A Pilot-Scale Demonstration of Mobile Direct Air Capture Using Metal-Organic Frameworks

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It is increasingly apparent that negative emissions technologies, such as direct air capture (DAC), are required as part of the technology mix for limiting global atmospheric temperature increase. For all DAC technologies, the requisite energy for regeneration of the separation media strongly influences the overall cost of the process and therefore directly influences their likely implementation. Herein, the results of a pilot-scale demonstration of a new metal organic framework (MOF) based technology, Airthena, incorporated within a mobile unit for distributed deployment, are reported. Careful preparation of a MOF nanocomposite results in a CO2-selective sorbent with fine-tuned kinetic and thermodynamic properties. An optimum regeneration temperature of 80 °C is achieved, along with strong repellence of water vapor during the adsorption process. Taken together, this demonstrator has delivered one of the lowest regeneration energy consumptions, 1.6 kWh kg-CO2⁻¹ with output purity of 70–80%. This equates to an operational cost of $35–$350 ton-CO2⁻¹ depending on the source of regeneration energy. Over the duration of the pilot-scale testing, the demonstrator captures a total of 8 kg of CO2 over 2680 cycles.

1. Introduction

The capture of carbon dioxide (CO2) directly from air has been identified as a potentially useful mitigation pathway to limit global warming to 1.5 °C above preindustrial levels.[3] The concept of direct air capture (DAC) as a practicable means to reduce atmospheric CO2 concentrations can be traced back to the work of Lackner et al.,[2] whose presentation of DAC for controlling atmospheric CO2 levels was focussed on maintaining the viability of existing fossil fuel energy sources and processes. A more recent approach proposes the use of DAC[3] to complement the implementation of renewable energy sources in order to facilitate a reduction in global atmospheric CO2 concentrations. In addition to new processes reported for CO2 capture from stationary sources, such as the metal-mediated CO2-regenerative amine-based battery process that directly converts CO2 reaction enthalpy into electrical energy,[4] DAC offers a practical mitigation of CO2 emissions from highly distributed or mobile point sources. As an alternative to storage of captured CO2 in deep saline aquifers suggested for large stationary emitting sources,[5] DAC-produced CO2 could be used as a chemical feedstock for the synthesis of value added products.[6,3b,7] Examples of such demonstrated technologies include the use of CO2 instead of water to cure concrete leading to permanent sequestration of the CO2,[8] efficient growth of plants in greenhouses, and conversion of CO2 into alcohols by algae.[3b,9] Additionally, the uptake of distributed point-of-use DAC CO2 could mirror, and even be facilitated by, consumer-driven selection of point-of-use solar photovoltaics (PV) electricity generation and storage.[1a,10]

Proposed routes for DAC include the use of aqueous basic solutions[11] and solid adsorbents[12] as capture media. Aqueous basic solutions are used because they offer the opportunity to continuously contact the feed air with the solution in the presence of contaminants and other constituents in the air.[13] From a process engineering perspective, this approach is excellent for large-scale carbon capture in the form of a processing plant permanently located alongside free waste-heat sources, such as a coal or gas power plant.[13c,d,14] Solid adsorbents offer the prospect of DAC with a low energy input, low operating costs, minimal infrastructure, and the potential for application over a broad range of scales.[13a,15]

Transitioning to a sustainable carbon cycle will require a suite of technologies from large-scale carbon capture plants to a large number of small and distributed carbon capture units.[16] Inspired by the trend of individual responsibility, small and mobile carbon capture units could enable small business enterprises to play their part in reducing global carbon emissions. Recycling carbon dioxide from the air can be a valuable process in beverage carbonation, food preservation, and dry ice cleaning devices.[17] However, if small mobile DAC units relying solely on

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electricity are to become a reality then their energy consumption needs to be low enough for both economic and environmental reasons. Economically, carbon dioxide is generally cheap as a bulk commodity and more expensive for smaller volume applications. At this stage, it is difficult to estimate the capital cost of DAC technology prior to its widespread deployment. Environ-mentally, the mobile DAC units must be carbon negative where the sources of electricity are a mix of renewables and fossil fuels. Therefore, there is the need for a DAC technology that exhibits fast adsorption kinetics, low regeneration energy, physical and chemical stability, and optimal CO₂ uptake and selectivity in the presence of other components of atmospheric air.

Here an adsorbent-based process that uses a metal organic framework (MOF) polymer nanocomposite for DAC is reported. The nanocomposite is a proprietary technology, termed Airthena, which is incorporated into a DAC demonstrator capable of producing 140 g day⁻¹ of CO₂ with very low energy input during regeneration. The DAC demonstrator contains three modules that process an atmospheric air feedstock. CO₂ is stripped selectively from the feed at a flowrate of 50 m³ h⁻¹ per module with negligible back pressure. Cycling data collected from the Airthena DAC demonstrator (Figure 1a) shows physical and chemical stability of the nanocomposite over 2680 cycles. Details of the process are described in the next section.

2. The Airthena DAC Demonstrator

The DAC process is designed to strip CO₂ from air by contacting the feed air with a MOF–polymer nanocomposite

Figure 1. a) Airthena direct air capture (DAC) demonstrator with dimensions 1.8 × 1.4 × 1.56 m, designed to host a maximum of nine modules. b) Single DAC module incorporating the blower, adsorption chamber (proprietary Airthena technology) and vacuum pump. c) Continuous operation using three modules with alternating adsorption and desorption phases.
loaded into a modular unit. As shown in Figure 1b, a single module comprises of three major units: the blower, the adsorption chamber, and a vacuum pump.

- Adsorption at atmospheric pressure greatly reduces the energy and cost of feedstock compression.
- The use of low cost and energy efficient blowers allows a high volume of air to be processed without incurring a back-pressure penalty or reduced performance. The blowers can generate flow rates up to 50 m$^3$ h$^{-1}$ with a backpressure less than 100 Pa.
- The adsorption chamber contains the core Airthena technology: a MOF−polymer nanocomposite and substrate configuration responsible for the adsorption and desorption of CO$_2$ from the feed air. The MOF−polymer nanocomposite is coated as thin layers onto long resistive heating sheets wound into a spiral configuration which are installed within each adsorption chamber. The regeneration phase of the DAC process uses a simple, low-energy and, thereby, efficient resistive heating technology.
- The vacuum pump has a dual function in the DAC process. After the adsorption step, it removes excess air from within the module. During the desorption step the pump drains the liberated CO$_2$ from the adsorption chamber after the target regeneration temperature is achieved.

The composition of the nanocomposite and the scroll configuration of the substrates are designed to ensure optimum contact between the feed air and the nanocomposite. This ensures efficient stripping of the CO$_2$ from the feed air while maximizing the rejection of atmospheric moisture. As has been highlighted in previous DAC research publications, a major factor that contributes to the cost of DAC is the amount of energy required to liberate the captured CO$_2$.[3b,14a,18,20] To overcome this challenge, the Airthena technology uses a low-energy adsorbent and resistive heating technology for the regeneration phase of the DAC process. Significantly, the heating substrate also provides most the mechanical strength of the contactor system, which is coated with the nanocomposite. This means the mass of heated components within the Airthena unit is limited to that of the heating element, the nanocomposite, and some minimal support structures. Consequently, this system is inherently efficient, as heat energy is conducted directly to the adsorbent nanocomposite with little opportunity for loss to other parts of the device. Experiments revealed an optimum desorption temperature of 80 °C, compared to 900 °C reported for calcination-based CO$_2$ capture.[14a] The heating rate is controlled by the voltage (20–120 V) applied to the resistive heater. Critically, the target regeneration temperature of 80 °C can be achieved within 5 min when the applied voltage exceeds 45 V, see Figure 2. This is significant because high-porosity adsorbents such as those used in the Airthena system are inherently good thermal insulators and, therefore, they are generally difficult to heat quickly.

Figure 1c presents the simplified Process and Instrumentation Diagram for the continuous operation of the DAC process. The three-adsorption chambers each containing the core Airthena technology are connected in parallel. This allows the smooth interchange between the adsorption and desorption phases, described in the continuous production section.

### 2.1. Preliminary Experiments on a Single Module

In order to evaluate the suitability of the Airthena technology for DAC, breakthrough experiments were first performed on a single module under the conditions listed in Table 2. The adsorption chamber contained a loading of 60 kg m$^{-3}$ for the MOF−polymer nanocomposite and around 10 kg was produced. The module is fitted with thermocouples, and pressure transducers on the feed and downstream sides. The concentration of each component including CO$_2$, H$_2$O, O$_2$, and N$_2$ was monitored using a Pfeifer Omnistar GSD 320 O series mass spectrometer. Results from the preliminary breakthrough experiments on a single module were used to demonstrate viability of the composite material for DAC. All energy costs were based on the automated continuous process described in Section 2.2.

**Figure 2.** Temperature rise profile of Airthena module as a function of applied voltage during regeneration for an electrically powered mobile direct air capture (DAC) unit.

**Table 1.** Continuous production process using a cascade of adsorption-regeneration steps through the three modules.

<table>
<thead>
<tr>
<th>Cycle 1$^{a}$</th>
<th>Cycle 2</th>
<th>...</th>
<th>Cycle N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time (mins)</td>
<td>30</td>
<td>60</td>
<td>90</td>
</tr>
<tr>
<td>Module 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blue</td>
<td>Red</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>Module 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Module 3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^{a}$Blue indicates adsorption/cooling time and red indicates regeneration time. N stands for total number of cycles. Regeneration time includes both evacuation and desorption processes.
module, the CO₂ breakthrough time is almost instantaneous while the equilibration or saturation time is between 60 and 90 min, Figure 3b. Desorption was tested at 80 °C using a helium carrier gas at a flow rate of 500 cm³ min⁻¹, see Figure 3c. The use of a carrier gas during desorption allowed the output to be measured more accurately than with a vacuum-driven desorption. Results reveal a slight difference for CO₂ produced from the module after different adsorption times. The 3 h adsorption time recorded the highest yield of 6.3 g of CO₂, with the 2 and 1 h adsorption time recording a yield of 5.9 and 5.5 g, respectively. The configuration and composition of the module ensured minimal water uptake. The mass of H₂O produced after 120 min of regeneration for 3, 2, and 1 h of adsorption was 0.29, 0.16, and 0.16 g, respectively. Prolonging the adsorption time by an extra hour from 2 to 3 h resulted in almost double the H₂O uptake (×1.8) compared with a minor increase in CO₂ uptake (×1.08). In this way, the kinetics of the system may be exploited by shortening the adsorption time to deliver a small drop in CO₂ adsorption while minimizing water uptake. The purity of the CO₂ released as a function of regeneration time was also monitored, see Figure 3d. More than 70% purity was

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**Table 2.** Process parameters for each module in the Airthena direct air capture (DAC) demonstrator.

<table>
<thead>
<tr>
<th>Parameter [units]</th>
<th>Preliminary testing (single module)</th>
<th>Pilot-scale demonstration (per module)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed flow rate [m³h⁻¹]</td>
<td>5.4</td>
<td>50</td>
</tr>
<tr>
<td>Adsorption time [min]</td>
<td>180</td>
<td>60</td>
</tr>
<tr>
<td>Regeneration time [min]</td>
<td>120</td>
<td>30</td>
</tr>
<tr>
<td>Feed H₂O [ppm]</td>
<td>180</td>
<td>1000</td>
</tr>
<tr>
<td>Feed CO₂ [ppm]</td>
<td>450</td>
<td>400</td>
</tr>
<tr>
<td>Regeneration temperature [°C]</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Regeneration method</td>
<td>Helium sweep</td>
<td>Vacuum</td>
</tr>
<tr>
<td>CO₂ output per cycle [g (g-CO₂/g sorbent)]</td>
<td>6 (26.4)</td>
<td>3 (13.2)</td>
</tr>
<tr>
<td>Total energy consumption [kWh kg⁻¹]</td>
<td>–</td>
<td>2.28</td>
</tr>
<tr>
<td>• Heating (measured)</td>
<td>–</td>
<td>1.6</td>
</tr>
<tr>
<td>• Air flow (calculated)</td>
<td>–</td>
<td>0.17</td>
</tr>
<tr>
<td>• Evacuation vacuum (calculated)</td>
<td>–</td>
<td>0.33</td>
</tr>
<tr>
<td>• Desorption vacuum (calculated)</td>
<td>–</td>
<td>0.18</td>
</tr>
</tbody>
</table>

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**Figure 3.** a) Preliminary breakthrough curves for a single module b) CO₂ breakthrough curves for different adsorption times. Feed air initially bypasses the adsorption chamber to establish a background signal before switching the feed to the chamber. c) Mass of CO₂ and H₂O produced for different adsorption times at a regeneration temperature of 80 °C. d) Purity of CO₂ produced during regeneration of the direct air capture (DAC) module. See Figures S1 and S2 (Supporting Information) for nine repeated experiments.
achieved after 1 h of regeneration. Note that the purity is calculated by subtracting the amount of helium in the feed, i.e., the balance contains N₂, O₂, and H₂O remaining in the void spaces of the Airthena module. As the temperature increases during regeneration, a peak in CO₂ purity was observed as more CO₂ is released from the adsorbent which is detected by the mass spectrometer with the aid of the helium sweep gas. When the target temperature of 80°C was attained, the maximum amount of CO₂ released is indicated by the CO₂ peak in purity. Afterwards, the residual CO₂ is desorbed at a decreasing rate. Occasionally, a second peak is observed as the thermostat controller switches the voltage back on to maintain the target temperature. To examine the reproducibility of the single module test, CO₂ breakthrough experiments for different adsorption times were performed. Results for nine cycles that demonstrated reproducibility with a little variation shown in Figures S1 and S2 (Supporting Information). For the pilot-scale demonstration, vacuum was used instead of the helium sweep to extract the captured CO₂ that was directed from the vent to product at a maximum purity of 80%, as shown in Figure 4.

2.2. Continuous Production Using Multiple Modules

Results obtained from the single DAC module were used as a basis to build a demonstrator with multiple modules capable of continuous capture and production. The demonstrator was automated to combine the product of three modules. Table 1 demonstrates the cascading process of the adsorption-regeneration cycle using Temperature-Vacuum Swing Adsorption (TVSA). Table 2 lists the process parameters. Figure 4 depicts the data collected during a complete cycle including CO₂ output purity, temperature, and pressure. The adsorption-regeneration cycle consists of the following phases:

1. Adsorption phase (1 h). During adsorption, the valves are OPEN, and fans are switched ON to process incoming air at ambient conditions at around 50 m³ h⁻¹. This step also enables cooling from the previous desorption step lasting around 15 min (see in Figure 3).
2. Regeneration Phase (30 min).
   a. Evacuation Step (15 min). After the adsorption phase, the valves are CLOSED and the vacuum pump is switched ON to remove excess air within the module. The vacuum pump reduces the internal pressure from ambient to around 35 mbar.
   b. Desorption Step (10 min). After the evacuation step, the valves remain CLOSED, the vacuum pump is switched OFF and the heaters are turned ON. The temperature reaches 80°C within 10 min. During this time, the internal pressure increases as the CO₂ is released from the adsorbent.
   c. Collection Step (5 min). After the desorption step, the heaters are switched off, and the vacuum pump is switched ON to collect the CO₂ reaching a purity of around 80%. After the collection step, the adsorption-regeneration cycle is repeated.

At the end of the collection step, there is a pause step where the operational module waits for another module to complete its cycle. From Figure 4, the temperature within the module is seen to gradually increase beyond the set desorption temperature despite the heater being turned off. To overcome the potential effects on the kinetics of CO₂ adsorption during the consequent adsorption cycle, the configuration used within
the module allows for rapid cooling of the bed at the onset of the adsorption step (see Figure S3, Supporting Information). For our process, the rapid cooling which allows the temperature inside the module to drop to less than 40 °C in less than 10 min provides a suitable condition for DAC to proceed without any significant impact on the kinetics.

In all scenarios, temperature, pressure, CO₂ purity, and power consumed by the process were monitored during operation. For the adsorption runs, air with a CO₂ concentration of 400–500 ppm and a H₂O concentration of 1000 ppm at 25 °C was fed into adsorption chamber at a flow rate of 50 m³ h⁻¹. Regeneration was carried out at 80 °C by applying a voltage of 120 V to the resistive heating system.

Analysis of the resistive heating process revealed a minimal energy consumption of 1.6 kWh kg⁻¹ CO₂ to achieve desorption of the CO₂ from the nanocomposite adsorbent. Power usage was uniform across all cycles as the regeneration times were identical for each module. The total system energy consumption of 2.28 kWh kg⁻¹ is estimated by calculating the fan and vacuum energy consumption based on measured operational performance, summarized in Table 2. Air flow N_fanout was measured at a rate of 50 m³ h⁻¹ with a back pressure Δp of 20 Pa. Assuming a fan efficiency η_fan of 0.8, the associated energy cost E_fan for fan airflow is estimated to be 0.17 kWh kg⁻¹ according to the following equation [6]:

\[ E_{\text{fan}} = \frac{1}{\eta_{\text{fan}} N_{\text{output}}} \times \Delta p \times t_{\text{ads}} \]  \hspace{1cm} (1)

where \( t_{\text{ads}} \) is the adsorption time of 60 min and \( N_{\text{output}} \) is amount of CO₂ output of the per cycle. Vacuum costs include the energy consumption \( E_{\text{vacuum}} \) during an evacuation step of 0.33 kWh kg⁻¹ and a desorption step of 0.18 kWh kg⁻¹. Prior to heating, the canister is pumped down from ambient pressure (1 bar) to 37 mbar to evacuate the residual air in the void space in and around the nanocomposite. After heating, the canister pressure rises to 264 mbar as the CO₂ is desorbed from the nanocomposite, which is subsequently extracted using the vacuum pump. The final pressure of the canister is around 60 mbar, see Figure 4. The energy consumption of both vacuum steps is calculated from the following equation [6]:

\[ E_{\text{vacuum}} = \frac{V}{\eta_{\text{pump}}} \left( \frac{p_{\text{start}}}{p_{\text{ambient}}} - \frac{p_{\text{end}}}{p_{\text{ambient}}} + \ln \left( \frac{p_{\text{end}}}{p_{\text{start}}} \right) \right) \]  \hspace{1cm} (2)

where \( V \) is the free volume of the canister measured at 7 L, \( \eta_{\text{pump}} \) is the efficiency of the vacuum pump assumed to be 0.7, \( p_{\text{ambient}} \) is the pressure of the outside atmosphere, and \( p_{\text{start}} \) and \( p_{\text{end}} \) are the pressures of the canister before and after vacuum, respectively.

The Airthena technology for DAC is designed to operate completely relying on electricity for both the adsorption and regeneration phases. As shown in Table 2, the pilot scale demonstrator has four major operations that are powered by electricity: heating, airflow, vacuum evacuation, and vacuum desorption. Fasihi et al. [24] highlighted the scarcity of economic estimations in most reported literature for DAC systems. For this reason, they proposed a generic standardized cost evaluation based on regeneration models for a number of scenarios. The model combines the use of electricity and steam for regeneration with the potential for free waste heat and carbon-free sources of electricity. For the Airthena DAC demonstrator, the resistive heating technology solely relies on electricity to generate heat for regeneration to ensure a mobile unit can be deployed and operate on-site in distributed locations. Cost estimations for operation were calculated for energy use per kg of CO₂ captured for four different scenarios with different sources of electricity, listed in Table 3.

Electricity generation from solar PV, solar thermal, hydro, and natural gas with carbon capture and storage (CCS) were considered to power the DAC process. The U.S. Department of Energy in their annual energy outlook for 2018 estimated levelized cost of electricity (unweighted average) for new generation resources listed in Table 3. All these sources are classified as carbon free sources of electricity except for natural gas with CCS which has a very low CO₂ emission of 0.08 tCO₂e MWh⁻¹. Thus for the Airthena technology, the cheapest cost of electricity that will be required to drive the process will be from solar PV. Additionally, for process industries where waste heat is readily available and can be used for adsorbent regeneration, the overall operational cost of DAC for Airthena will be reduced due to a lower levelized cost of DAC estimated to be about 40 € ton-CO₂⁻¹ (46 US$ ton-CO₂⁻¹). It is important to note that additional energy costs will need to be considered to upgrade the purity for sequestration (99.5%), anaerobic (99.95%), food (99.9%), and industrial (99.5%) applications using the CO₂ product. A comparison of these operational costs relative to other DAC technologies reported by Fasihi et al. [24] reveals a promising energy requirement and associated cost for the Airthena technology for advancing the commercial viability of mobile DAC units. Furthermore, a projected 50% decrease in MOF production costs to about $10 kg⁻¹ for natural gas storage and other applications [22] encourage the evaluation of several theoretical MOFs in commercially viable DAC units.

Figure 5 presents the CO₂ output from the Airthena DAC demonstrator consisting of three modules over the duration of the testing period. With an average capture rate of 3 g of CO₂ per cycle per module, the Airthena DAC demonstrator produced a total of 8 kg of CO₂ over 2680 cycles. The performance of the nanocomposite adsorbent also revealed a very good level of stability of the system with no evidence of capacity loss. Fluctuations in the observed output were due to the range of process parameters tested throughout the work program. The optimized process parameters for the demonstrator are listed.

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Table 3. Airthena direct air capture (DAC) demonstrator CO₂ cost evaluation of operation.

<table>
<thead>
<tr>
<th>Source</th>
<th>Levelized costs of electricity for plants in 2022 [US$ MWh⁻¹]</th>
<th>Airthena DAC technology CO₂ Cost [US$ ton-CO₂⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar photovoltaics (PV)</td>
<td>49.9</td>
<td>102</td>
</tr>
<tr>
<td>Solar thermal</td>
<td>126.6</td>
<td>258</td>
</tr>
<tr>
<td>Hydroelectric</td>
<td>61.7</td>
<td>126</td>
</tr>
<tr>
<td>Natural gas with CCS</td>
<td>74.9</td>
<td>152</td>
</tr>
<tr>
<td>Waste heat</td>
<td>-</td>
<td>45[24]</td>
</tr>
</tbody>
</table>

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in Table 2, including the adsorption and regeneration times of 60 and 30 min, respectively. Assuming a 9-module system and further optimization, the demonstrator could capture 6 kg of CO₂ per day.

A direct comparison with other sorbent materials was not made due to the scale and nature of the process as well as the lack of cost and lifetime data available for alternate materials. The parameters used in operating the demonstrator were arrived at by analyzing the performance of a single canister (Figure 3) and selecting conditions representative of those that will be used in running a full-scale DAC process. For example, the helium sweep used to evaluate the volume of CO₂ produced was replaced with a vacuum collection step in the automated cyclic process.

3. Conclusion

A pilot-scale demonstration of mobile DAC using a MOF-based nanocomposite and electrically powered regeneration was assessed. The demonstrator showed stable CO₂ output at 70–80% purity over 2680 cycles and required a minimal regeneration energy of 1.6 kWh kg⁻¹ CO₂. The capacity to handle ambient air and high feed flow rates up to 50 m³ h⁻¹ per module were observed. A major advantage of the Airthena module is its relative stability in ambient air, ability to deploy standalone units in remote locations, and low energy requirement, which can be completely satisfied with renewable energy sources. The data produced by this demonstrator has informed the design of a second 6 kg CO₂ day⁻¹ minimum viable scale production unit. Design and construction of this full-scale Airthena unit will focus on reducing component and assembly costs for mass production. The data produced by it will allow operational parameters to be optimized in the field to give accurate and practicable measures of productivity at scale. This will be used to further confirm the high performance outlined in this paper, and to provide accurate capital and operational cost estimates for commercial deployment.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

carbon dioxide, CO₂, direct air capture, efficiency, regeneration

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