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Exploring small-scale direct air capture in a building ventilation system: a case study in Linköping, Sweden

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Direct Air Capture (DAC) technologies have emerged as a promising solution to address climate change and meet global climate goals. However, despite the importance of DAC in designing carbon-negative buildings, there is a lack of research focusing on the energy and cost aspects in building ventilation systems. The objective of this research is to investigate the CO_2 capture potential and economic viability of integrating small-scale DAC into a building ventilation system integrated within a gym space. A gym space located in the city of Linköping, Sweden, is used as the research object. Furthermore, the study investigates the CO_2 capture potential across a portfolio of gym spaces corresponding to an area of 24,760 m^2. The results show that the CO_2 capture potential varies between 54 kg/day and 83 kg/day for the investigated gym space. Moreover, the total CO_2 capture potential is between 588 ton CO_2/year and 750 ton CO_2/year for the portfolio of gym spaces. The results also demonstrate that regenerating the sorbent during non-operating hours is more energy-efficient and economically advantageous compared to performing four complete regeneration cycles during operating hours. Based on a sorbent capture potential of 0.2 mmol/g and 2.0 mmol/g, and a CO_2 price of 1,000 SEK, the break-even price for energy is 0.25–0.53 SEK/kWh. Lastly, the research shows that, among the investigated cases, the only economically viable solution corresponds to sorbent capture potential 2.0 mmol/g and utilizing low-grade heat for the generation process, resulting in a total cost of 663 SEK/ton CO_2.

KEYWORDS

direct air capture, CO2 capture, ventilation systems, climate-neutral buildings, metabolic CO2

Highlights

- This research studies the CO_2 capture potential and economic viability of integrating small-scale DAC into a building ventilation system integrated within a gym space.
- The study also investigates the CO_2 capture potential across a portfolio of gym spaces corresponding to an area of 24,760 m^2.
- The total CO_2 capture potential is between 588 ton CO_2/year and 750 ton CO_2/year.
- The break-even price for energy is 0.25–0.53 SEK/kWh

1 Introduction

1.1 Background

The concentration of atmospheric CO_2 has increased since the industrial revolution, contributing to global warming and its adverse effects such as ecosystem disruptions and natural disasters (IPCC, 2021). To address this issue, organizations have established goals and targets for decreasing global CO_2 emissions, such as the Paris Agreement and the European Green Deal (United Nations Climate Change, 2015; European Commission, 2019). Today, the concentration of CO_2 in the atmosphere is 420 ppm (NASA, 2023). In their widely cited paper on atmospheric CO_2, (Hansen et al., 2008) underscore that that the atmospheric CO_2 concentration needs to be reduced to below 350 ppm to prevent irreversible impacts. This means that regardless of whether all sectors achieve climate neutrality, there is still a need to reduce the concentration of CO_2 in the atmosphere. In pursuit of global climate goals, the IPCC highlights the importance of Carbon Dioxide Removal (CDR) measures (IPCC, 2021). An advancing method for CDR is Direct Air Capture (DAC), which refers to the process of extracting CO_2 directly from the ambient air (Honegger and Reiner, 2018). DAC has gained significant attention recently, not least due to the inauguration of the world's first large-scale plant in Iceland in 2021 (Reuters, 2021). DAC demonstrates a lot of promise in the pursuit of CO_2 removal (Lenton, 2014) and IPCC (IPCC, 2021) states that DAC technology has the potential to remove 310 $GtCO_2$ by 2,100. However, the current high expenditures and energy use related to DAC hinder its broad implementation (Ji et al., 2023). This is because of the significant energy use for the fans and desorption of sorbents. The CO_2 capture cost for large-scale DAC with current technologies is approximately 1,400–3,600 SEK/$tC0_2$ (IEA, 2022) based on an exchange rate of 1 \$ ≈ 10.8 Swedish Krona (SEK) (European Central Bank, 2023). For DAC to become scalable and economically viable, a commonly recognized threshold is 100 \$ (≈1,100 SEK) per ton of CO_2 (Ozkan et al., 2022).

Within the built environment context, there is a broadening gap between the building sector's current climate performance and decarbonization pathway (UNEP, 2022). This is reinforced by the fact that the current practices in the built environment are insufficient for achieving a decarbonized built environment (Maduta et al., 2022). Additionally, by 2050, the anticipated capture is 700 Mt CO_2 yr^{-1}, significantly less than 7,000 Mt CO_2 yr^{-1} required to meet the upper climate target of 2°C (Shen et al., 2022). According to the Swedish Energy Agency (Swedish Energy Agency, 2021), public buildings in Sweden amounted to a total area of 176 million m^2, representing 25% of the total area in the built environment. Given the fact that this part of the built environment is characterized by high occupancy rates and prolonged periods of public space usage, it presents an overlooked opportunity for CO_2 capture. Based on a human metabolic emission rate of 34 g/CO_2 $person^{-1}$ h^{-1} (Smith, 1998) and an occupancy rate of 0.25 in public buildings for approximately 6.5 million people aged 15-64 (Statistics Sweden, 2023b), who spend a significant amount of time in public buildings, initial approximation show a CO_2 capture potential of 0.5 Mton/year. This corresponds to 1% of Sweden's CO_2 emissions (Statistics Sweden, 2023a) or compensates the CO_2 emissions of more than 100,000 persons nationally. Hence, DAC in buildings can contribute to huge reductions in CO_2 emissions from the building sector, and thus is an important step towards carbon neutral buildings. This not only offers the potential for decreasing CO_2 emissions, but also reduces the demand for Carbon Capture and Storage (CCS) in large point sources such as energy utilities and large-scale power plants, which require large amounts of energy to capture CO_2 and are associated with high resource exploitation and costs (Shen et al., 2022; Eldariry and Habib, 2018).

In recent years, the interest in DAC as a means to address climate change has grown within the research community. For example, (McQueen et al., 2020) investigated DAC connected to nuclear and geothermal plants in the United States. The findings demonstrated a cost reduction that promotes the large-scale deployment of DAC. Breyer et al. (2020) studied the possibilities of integrating low-cost renewable energy sources to DAC in Western and Central North Africa. Using solar power PV plants, wind power plants, battery storage, thermal energy storage coupled with DAC units, the costs for the captured CO_2 is calculated to 105 €/tCO_2, 70 €/tCO_2, and 55 €/tCO_2, for 2030, 2040 and 2050, respectively. In the context of the built environment, research has shown that metabolic CO_2 capture from building occupants is underexplored (Gall and Nazaroff, 2015). However, if implemented, it shows promising results for energy savings by employing CO_2 capture integrated with air recirculation (Kim et al., 2015; Harrouz et al., 2022; Baus and Nehr, 2022). Specifically, numerical studies show a potential of 30%–60% reduction in energy usage related to the ventilation system in both tropical and cold climates (Kim et al., 2015). Harrouz et al. (2022) found energy savings of 30% and 24% in classrooms and residential buildings, respectively. Baur and Nehr (Baus and Nehr, 2022) report an energy savings of 37%. Literature shows that the potential of ventilation integrated CO_2 capture offers a lot of opportunities, not only with energy savings, but also on atmospheric reduction of CO_2 and possibilities of improved indoor air quality in systems with recirculation. While scientific investigations within the built environment exist, it is crucial to emphasize that, as of the present, there has been insufficient focus on the role of metabolic and atmospheric CO_2 emissions in addressing the climate crisis (Li et al., 2022).

1.2 Objective and novelty of the research

New opportunities for decarbonization in the building sector can arise with metabolic CO_2 capture in ventilation systems integrated with DAC. In addition to reducing building CO_2 emissions, DAC contributes to offsetting the pressure on CCS at large energy supply systems, such as power plants, which require significant energy resources and are costly. Although scientific investigations on the integration of DAC into various sectors has attracted more research attention recently, research on energy and cost aspects in building ventilation system is scarce (Ji et al., 2023; Zhao et al., 2019). Furthermore, this constitutes an important step in the quest for designing negative carbon buildings from a lifecycle standpoint.

The aim of this paper is to investigate the CO_2 capture potential and economic viability of integrating small-scale DAC into a building ventilation system integrated within a gym space. This

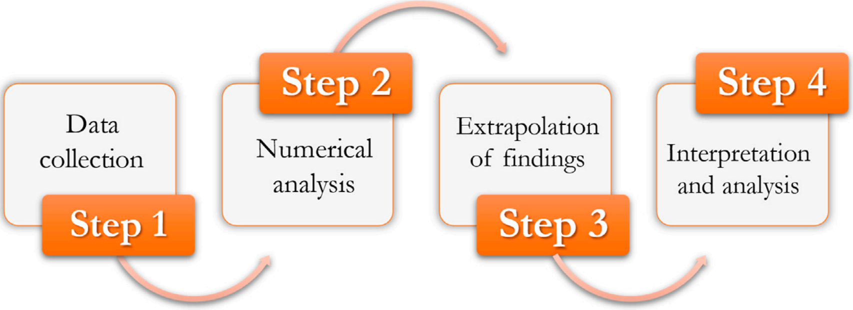

FIGURE 1
Schematic of the methodology.

research also studies the effects on economic viability when utilizing electric heat or low-grade heat for the regeneration process. Additionally, the study explores the CO_2 capture potential across a portfolio of gym spaces. The aim is achieved by investigating relevant literature, on-site measurements, numerical analysis, and extrapolation of the findings. A gym space located in the city of Linköping, Sweden, is used as the study object. Furthermore, the extrapolation is performed considering a total of 20 gym spaces in the city of Linköping.

2 Methodology

This research consists of four steps, as shown in Figure 1. In Step 1, data for energy use related to the ventilation system is collected. The collected data includes information provided by the operators of the ventilation system, direct measurements from the ventilation unit, and data from literature related to DAC technology. This comprehensive data set allows for numerically analyzing the CO_2 capture potential of integrating a DAC unit into the ventilation system. Step 2 consists of numerical analysis related to the performance of the DAC unit, which is performed in the software MATLAB. In Step 3, the findings from the numerical analysis are extrapolated to investigate the CO_2 capture potential in a portfolio of gym spaces. Lastly, in Step 4, the numerical analysis of the ventilation system, along with the extrapolation of findings, enables the interpretation and analysis of energy and economic figures.

2.1 Data collection

Firstly, data collection related to the ventilation system was performed. This includes information on system performance and energy use, which was obtained from operators of the ventilation system. Information on the parameters operating hours, volume of the ventilated space, temperature differentials, efficiency of the fans, and energy use, was collected. In addition to the data provided by the operators, on-site measurements were conducted to obtain missing data relevant to the study, such as the CO_2 concentration of the system. These measurements also served as a means of validating the accuracy of the provided data. To measure the CO_2 concentration in the air, a multiple parameter meter (Rotronic, 2023) with a measurement error of ±30 ppm ±5% was utilized. The measuring instrument was positioned in the exhaust air, measuring and collecting data on ppm, relative humidity, and temperature at 1-min intervals. The measurements were conducted over a 4-day period with varying occupancy levels. The property owner of the studied gym space supplied data on the occupancy levels during the measurement period. The collected data from the 4-day period was utilized to generate hourly average CO_2 levels, representative of the occupant levels during operational hours over a single day. Additionally, these measurements facilitated a deeper understanding of the ventilation system’s performance under varying loads and CO_2 concentrations, which enables a more thorough analysis of the integration of DAC technology into the system.

Relevant literature within the field was used to obtain data concerning energy demand per cycle and sorbent capacity in DAC technology during different conditions (Wurzbacher et al., 2011; Wurzbacher et al., 2012). Moreover, it was not feasible to conduct experiments on an implemented DAC device in the ventilation system itself. It should be noted that the data collected from the literature played a crucial role in evaluating the performance and feasibility of integrating a DAC device into the building ventilation system. Furthermore, this, along with data on the ventilation system and the on-site measurements, served as the foundation for the numerical analysis conducted in Step 2 of this research.

2.2 Numerical analysis

The numerical analysis in the presented research is performed in the Matlab software (Matlab, 2023), with a 1-min time interval, consistent with the data collection process. The sorbent characteristics used to numerically evaluate the performance of integrating DAC are based on the study by (Kim et al., 2015), which investigated a sorbent titled diamine-functionalized silica gel, consisting of 2–5 mm diameter beads, earlier presented in (Wurzbacher et al., 2011). Additionally, Kim et al. (2015) developed based on measurement procedures a calculation model for prediction of the amount of CO_2 adsorbed with an adsorption capacity of 1 kg, see Equation 1.

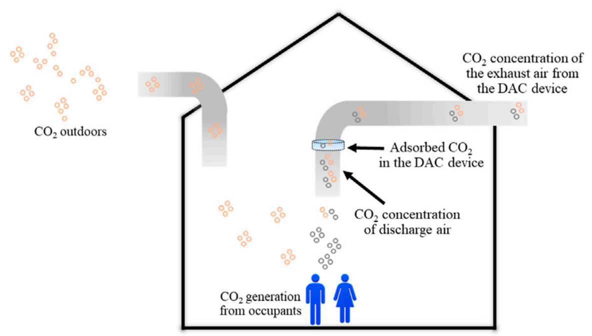

FIGURE 2
Schematic of CO$_2$ flows.

$$\mathrm{CO_{2,Ads}}(t) = \mathrm{CO_{2,Discharge}}(t)\cdot E_f \cdot \frac{2.388\cdot 10^6\cdot H_{ef} - \sum_2^t \mathrm{CO_2}\,(\mathrm{adsorption})\mathrm{ppm}\,(t\text{-}1)\cdot 0.4435}{2.388\cdot 10^6\cdot H_{ef}} \tag{1}$$

where $\mathrm{CO_{2,\ Ads}}(t)$ = the amount of CO$_2$ adsorbed (ppm) during the time t, $\mathrm{CO_{2,\ Discharge}}$ = CO$_2$ concentration of the discharge air (ppm) that will enter to the DAC unit, E_f = adsorption effectiveness, 0.75, and H_{ef} = a factor that takes into account the moisture effect of the air. This is one at a temperature of 20°C and 50% relative humidity ratio. Figure 0.4435 denotes the sorbent's deficiency factor as it captures and adsorbs CO$_2$.

Using Equation 1 until the sorbent reaches its capacity, the amount of CO$_2$ adsorbed can be calculated according to Equation 2, which enables predictions of the CO$_2$ concentration in the exhaust air from the ventilation system to the atmosphere after the DAC system, and the CO$_2$ capture potential of the ventilation system.

$$\sum_1^t \mathrm{CO_{2,Ads}} \leq 2.388\cdot 10^6 \tag{2}$$

Moreover, the CO$_2$ concentration in the discharge air as a function of time, $\mathrm{CO_{2,Discharge}}(t)$, was calculated using the mass balance equation for a studied building during the occupancy period, as shown in Equation 3.

$$V\frac{d\mathrm{CO_{2,Discharge}}}{dt} = Q\cdot \mathrm{CO_{2,O}} - Q\cdot \mathrm{CO_{2,Discharge}}(t) + G(t) \tag{3}$$

where V = volume of the studied building (m^3), $\mathrm{CO_{2,Discharge}}(t)$ = CO$_2$ concentration in the discharge air (ppm), G = CO$_2$ generation due to occupants (ppm), $\mathrm{CO_{2,o}}$ = CO$_2$ concentration outdoors (ppm), Q = volume flow rate (m^3/h). Integration of Equation 3, will predict the level of CO$_2$ concentration in the discharge air as a function of time, as shown in Equation 4.

$$\mathrm{CO_{2,Discharge}}(t) = \mathrm{CO_{2,O}} + \frac{G(t)}{Q} + \left(\mathrm{CO_{2,O}}(0) - \mathrm{CO_{2,O}} - \frac{G(t)}{Q}\right)\bullet e^{-n\bullet t} \tag{4}$$

It is important to mentioned that $\mathrm{CO_{2,O}}(0)$ = CO$_2$ concentration indoors at time 0, and $n = Q/V$ corresponds to the air change rate. Using data from the CO$_2$ measurements and Equation 4 for predictions of the amount of possible CO$_2$ adsorbed, the CO$_2$ concentration of the exhaust air from the DAC device, $\mathrm{CO_{2,Exhaust\ DAC}}(t)$, can be described following Equation 5.

$$\mathrm{CO_{2,Exhaust\ DAC}}(t) = \mathrm{CO_{2,Discharge}}(t) - \mathrm{CO_{2,Ads}}(t) \tag{5}$$

Thereafter, the total amount of CO$_2$ captured, in kg, can be calculated using the Ideal Gas Law, as shown in Equation 6.

$$\rho = \frac{M\cdot P}{R\cdot T} \tag{6}$$

where ρ = gas density (g/L), M = molar mass of the gas (g/mol), P = pressure (atm), R = the gas constant, and T = temperature (K). Moreover, it is important to note that the integration of a DAC unit to the current system will increase the pressure, and result in an increase in energy use. This is included in the numerical analysis related to the performance of the DAC unit.

A schematic of the CO$_2$ flows in the numerical analysis can be seen in Figure 2. The CO$_2$ flows are differentiated based on the outdoor CO$_2$, CO$_2$ generation from occupants, the CO$_2$ concentration in the discharge air, and the CO$_2$ concentration in the exhaust air after passing through the DAC device before it enters the atmosphere.

2.3 Extrapolation of findings

Analyzing the CO$_2$ capture potential in the investigated gym space enables extrapolation to 20 gym spaces in Linköping. This extrapolation assumes that the CO$_2$ capture potential is proportional to gym area, with consistent ventilation rates, usage patterns, etc., across locations, allowing for linear scaling based on gym space area. Additionally, the areas of the gym spaces were obtained through on-site visits and communication with on-site personnel responsible for each location. Through this approach, it is possible to predict CO$_2$ capture in gym spaces of various sizes, with the ultimate aim of contributing to the CO$_2$-neutral status of the city of Linköping. Figure 3 shows the areas of the investigated gym spaces in ascending order. There is a rather large variation in areas, ranging from 425 m^2 to 3,040 m^2. The total area in the studied gym spaces is 24,760 m^2, with an average area of 1,098 m^2 per gym.

2.4 Interpretation and analysis

The numerical analysis in Step 2 and the extrapolation of findings in Step 3 allow for the interpretation and analysis of energy use and economic performance related to the ventilation system. This enables a comprehensive understanding of the performance of implementing DAC into ventilation systems, both in the studied gym space and in the other gym spaces analyzed in Step 3.

3 Description of the study object

3.1 The gym space and the ventilation system

The object of study in this research is a ventilation system unit in a gym space located in central Linköping, Sweden, with a volume of

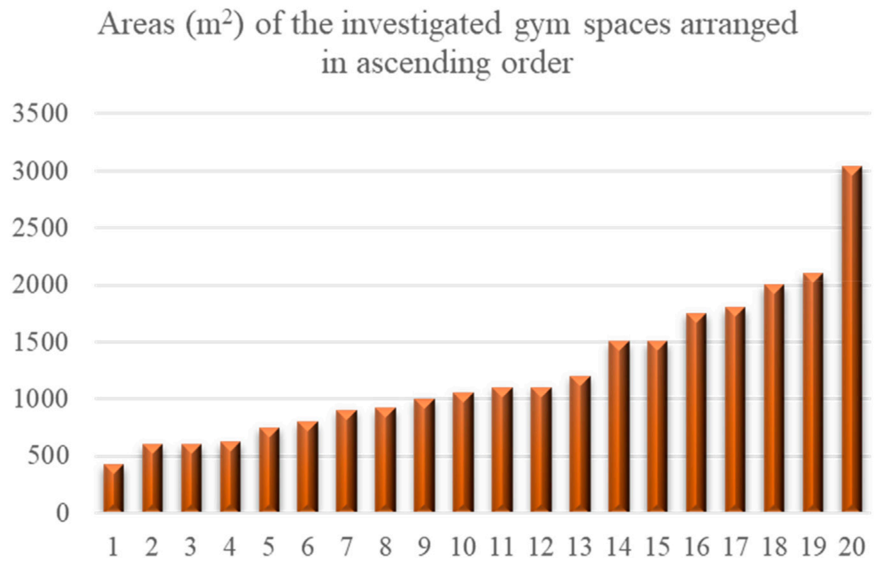

FIGURE 3
Areas (m^2) of the 20 investigated gym spaces in ascending order.

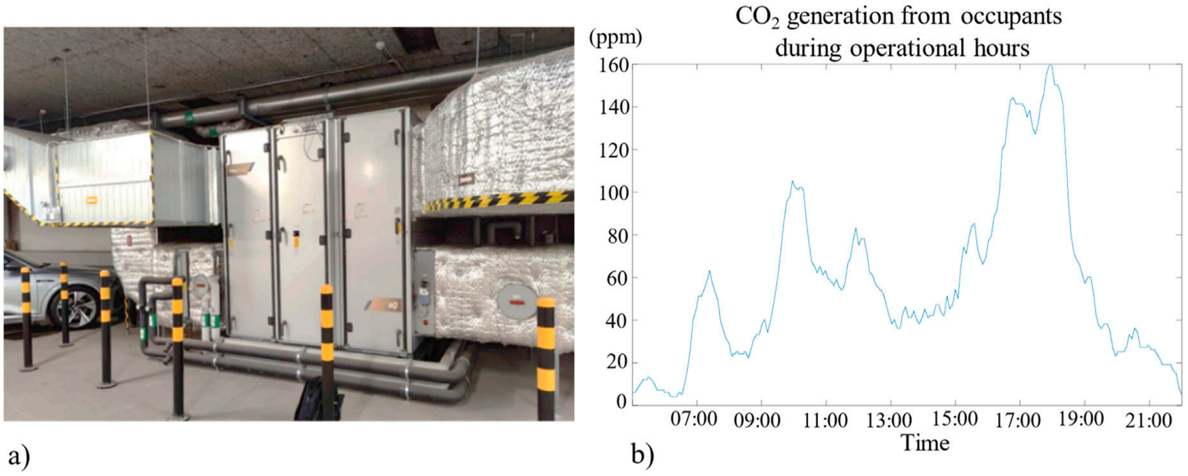

FIGURE 4
(A) The ventilation system unit in the studied gym space, located in Linköping, Sweden, and **(B)** the generation of CO_2 from occupants during operational hours, which is predicted by subtracting the $CO_{2,Discharge}$ with the $CO_{2,o}$.

3,000 m^3 and an area of 1,000 m^2. The ventilation system consists of a heat exchanger, two filters, two pumps, a valve as well as gauges to measure the airflow, temperatures, and pressures in the system. To the left in Figure 4, a photo of the ventilation system can be seen, while to the right, the CO_2 generation from occupants during operational hours (05.00–22.00) is shown. The CO_2 generation is based on the average from measurements taken over a period of 4 days, by subtracting the $CO_{2,Discharge}$ with the $CO_{2,o}$, which is the CO_2 outdoors. Moreover, it can be observed that the CO_2 generation levels from occupants are close to 0 at the beginning and end of the operational hours, with a peak of approximately 160 ppm at 18:00.

Figure 5 visualizes a flow chart of the ventilation system, including the positioning of the heat exchanger, filters, temperature and pressure sensors, and fans. Before entering the gym space, the supply air passes through a heating battery and a cooling unit. This is in order to adjust the temperature of the supply air to achieve the desired temperature of 17°C inside the gym space.

Table 1 presents generic values measured from the gauges shown in Figure 5. The system operates with a constant airflow of 3,000 m^3/h for the supply air, while the exhaust air maintains a constant airflow of 2,740 m^3/h. The discrepancy in airflow between the supply and exhaust air is due to system instability, which is caused by leakages in both the system and the gym space. Considering the baseline operating conditions, the total power consumption of the system is 3,408 W. The supply air fan consumes 1,788 W, and the exhaust air fan requires 1,620 W.

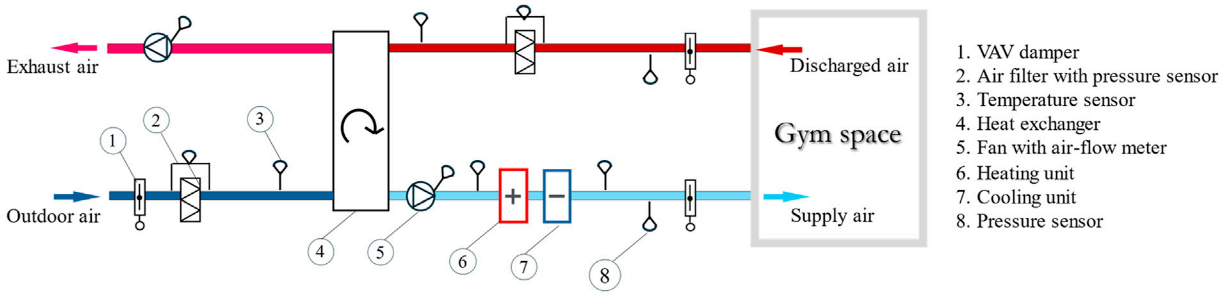

FIGURE 5
Flow chart of the ventilation system unit in the gym space.

TABLE 1 Data related to the gym space and ventilation unit.

	Value	Unit
Operating hours Space volume Air flow (in)	*05:00–22:00* *3,000* *10,800*	*hh:mm m^3* *m^3/h*
Air flow (out)	*9,900*	*m^3/h*
η fan	*65*	*%*
Total fan power	*3,408*	*W*
Outdoor CO_2 concentration	*420*	*ppm*

3.2 Investigated cases

This research investigates two cases in which different regeneration patterns were used. In Case 1, the sorbent is regenerated once daily during non-operating hours, whereas in Case 2 it operates through four full cycles during operating hours inspired by the study from (Wurzbacher et al., 2011), resulting in four regenerations. The reason for studying two different cases is because they have different energy needs, and therefore different operating costs. In Case 1, as the sorbent is regenerated during non-operating hours, the additional pressure drops over the DAC unit affects the system throughout its entire operating period. In contrast, this pressure drop is avoided in Case 2 during the regeneration periods of the sorbent. Moreover, the two cases require varying amounts of sorbent to achieve their maximum capacity during the sorption periods before regeneration. Temperature-Vacuum Swing Adsorption (TVSA) is the selected regeneration techniques based on (Wurzbacher et al., 2012; Sodiq et al., 2023).

A number of assumptions are made to facilitate the analysis of the DAC unit's performance. Firstly, it is assumed that both the temperature and humidity ratio of the air remain constant for calculation purposes, with a temperature assumption of 20°C and a humidity ratio assumption of 50%. In line with the experimental study by (Kim et al., 2015) on the sorbent, it is assumed that there is no infiltration, the gases are well-mixed, and the ventilation effectiveness is close to 100%. A pressure drop of 100 Pa over the DAC unit is assumed based on (Brillman, 2020), resulting in increased power usage. The investment cost for the DAC unit is not considered in this study. Monthly electricity prices for 2022 have been collected for the electricity price area in which Linköping is located, with an average price of 1.37 SEK/kWh, a maximum price of 2.69 SEK/kWh, and a minimum price of 0.77 SEK/kWh. Meanwhile, the price of heat has been obtained from the local energy company, Tekniska Verken AB. Moreover, the CO_2 price is based on carbon permit price in the EU using an approximate mean value for 2023 (90 €≈1,000 SEK) as reported by (Trading economics, 2023). The system's energy demand is calculated by taking into account the fans' power requirements, airflow rate, operating hours, and CO_2 capture, utilizing the molar mass of CO_2. Due to the differing regeneration patterns and varying amounts of sorbent required in the two cases, this results in distinct energy and power needs, and ultimately different operational costs for the system. The EU carbon permit price and calculations of the system's energy demand, together with the other assumption, allows for calculations of the break-even price of electricity using the numerical procedure described in Section 2.2.

4 Results and analysis

4.1 CO_2 concentration in the studied cases

Figure 6 presents the measured $CO_{2,\text{Discharge}}$ and the numerical prediction of $CO_{2,\text{Exhaust DAC}}$ during operational hours for Cases 1 and 2. The $CO_{2,\text{Discharge}}$ represents the CO_2 concentration that leaves the gym space and enters the DAC device, is based on experimental data obtained through on-site measurements. The $CO_{2,\text{Exhaust DAC}}$ represents the CO_2 concentration that is exhausted to the atmosphere, see Equation 5, and the difference between these two curves shows the CO_2 capture potential by integrating a DAC device, as derived from Equation 1. In Case 1, a sorbent capacity of 86 kg is used to reach the maximum sorbent capacity. This results in a CO_2 capture potential of 83 kg. In Case 2, a sorbent capacity of 14 kg is used. The adsorption period is 3 h and the regeneration period of the sorbent is 1 h and 15 min (Wurzbacher et al., 2011), which results in a CO_2 capture potential of 54 kg. Furthermore, the average decrease in CO_2 concentration after the DAC unit is 271 ppm in Case 1, while it is 177 ppm in Case 2.

4.2 Energy use of the DAC unit in the studied cases

Table 2 presents the energy use differentiated on thermal and mechanical energy use for the TVSA process, fan energy, as well as

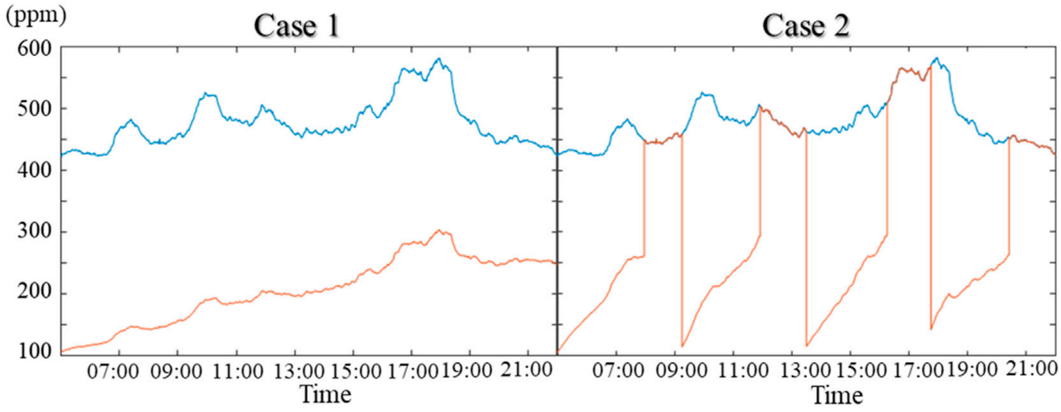

FIGURE 6
Measured $CO_{2,Discharge}$ (blue line) and numerically predicted $CO_{2,Exhaust\ DAC}$ (orange line) in Cases 1 and 2.

TABLE 2 Energy use (kWh/tC0$_2$) for Cases 1 and 2 differentiated on thermal and mechanical energy use, fan energy, and additional fan energy due to the DAC unit.

Case	Capture potential of the sorbent (mmol/g)	Thermal energy use[a] (kWh/tC0$_2$)	Mechanical energy use[a] (kWh/tC0$_2$)	Fan energy (kWh/ton C0$_2$)	Additional fan energy[b] (kWh/ton C0$_2$)	Total energy use (kWh/ton C0$_2$)
Case 1	0.2	2,714	61	694	94	3,563
	2.0	1,048	61	694	94	1,897
Case 2	0.2	2,714	61	1,070	102	3,947
	2.0	1,048	61	1,070	102	2,281

[a] For the TVSA, process.
[b] As a result of the pressure drop caused by the DAC, unit.

additional fan energy due to the DAC unit. Two figures on the capture potential of the sorbent are analyzed, i.e., 0.2 mmol/g and 2.0 mmol/g, based on the study by (Wurzbacher et al., 2011) that concluded that the performance of a sorbent varies between 0.2 and 2.0 mmol/g. The total energy varies between 1,897 kWh/ton C0$_2$ (Case 1 with a capture potential of 2.0 mmol/g) and 3,947 kWh/ton C0$_2$ (Case 2 with a capture potential of 0.2 mmol/g) as can be seen in Table 2. Moreover, it is important to note that the thermal and mechanical energy use are the same for the studied cases since the calculations are based on the energy use per mole capture CO_2. However, the energy use for the fans is higher in Case 2 due to a lower CO_2 capture potential as presented in Section 4.1.

For Case 1 with a capture potential of 2.0 mmol/g, the amount of sorbent required is 978 kg, while 159 kg is needed for Case 2. It is important to highlight that the required sorbent volume can create problems due to space restrictions within the ventilation system. Therefore, it is crucial to choose the most suitable sorbent with the highest CO_2 capture potential, as a higher capture potential reduces the amount of sorbent needed.

4.3 Economic analysis

The results related to the economic analysis are based on price of 1,000 SEK per ton CO_2 according to Section 3.2. Table 3 shows the break-even prices for energy in Cases 1 and 2 considering a capture potential of the sorbent of 0.2 mmol/g and 2.0 mmol/g. The highest break-even price for energy corresponds to 0.53 SEK/kWh (Case 1 with a sorbent capture potential of 2.0 mmol/g) and the lowest 0.25 SEK/kWh (Case 2 with a sorbent capture potential of 0.2 mmol/g). It should be noted that the costs for running the fans are included in the calculations.

Based on the CO_2 capture potential from Case 1, which has a higher break-even price for energy compared to Case 2, Table 4 shows the cost per ton CO_2 captured while either using low-grade heat or electricity in the regeneration process. The cost varies between 663 and 3,943 SEK/ton C0$_2$. At a price of 1,000 SEK per ton CO_2, the only economically viable scenario corresponds to utilizing low-grade heat and a sorbent capture potential of 2.0 mmol/g.

4.4 Extrapolation of findings to the 20 investigated gym spaces

Based on the CO_2 capture potential of the investigated gym space for Cases 1–2, the CO_2 capture potential is extrapolated for the investigated gym spaces in the city of Linköping. The areas of the investigated gym spaces (left y-axis) and the annual CO_2 capture potential for Cases 1–2 (right y-axis) can be seen in Figure 7. The

TABLE 3 Break-even prices for energy in Cases 1 and 2.

Case	Capture potential of the sorbent (mmol/g)	Break-even price for energy (SEK/kWh)
Case 1	0.2	0.28
	2.0	0.53
Case 2	0.2	0.25
	2.0	0.44

TABLE 4 Electric heat cost and low-grade heat cost per ton $C0_2$ captured.

Capture potential of the sorbent (mmol/g)	Electric heat cost (SEK/ton $C0_2$)	Low-grade heat cost (SEK/ton $C0_2$)	Percentage difference (%)
0.2	3,943	1,378	65
2.0	1,563	663	60

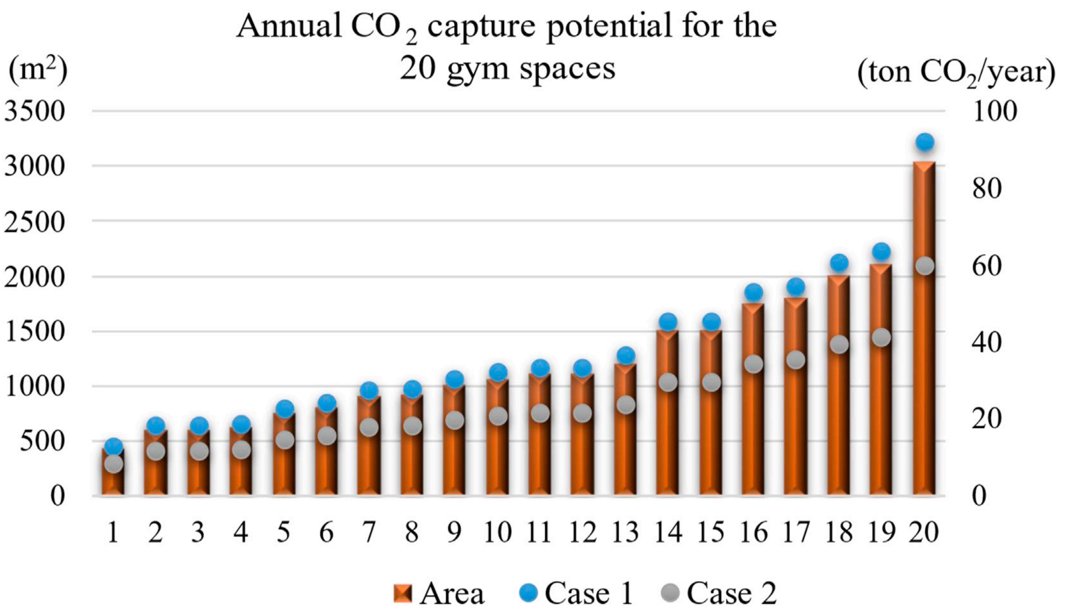

FIGURE 7
Areas (m^2) of the investigated gym spaces and their annual CO_2 capture potential, quantitative analysis in Section 2.2 and the extrapolation approach described in Section 2.3, with the assumption that the CO_2 capture potential is proportional to the gym area.

presented figures are based on the numerical analysis in Section 2.2, along with the extrapolation approach described in Section 2.3, assuming that the CO_2 capture potential is proportional to the gym area. In Case 1, the potential varies between 12.9 ton CO_2/year and 92.1 ton CO_2/year. The corresponding figures for Case 2 are 8.4–60.0 CO_2/year. The total CO_2 capture potential in Case 1 is 750 ton CO_2/year and in Case 2 it amounts to 588 ton CO_2/year. This offsets the CO_2 emissions from 994 to 647 cars from 2022 in Sweden, respectively. Additionally, considering the average annual emissions of an individual in Sweden (≈3.4 tons of CO_2 per year), a DAC unit has the potential to compensate for the CO_2 emissions of 221 individuals in Case 1 and 144 individuals in Case 2. It should be noted that this potential is solely based on 20 major gym spaces in Linköping. If applied to gym spaces or other public buildings, such as office buildings and schools, in entire cities, regions, or nations, DAC can play a crucial role in achieving a climate-neutral building stock.

5 Concluding discussion

The results show that the CO_2 capture potential varies between 54 kg CO_2/day and 83 kg CO_2/day, which corresponds to 19.7–30.3 ton CO_2/year. When considering the 20 investigated gym spaces in the city of Linköping, corresponding to an area of 24,760 m^2, the total CO_2 capture potential is between 588 ton CO_2/

year and 750 ton CO_2/year. If implemented, this compensates the CO_2 emissions from 994 to 647 cars from 2022 in Sweden, respectively.

With regard to economic aspects, it is important to highlight the impact from CO_2 and energy prices on the profitability of the DAC technology. CO_2 prices can fluctuate significantly depending on a number of factors, such as global economic conditions and market supply and demand. The considered energy prices in this research are based on local energy prices, both for electricity and heat. The electricity prices fluctuate depending on electricity price area, and the cost for heat varies depending on the local energy utility. Ultimately, the CO_2 and electricity prices, together with system performance of the DAC unit, dictates the profitability of DAC. Even though the investment cost for the DAC unit is not considered in the presented research, it is important to be aware of its impact on profitability aspects. The break-even price for energy is 0.25–0.53 SEK/kWh based on the assumptions used. Furthermore, the sole economically viable solution in this study corresponds to sorbent capture potential 2.0 mmol/g and utilizing low-grade heat for the generation process, which results in a total cost of 663 SEK/ton CO_2. Concerning the replicability of the results to other case studies, the authors would like to point out that it is difficult to generalize the performance of the studied DAC system. This is due to the fact that sorbent capture potential can vary significantly, as well as local energy prices for electricity and heat. For example, the price for low-grade heat is lower compared to electricity in the city of Linköping. Consequently, the utilization of low-grade heat is the most financially viable option. However, it is important to acknowledge that variations in electricity prices could significantly impact the outcome of this research. Lower electricity prices may lead to different conclusions and impact the overall economic viability of the studied cases.

Data availability statement

The datasets presented in this article are not readily available because only the presented data is available, due to restrictions from the owner of the gym space. Requests to access the datasets should be directed to vlatko.milic@liu.se.

Author contributions

VM: Conceptualization, Methodology, Visualization, Writing–original draft, Writing–review and editing, Formal Analysis. AS: Data curation, Formal Analysis, Investigation, Writing–original draft. AG: Data curation, Formal Analysis, Investigation, Writing–original draft. BM: Conceptualization, Formal Analysis, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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