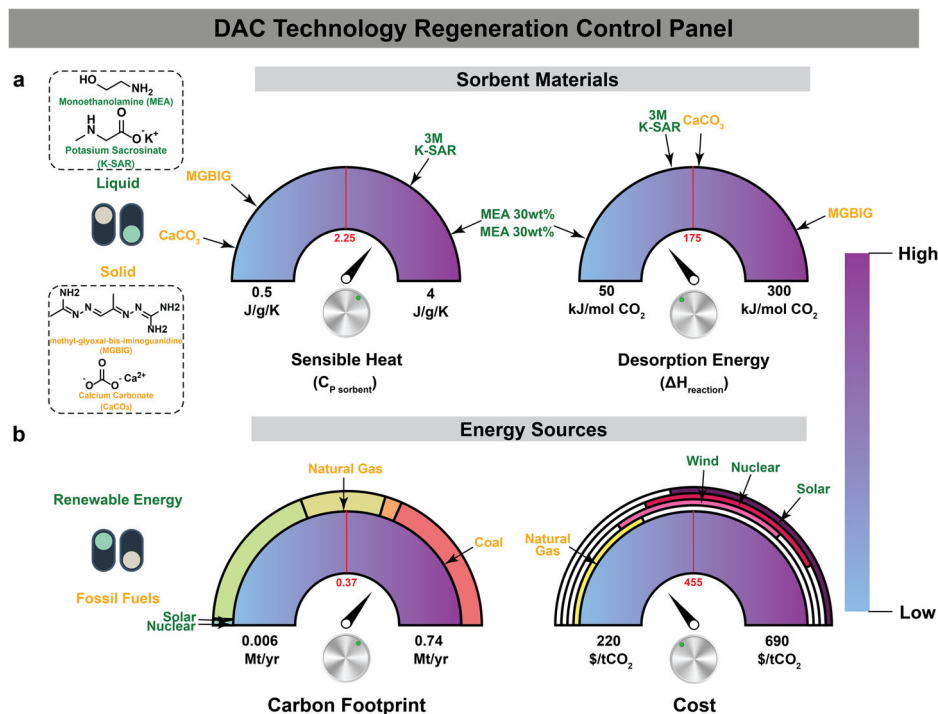
negative<sup>14</sup>. For example, thermal regeneration of CaO and the subsequent production of high-purity CO<sub>2</sub> account for approximately 63% of the energy in the overall DAC process<sup>1</sup>. Therefore, controlling the energy demand and minimizing the carbon emissions during regeneration is essential. A thorough assessment of the regeneration process is critical for developing an efficient DAC system.

In the regeneration of DAC sorbents, temperature swing desorption (TSD) and temperature-vacuum swing deposition (TVSD) are among the most widely used regeneration methods. Thermal regeneration typically requires heat or electricity input from different energy sources<sup>15</sup>, and its effectiveness depends heavily on the types of sorbents and energy sources used.

To better understand the energy consumption related to the materials properties, we take a deeper look into the components of regeneration energy in detail. The total energy required for sorbent regeneration is the sum of several thermodynamic quantities. ( $Q_{\text{regeneration}} = Q_{\text{desorption}} + Q_{\text{sensible}} + T\Delta S_{\text{separation}} + Q_{\text{non-ideal}}$ ) The entropy of separation ( $T\Delta S_{\text{separation}}$ ) and non-ideality ( $Q_{\text{non-ideal}}$ ), which accounts for entropic irreversibility (e.g., mass and heat transfer inefficiencies), are included in the calculation of regeneration energy. Due to the low CO<sub>2</sub> concentration in the gas mixture and its rapid removal, entropic terms contribute minimally compared to other terms in the regeneration process. So we narrow the focus of discussion only into  $Q_{\text{desorption}}$  and  $Q_{\text{sensible}}$ .

The heat of desorption ( $Q_{\text{desorption}}$ ) refers to the energy needed to break chemical bonds and release CO<sub>2</sub>. For DAC,  $Q_{\text{desorption}}$  should be sufficiently large and should not be treated as a drawback. But if the heat of desorption is excessively high, the energy and associated costs required to desorb the

**Fig. 2 | Direct air capture regeneration control panel, with two switches and four dials comparing key factors for choices of sorbents and energy sources.** The components of regeneration energy include the sensible heat, heat of desorption and heat of vaporization. **a** Upper panel: Solid and liquid sorbents are compared based on their specific heat capacity of sorbent ( $C_{p\text{ sorbent}}$ ) and enthalpy of reaction ( $H_{\text{reaction}}$ ), measured from thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC). The  $C_{p\text{ sorbent}}$  of 30 wt% MEA, 3M K-SAR, mesoporous silica (SBA-15), MGBIG and  $\text{CaCO}_3$  have been reported as approximately 3.53<sup>40</sup>, 2.92<sup>18</sup>, 1.08<sup>41,42</sup>, 1.30<sup>18</sup>, 0.834<sup>43</sup> J/(g·K) in the temperature range of 25 °C to 70 °C. The  $H_{\text{reaction}}$  for 30 wt% MEA, 3M K-SAR, branched PEI on SBA mesoporous silica 15 (7.55 mmol/g amine loading), MGBIG and  $\text{CaCO}_3$  are reported to be 80<sup>44</sup>, 161<sup>18</sup>, 93<sup>45</sup>, 264<sup>18</sup>, 187<sup>46</sup> kJ/mol  $\text{CO}_2$ . **b** Lower panel: The carbon footprint and energy cost of DAC systems vary depending on the energy sources used, whether renewable or fossil-based. The reported carbon footprints for solar, nuclear, natural gas, and coal are 0.0084–0.018, 0.006–0.009, 0.29–0.44, 0.47–0.74 Mt  $\text{CO}_2$  for 1 Mt  $\text{CO}_2$  captured per year<sup>1</sup>. The corresponding energy costs of  $\text{CO}_2$  removal in calcium looping using solar, nuclear, natural gas, and wind are reported to be \$430–690, \$400–620, \$220–390, and \$360–570/t  $\text{CO}_2$  captured<sup>23</sup>.



captured  $\text{CO}_2$  could become a significant challenge. Sensible heat ( $Q_{\text{sensible}}$ ) is the energy required to heat the sorbent to the regeneration temperature<sup>16</sup>. The sensible heat is determined by the specific heat capacity ( $C_{p\text{ sorbent}}$ ) of the sorbent and  $\text{CO}_2$  capacity of the sorbent in a single adsorption-desorption cycle. For solvent-based processes, it is additionally influenced by the liquid flow rate. Besides that, the latent heat from the vaporization of co-adsorbed water should also be considered, originating from ambient air or steam used for regeneration. To narrow the focus of our discussion, the specific heat capacity ( $C_{p\text{ sorbent}}$ ) of the sorbent is used for quantitative comparisons of the sensible heat. Minimizing the sensible heat is crucial for optimizing the full regeneration process.

For example,  $\text{CO}_2$  capture using liquid absorbent like NaOH is thermodynamically favorable due to the formation of carbonate and bicarbonate, however, the regeneration can be energy intensive. The regeneration temperature necessary for NaOH exceeds 800 °C, with an energy consumption of around 6.57–9.9 GJ/t  $\text{CO}_2$ <sup>14</sup>. In contrast, solid sorbents require lower regeneration temperatures, reducing the energy demand to 5–8.3 GJ/t  $\text{CO}_2$ <sup>17</sup>. Consequently, sensible heat contributes significantly to the overall energy consumption during regeneration. Strategies to reduce this loss include selecting sorbent substrates with lower heat capacity, minimizing the temperature swing rate and contactor area during the regeneration<sup>1</sup>. (Fig. 2)

For the commonly used liquid amine-based sorbent, monoethanolamine (MEA) aqueous solution, the heat loss from water evaporation ( $Q_{\text{vaporization}}$ ) must be considered besides the substantial  $Q_{\text{sensible}}$  from water (4.2 J/g·K)<sup>16</sup>. During regeneration, the  $\text{CO}_2$  at the top of the regenerator becomes saturated with water<sup>18</sup>. While sorbents with low  $Q_{\text{desorption}}$  may reduce the direct energy consumption from desorption, sorbent with high  $Q_{\text{desorption}}$  can reduce the water vapor loss by increasing the partial equilibrium pressure of  $\text{CO}_2$ , and the need for excess water vapor can be minimized. Therefore, the choice of sorbent should balance the regeneration temperature and  $Q_{\text{vaporization}}$  for optimal efficiency<sup>19</sup>. The upper panel of DAC regeneration in Fig. 2 outlines the thermodynamic quantities and corresponding heat components for several DAC sorbents.

Another important property is the sorbent longevity. The replacement of sorbents leads to increased energy consumption and carbon emissions if

the sorbents have a short lifetime after adsorption-regeneration cycles. This aspect is often overlooked by those prioritizing higher sorption capacity and mild regeneration conditions. First, deterioration occurs over repetitive capture and regeneration cycles, where poorer sorbent quality compromises the effectiveness of capture by lowering the adsorption capacity<sup>17</sup>. The causes of degradation include moisture effect<sup>20</sup>, air oxidation<sup>21</sup> and low tolerance to impurities<sup>22</sup>. Last but not least, rapid sorption/desorption kinetics is also crucial to enhance the turnover frequency of DAC. Besides the intrinsic chemical reaction rate constants, kinetics is also influenced by pore structure, surface area, and specific heat capacity.

### Carbon footprint and cost consideration of energy sources

From the previous discussion, different sorbents require different energy inputs for regeneration, which determines the weighting of this step among the entire life cycle of DAC. Accordingly, the choice of energy sources for regeneration significantly impacts overall energy efficiency and carbon emissions. One can picture an extreme case that fossil fuel is used to regenerate the sorbents, then it is likely that the emitted  $\text{CO}_2$  could approach the amount captured, making the overall DAC process less effective. Renewable energy sources can result in carbon negativity but still vary drastically among different types and locations. For example, when solar energy is used for both heat and electricity in solid sorbent, carbon emission is around 0.0084 to 0.018 Mt  $\text{CO}_2$  for 1 Mt  $\text{CO}_2$  captured per year in the mid-range, whereas natural gas can produce 0.29 to 0.44 Mt carbon emission per year<sup>1</sup>. The numbers show that natural gas in regeneration can additionally contribute nearly half of the captured 1 Mt  $\text{CO}_2$ , proving to be very counterproductive.

On the other hand, the financial cost of natural gas is lower than that of solar energy. For gross capture cost per ton of  $\text{CO}_2$  removal using liquid solvent sorbent, natural gas costs \$220–390, while solar energy costs \$430–690<sup>23</sup>. A more accurate cost estimate must consider net  $\text{CO}_2$  removal, as burning natural gas for regeneration produces additional carbon emissions. While renewable energy sources achieve a similar removal rate, they come at much higher costs than fossil fuels. Achieving a balance between effectiveness and low cost remains challenging in fostering clean

alternatives. In Fig. 2, the lower panel of DAC regeneration outlines the carbon footprint and energy cost of DAC systems using different energy sources.

Additionally, the optimization of flow configuration can reduce both capture costs and energy demand. In the capture process, electricity is required to operate fans and pumps, highlighting its role as a key component of energy consumption alongside the thermal energy needed for regeneration. Traditional CO<sub>2</sub> absorption methods in industry employ towers filled with packing materials. However, DAC contactor has a different dimension compared to traditional tower. To minimize the pressure drop caused by the dilute concentration of CO<sub>2</sub> and the large volume of gas intake, shallow contactors with a large contacting surface area are more effective<sup>24,25</sup>.

## Distributed DAC

From previous discussions, careful location selection is crucial for a centralized DAC plant to be carbon-negative and financially sustainable upon scaling up due to land occupation, energy requirements for ventilation, and post-regeneration CO<sub>2</sub> collection. The limited land available in dense cities relative to nonurban global areas might imply priority of the deployment of the less land-intensive DAC<sup>1</sup>. These stringent conditions suggest that centralized DAC may not always be a flexible and efficient option for large-scale deployment. To expand the overall carbon removal potential, rather than piling up large contactors in DAC plants as single-point sources for CO<sub>2</sub> capture, a distributed deployment model within urban areas complementary to the centralized DAC could overcome these limitations.

Distributed DAC systems in urban areas can offer significant benefits by leveraging existing infrastructure and serving large populations. Placing these systems in cities takes advantage of the growth of carbon economy, especially in areas where CO<sub>2</sub> emission sources and the carbon industry are easily accessible. Using captured CO<sub>2</sub> as a feedstock for producing sustainable fuels has the potential to replace fossil-based inputs in industrial processes (Fig. 1a). Our analysis indicates that clean energy can greatly reduce carbon emissions. With cities increasingly advocating for clean energy sources, including wind, solar, and nuclear, the availability of renewable low-carbon electricity will enhance the efficiency of DAC systems<sup>26</sup>. Both the capture and utilization of CO<sub>2</sub> can be effectively implemented in urban areas. (Fig. 2, lower panel)

The distributed design for CO<sub>2</sub> removal in urban areas significantly enhances the potential for carbon capture and storage. By integrating DAC with existing urban building infrastructure, this approach reduces location dependency and lowers energy costs associated with ventilation and transportation, making it both environmentally and financially sustainable<sup>1</sup>. A major contributor to operational costs in centralized DAC is the contactor. For instance, in the case of CO<sub>2</sub> regeneration with liquid-based sorbents, air contactors contribute 20% of the capital costs and 30% of the operating and maintenance costs of the entire direct air capture (DAC) plant<sup>1</sup>. To optimize DAC design and minimize costs, systems-level strategies may include adopting more integrated designs, such as utilizing existing hardware and infrastructure (e.g., heating, ventilation, and air conditioning (HVAC) systems in buildings or combined heat and power systems) and integrating with industrial systems (e.g., steel and cement production) that generate significant quantities of low- to high-quality waste heat<sup>1</sup>. Additionally, urban areas offer access to various transportation methods, including rail, pipelines, and commercial trucks, further enhancing the feasibility of DAC deployment in such settings. (Fig. 1c)

## Large-scale and flexible deployment

Recirculating air through a building's HVAC system offers great potential for implementing indoor DAC. Capturing CO<sub>2</sub> from indoor environments, where concentrations are about two to three times higher than the atmospheric level of 420 ppm, represents a thermodynamic advantage over conventional centralized DAC<sup>27</sup>. The estimated capacity for carbon storage from indoor spaces ranges from 0.02 to 0.13 Gt CO<sub>2</sub> per year<sup>28</sup>. Moreover, the utilization of urban vegetation, soil, and construction materials such as wood and biochar within built environments can be estimated to contribute to

0.2–1.1 Gt CO<sub>2</sub> per year<sup>28</sup>. Currently, the scale of distributed DAC, though still in its early stages, is estimated to reach approximately 9 kt CO<sub>2</sub> per year in Germany<sup>10</sup>.

A typical volumetric exchange rate in office buildings is about 5–10 times per hour<sup>29</sup>. Despite the low concentration of CO<sub>2</sub> in the air, the absolute amount of CO<sub>2</sub> passing through the HVAC system is substantial<sup>29</sup>. For example, the Willis Tower, a landmark building in Chicago, U.S., provides 418,000 m<sup>2</sup> of office space. Assuming an average ceiling height of 4 m, this results in a total air volume of around 1,670,000 m<sup>3</sup><sup>30</sup>. Based on the recommended ventilation rate for office buildings, the estimated airflow is 8–17 Mm<sup>3</sup> h<sup>-1</sup>. With a CO<sub>2</sub> concentration of 400 ppm in air, this translates to 6–14 tCO<sub>2</sub> h<sup>-1</sup> available for capture in a single building. Implementing additional distributed DAC filters in buildings is expected to significantly enhance CO<sub>2</sub> capture efforts.

## Building sector energy efficiency and improved public health

By integrating building HVAC systems with DAC units, energy use by air contactors is minimized as the system takes advantage of the existing airflow for CO<sub>2</sub> capture. CO<sub>2</sub>-lean air can be supplied to indoor occupants without the need for additional fans and pumps, by retrofitting distributed DAC filters downstream of conventional air filters in buildings. Filtering the air post-capture reduces indoor air pollutants and enables air to be recirculated within the building, avoiding the frequent intake of fresh outdoor air, which is typically energy-intensive and inefficient<sup>31</sup>.

Moreover, distributed DAC systems can directly benefit the large population living in the urban area, helping to decrease indoor CO<sub>2</sub> concentration and improve public health. According to the ASHRAE 62.2-2022 standard, buildings require a minimum circulation rate of 15 cubic feet per minute to maintain air quality and occupant comfort<sup>32</sup>. Average indoor CO<sub>2</sub> levels in offices and homes typically range from 600 to 1,000 ppm, but can exceed 2,000 ppm with higher occupancy and lower building ventilation<sup>33</sup>. The elevated CO<sub>2</sub> level can adversely impact both work productivity and sleep quality<sup>34</sup>. For instance, high CO<sub>2</sub> levels are associated with increased headaches, higher student absenteeism, as well as reduced cognitive performance<sup>35</sup>.

## Efficient low-carbon-footprint regeneration with optimal transportation modes

Minimizing capture costs, energy demand, and carbon emissions are essential for developing the most efficient CO<sub>2</sub> capture system. A comprehensive life-cycle analysis (LCA) must account for the carbon emissions to accurately evaluate the overall CO<sub>2</sub> removal. A low-carbon-footprint heat source is essential to ensure positive carbon capture efficiency. Current centralized DAC plants are typically situated near renewable energy sources such as geothermal or other renewable energy options. To implement distributed DAC effectively, the regeneration energy source also needs to be decentralized.

The availability of renewable low-carbon electricity and heat sources near urban areas can remove location constraints, making them ideal for regeneration. Low-carbon electricity and heat sources, such as wind, solar, biomass, nuclear, and geothermal energy, can all contribute to the energy supply. According to the map of low-carbon heat sources<sup>26</sup>, biomass and nuclear energy are more readily accessible around urban areas in the U.S. Additionally, rural areas with abundant renewable energy sources are often located not far away from urban centers. The efficient transport and regeneration of sorbents can be supported by urban transportation infrastructure, while the use of electric vehicles can further reduce capital costs and carbon emissions. This enables large-scale deployment of distributed DAC systems.

Reflecting on the example of CO<sub>2</sub> capture using air filters at Willis Tower, the energy demand for regenerating CO<sub>2</sub> with solid sorbents is estimated to be 5–8.3 GJ/t CO<sub>2</sub>. Consequently, the additional power requirement for regenerating saturated sorbents will range from 8–33 MWh. Integrating the HVAC system with the DAC system does not require energy to facilitate gas intake, assuming the pressure drop is



negligible. It is anticipated that sorbents will be regenerated using onsite renewable solar energy or electricity. Given the substantial energy required for regeneration and the collection of carbon products, CO<sub>2</sub> must be processed and transported to collection sites. The subsequent deployment involves selecting optimal transport modes to collection sites around urban areas for short-term storage or geological chambers for long-term storage, eventually leading to geological sequestration at specific locations<sup>28</sup>.

### Additional consideration

The rapid scaling of DAC technology can greatly benefit from its distributed design, along with public acceptance and political support. However, the discrepancies in technological and social feasibility of distributed DAC across different regions pose additional challenges case by case, such as the availability of renewable energy supply for regeneration and integration into existing hardware and infrastructure, including ventilation systems in buildings and industrial settings<sup>1,10</sup>. Further justification and evaluation are required to address these challenges effectively.

Additional energy costs and carbon emission associated with transportation to collection sites for storage must also be considered in the full analysis. For example, utilizing existing urban transportation infrastructure, including water pipelines, railways, and other systems, can reduce capital costs. The widespread adoption of electric vehicles can further minimize carbon footprints, making transportation in distributed DAC systems more sustainable. According to transportation model<sup>36</sup>, a less frequent pickup is preferred to reduce the transportation's impact on the overall CO<sub>2</sub> removal efficiency, while daily pickups reduce net CO<sub>2</sub> removal efficiency by 40%. The efficiency approaches nearly 100% if transportation occurs as infrequently as bimonthly. However, less frequent pickups could cause issues if the saturated sorbent filters are not shipped promptly for regeneration. Once the sorbent reaches its capture capacity, it will no longer capture CO<sub>2</sub> effectively, decreasing system efficiency. While waiting for sorbent replacement, prolonged storage of saturated sorbents requires additional space, increases operational costs, and pose safety and maintenance concerns. It is important to determine how frequent pickups remain advantageous for overall CO<sub>2</sub> removal efficiency.

### Conclusions and future perspectives

Developing energy-efficient and cost-effective DAC systems is essential for reducing the global carbon emissions upon scaling up<sup>15</sup>. Efforts to advance energy-demanding thermal regeneration of sorbents in DAC is crucial for achieving efficient operations. As improvement and innovation of DAC technology mostly focus on the sorption capacity, limitation exists in evaluating the effectiveness of the regeneration process.

To optimize DAC effectiveness, it is important to assess the energy demands and carbon footprints associated with different sorbents and energy sources. Ideal sorbents exhibit low heat capacity, high durability, and efficient sorption/desorption kinetics to maximize both the energy efficiency and longevity. Despite their high energy costs, renewable energy sources with minimal carbon emissions are preferred for regeneration. Additionally, system optimizations that increase mass-transfer efficiency can also reduce overall operational expenses and energy demands.

Centralized DAC plants may face limitations in scaling up due to challenges such as land requirements, energy source availability, and CO<sub>2</sub> collection post-regeneration. A distributed deployment within urban areas can address these limitations, by integrating DAC with existing urban building infrastructure. This approach expands the capture scale, minimizes location constraints, and improves public health.

Several emerging technologies have the potential for further reducing carbon emissions in the full life-cycle analysis, including passive-air contactors and natural sorbents<sup>17</sup>. Passive air contactors help minimize energy and freshwater consumption, while natural sorbents, such as biomass and biochar, contribute to a reduced carbon footprint during production.

The National Academies' report emphasizes the development of low-cost solid sorbents with enhanced CO<sub>2</sub> sorption capacity and kinetics<sup>1</sup>. These solid sorbents, which require less energy for regeneration, can be

supported in various solid forms with amine functionalization. Chemical functional groups are introduced onto the surface or within pore structures of the sorbent materials through impregnation procedure<sup>37</sup>, combining the advantages of the host materials with enhanced chemical functionality to improve both the sorption capacity and efficiency. Additionally, identifying and recycling degradation products from sorbents is crucial for maintaining long-term efficiency.

Finally, besides the modular designs and collaborative efforts between academia and industry, the scale-up rate of DAC will largely depend on public acceptance and political support. This could be driven by strategies such as incentives (e.g., subsidies, tax rebates) and mandates (e.g., regulations, policy initiatives) that encourage widespread adoption<sup>28,38</sup>. Mandating the progressive deployment of DAC drives market investment, which sustains political backing from a feedback loop of incentives and mandates in turn<sup>38</sup>. In summary, for DAC to be truly sustainable and effectively contribute to meaningful global carbon reductions, it is essential to prioritize the efficient regeneration of sorbents after capture, especially as the technology scales.

### Data availability

Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

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## Author contributions

P. C. H. and Y. C. conceived the perspective. Y. C. wrote the manuscript under the supervision of P. C. H., and R.W. contributed to manuscript revisions.

## Competing interests

All authors declare no financial or non-financial competing interests.

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