



Potentials and limitations of direct air capturing in the built environment

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ABSTRACT

This concept study presents an approach for resolving the trade-off between energy-efficient building operation and the provision of hygienically harmless indoor air quality. A novel coupling of HVAC-systems (heating, ventilation and air conditioning systems) with DAC-technology (direct air capturing technology) is proposed to separate CO₂ in the exhaust air of buildings and recirculate the CO₂-depleted air back into the building. In a mainly theoretical approach, the corresponding potentials and limitations of the novel HVAC/DAC-coupling in recirculation mode are evaluated. For that purpose, CO₂-loads in the feed and exhaust air of four buildings located in Germany were measured using calibrated non-dispersive infrared (NDIR) sensors with pyroelectric detection principle. Subsequent numerical model simulations resort to typical meteorological data as well as building operation parameters grouped in different scenarios. The measurement and simulation results were assessed with regard to: (i) the unique possibilities of a HVAC/DAC-coupling in recirculation mode for the improvement of indoor air quality, (ii) the energy saving potentials through reduced air conditioning requirements enabled by a HVAC/DAC-coupling in recirculation mode, and (iii) the potential allocation of CO₂ separated from building exhaust air for energetic and/or material reutilization in decentralized systems. In conclusion, a HVAC/DAC-coupling in recirculation mode can not only reduce the energy demand of buildings but also facilitates access to unutilized CO₂-resources transported in the built environment and additionally offers the potential to improve indoor air quality. However, a suitable DAC module for operation in indoor air is not yet commercially available.

1. Introduction

1.1. Climate change and its challenges in Europe

In 2015, the United Nations agreed in Paris to put in all necessary effort to limit global warming to 1.5 °C compared to pre-industrial levels [1]. With its target to become climate-neutral by 2050, the European Union has set a sign of its motivation to participate in this task to prevent our society from the climate catastrophe that is slowly unfolding in front of us [2,3]. Germany recently went one step further and plans to achieve this goal already in 2045 [4,5]. Therefore new technologies to achieve this goal must be explored. Meanwhile, the constantly growing global energy demand must be reduced, especially in the built environment. Considering construction, usage, renovation and demolition, buildings in the European Union cause about 40% of the energy consumption and 36% of greenhouse gas emissions [6]. While thermal insulation plays an important role in every building, ventilation is an issue mainly for public or commercial buildings with an active ventilation system. In this

regard, efficient heating and cooling devices as well as energy recovery systems are essential for the energy management of modern buildings. Especially heat exchangers and demand controlled ventilation (DCV) have received growing attention over the last years [7–11]. Furthermore, smart ventilation strategies are emerging to further increase the energy efficiency of buildings [12]. These strategies are intended to resolve the conflict of aims between a hygienically harmless indoor air quality (IAQ) and a low energy demand of buildings. In this article, a novel approach for resolving this trade-off between energy-efficient building operation and provision of high indoor air quality is presented. This approach is based on coupling the DAC-technology (direct air capturing technology) into the ventilation infrastructure of buildings. DAC is a process designed to separate CO₂ from ambient air using a sorption technology. DAC-plants are already operated in ambient air and the further development is driven by several companies [13–15]. The proposed HVAC (heating, ventilation and air conditioning)/DAC-coupling is expected to not only recycle air to prevent its thermal energy getting lost, but also to effectively extract carbon

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dioxide (CO₂), the main molecule of interest in global warming.

The overarching goal of this study is to evaluate the possibility to attach a DAC-system to a larger building's ventilation machinery to achieve an overall energy saving in combination with the climate neutral CO₂-separation. This approach is expected to represent an essential contribution to business model development in emerging circular economies.

1.2. CO₂ - main actor in climate change and IAQ-management

Two major subjects, in which CO₂ is frequently discussed, are connected in this concept study. The first one is obviously the above-mentioned role in climate change. The elevated ambient CO₂-concentration is the main reason for global warming and therefore must be significantly lowered.

The other subject, in which CO₂ is a major player, is IAQ. Wherever several people occupy a room for a longer time without sufficient ventilation, the sensation of hygienically conspicuous air quality will be observed. Under these air quality conditions, the room occupants will suffer more frequently from headache, tiredness, attentiveness disorder and dizziness [16,17]. The reason for that is not a significantly lowered concentration of oxygen (O₂), as commonly supposed, but the build-up of CO₂ and humidity. While humans are not able to determine if the O₂-concentration in the air is 20% or 21%, the accumulation of less than 0.5% (5000 ppm) CO₂ is sensible for human beings, resulting in the typical symptoms mentioned above. Alongside with an increased air humidity and eventually unpleasant smells, CO₂ is a major factor when it comes to evaluating whether air is of low (hygienically conspicuous) or high (hygienically harmless) quality. Making the issue less dependent on personal sensations and tolerance, the absolute concentration of CO₂ is regarded as an important parameter to evaluate IAQ [8,18]. Over the last decades, several standards were established to give technicians and engineers guidance on how to control IAQ. The latest European Standard on the energy performance and ventilation of buildings, EN 16798-1, divides indoor air quality into four categories by considering design parameters for indoor environmental quality comprising indoor air composition and (thermal) comfort [19]. This study resorts to the design parameters temperature, relative humidity and CO₂-concentration. Category I requires the CO₂-concentration to not exceed 550 ppm above the atmospheric level of currently approximately 400 ppm. This category is designed for rooms occupied by sensitive people such as hospitals, retirement homes, and day care facilities. Category II, supposed to be the standard for offices and public buildings, requires not more than 800 ppm above the atmospheric level. This tolerance implies a maximum of approximately 1200 ppm for a category II building. However, environmental authorities advise not to regularly exceed a level of 1000 ppm as already stated by Pettenkofer in 1858, to prevent adverse health effects [20]. This issue shows how difficult it is to ensure a low CO₂-concentration in an energy-efficient system with conventional ventilation systems, especially in combination with elevated ambient CO₂-levels. For highly occupied building parts, such as seminar rooms or classrooms, it is almost impossible to maintain an acceptable low CO₂-level without either very large or further optimized ventilation setups [9,21–24]. At this point, this study proposes a novel ventilation concept, which uses DAC-technology to actively remove CO₂ from buildings' exhaust air, to filter remaining impurities and to recirculate the air back into the building at almost the same temperature without the use of heat exchangers.

1.3. DAC-technology

The DAC-technique and its potential role in future's energy and chemical industry has recently been object of scientific discussions [25–28]. Common DAC-principles are well known. However, evaluation of its commercial potential is complex due to several socio-political and economic uncertainties. The mass-specific CO₂-separation costs are

considered too high and the expected cost reductions in the future due to scale-up and further material development are uncertain [25,27]. Energy inputs of several MWh/t_{CO2} are needed to extract CO₂ from atmospheric air [15,29,30]. Taking first pilot plants of few companies into account, the concept of operating a DAC-module in atmospheric air to convert energy to CO₂ cannot be commercially feasible when the only benefit of such a plant is to sell carbon dioxide. To answer the question, if DAC can be commercially feasible, the general conditions of a carbon-based industry in 20–30 years must be considered. The EU anticipates to be climate-neutral by 2050. That means no fossil carbon-based resources can be used to produce energy and chemicals by then. However, while the energy demand of 2050's society might be covered by regenerative energy sources, the demand for chemical products such as plastics, oils, paints and others that contain carbon as major chemical building block cannot easily be altered. Furthermore, energy storage using carbon-based fuels can be an appropriate expansion to electrical and thermal storage solutions over a longer period of time [31–33]. Thus, it is mandatory to find a solution to efficiently produce carbon-based products via an alternative route. The DAC-technique combines this accessibility to non-fossil carbon with the slow but steady CO₂-removal from the atmosphere.

There are different DAC-concepts currently evolving to be accessible on the market [34]. One approach resorts to an absorption process using liquid absorbers, where CO₂ is first brought in contact with a reactive solution like, e.g., an aqueous solution of sodium hydroxide, potassium hydroxide or amines. In a second step, the CO₂-loaded solution is treated in a regeneration process to extract carbon dioxide [13]. The alternative is a solid-bed adsorption, where solid materials with active surfaces reversibly bind CO₂. The use of amine-functionalized silica which chemically bind CO₂ is one example [28]. Alternatives are porous materials such as zeolites or MOFs (metal-organic frameworks) [35–37]. Since this study is focussed on recirculating CO₂-depleted air back into the building, the concept of solid-bed adsorbers is investigated. Their major benefit is the lack of water in the regeneration process of the adsorber and therefore no additional humidification of indoor air.

The potential of buildings' exhaust air was recently pointed out by Dittmeyer et al., who mentioned the vast amount of ventilated air in the HVAC-systems of large buildings [26]. Starting from that point, where the main reason to use the exhaust air of buildings is the reduced effort to mechanically move air, the idea is extended to make use of the CO₂-depleted air.

Fig. 1 shows a simple theoretical setup for utilization of DAC to recycle indoor air. Ambient air enters the building and is first conditioned by a heat recovery system and an additional air conditioning device. The main air exchange is performed in a closed bypass system. Indoor air is mixed with ambient air via a three-way junction and directed to the recovery system. A primary filter removes impurities to protect the adsorbent and passes the air over the DAC's adsorber to remove CO₂. A secondary filter ensures an adequate indoor air quality. A major portion of air re-enters the building, while a minor fraction is exhausted. The ratio of the ambient air feed rate \dot{V}_{feed} to recycled air flow rate $\dot{V}_{recycling}$ can easily be adjusted by manipulating the three-way junctions. During the regeneration process, the CO₂-loaded adsorbers are treated with either heat [38], radiation [36], vacuum [39] or a combination of these methods [40,41] to remove CO₂, which can then be compressed, separated from condensing water and either stored or directly used for further applications.

A major issue for the development of DAC technologies is their specific energy demand. Typical values are often reported in megawatt hours per ton of bottled CO₂ (MWh • t⁻¹). State-of-the-Art solid bed DAC sorbents are designed to adsorb CO₂ at ambient temperature and pressure without further energetic input. The actual energy demand originates from the desorption process along with pumps, compressors and fans. Viebahn et al. provide an overview about state-of-the-art energy demands of DAC plants operated in ambient air as well as expectations

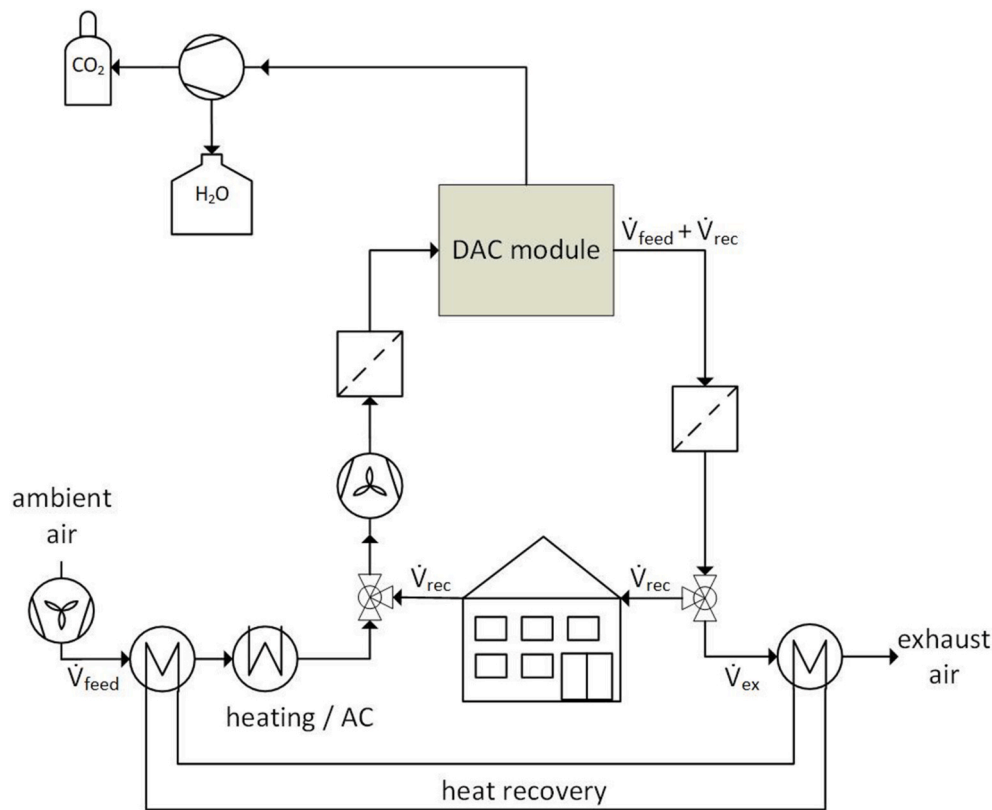


Fig. 1. Concept layout for a HVAC/DAC-coupling in recirculation mode.

of these demands in the future [25]. Values between 2 and 10 MWh per ton of bottled CO₂ are common. These energy costs - no matter if delivered as waste heat or electricity - render a standalone DAC plant economically unfeasible when selling captured CO₂ is the only financial yield of such a plant. The new approach, depicted in Fig. 1, offers the economic benefit of bottled CO₂ together with lowered buildings' energy costs due to less air-conditioning requirements when the major airstream of the building is recycled rather than exhausted.

For Germany, the CO₂-separation potential in the built environment can be estimated. Installed ventilation systems equipped with an air conditioning system featuring an electrical power of $P_{ac} > 12$ kW are taken into account. These ventilation systems exhibit a volumetric displacement of approximately $5 \cdot 10^9 \text{ m}^3 \text{ h}^{-1}$ air [42]. Assuming a continuous operation and a CO₂-concentration of 420 ppm in indoor air, about 32 million tons of CO₂ are transported per year in Germany's ventilation systems. This corresponds to about 4% of Germany's annual emissions of CO₂-equivalents of $739 \cdot 10^6 \text{ t year}^{-1}$ estimated for 2020 [43]. This shows that CO₂ from building's ventilation exhausts constitutes a potential future carbon source.

2. Methodology

In this study four buildings located in Germany are evaluated with respect to the potential implementation of a HVAC/DAC-coupling. Buildings with a mechanical ventilation system providing a volumetric flow rate in the order of $10^4 \text{ m}^3 \text{ h}^{-1}$ were chosen to assure comparability with currently available DAC systems. Furthermore, buildings with low occupancy in the order of up to 100 persons were chosen since ventilation systems of these buildings are characterized by low to medium CO₂-loads in building exhaust air and thereby represent a conservative scenario with respect to accessibility to non-fossil carbon sources. During the investigation period, the examined buildings were only partially populated. The measured amounts of CO₂ generated in the buildings are therefore lower than anticipated for regular occupancy.

2.1. Measurement of CO₂-loads in real buildings

The measurements are carried out using CL-11 NDIR CO₂-sensors by Rotronic. The sensors have a declared accuracy of ± 20 ppm and were furthermore calibrated at 0 and 3000 ppm. CL-11 sensors are equipped with an integrated capacitive hygrometer for the measurement of the relative humidity with a declared accuracy of $< 2.5\%$ as well as a thermistor for the temperature measurement with a declared accuracy of ± 0.3 K. The sensors are placed directly into the main feed and exhaust channels of the buildings' central ventilation units. The CO₂-concentrations are recorded over one week and the transported amount of carbon dioxide is calculated by numerical integration of the time-resolved concentration curves and subsequent multiplication with the volumetric flow rate. The investigated buildings are listed in Table 1.

2.2. Mass balances of H₂O and CO₂ in buildings using HVAC/DAC-coupling in a recirculation mode

As already outlined above, the concentrations of trace constituents play a vital role in the assessment of IAQ. For evaluating the (de)humidification requirements and the potential for CO₂-separation in the built environment, water and carbon dioxide loads are investigated in detail. While ventilation systems that are exclusively supplied with ambient air often result in dry indoor air (below 25% RH), recirculating systems may accumulate humidity, which results in too moist indoor air. The same applies for CO₂, that might accumulate in a building operated in a recirculating mode with insufficient ambient air feed.

Both, H₂O and CO₂ are exhaled from building occupants at an occupant-specific generation rate $s_{occupant}^i$ reported in $\text{g h}^{-1} \text{ person}^{-1}$ (i represents either H₂O or CO₂). The total occupant-related emission rate is given by the rate k_1^i that takes into account the number of occupants n :

$$k_1^i = n \cdot s_{occupant}^i \quad (1)$$

Table 1
Buildings investigated with respect to CO₂-loads and their ventilation parameters.

Time period	Building	Air exchange rate ^a [h ⁻¹]	Volumetric flow rate (operating conditions) [m ³ h ⁻¹]		Ventilation schedule [CEST]				
			\dot{V}_{feed}	\dot{V}_{ex}	Mon-Thu	Fri	Sat-Sun		
04/09/21-04/17/21	A: county administration Oberbergischer Kreis, Gummersbach	N/A	17 150	15 300	6:00–18:00	6:00–15:00	none	none	none
04/19/21-04/26/21	B: German Federal Ministry for the Environment, Bonn	1	27 400	24 000	6:00–16:00	6:00–16:00	none	none	none
04/27/21-05/04/21	C: county administration Städteregion Aachen, Aachen	1.35	21 590	19 240	5:45–19:00	5:45–19:00	none	none	none
05/05/21-05/12/21	D: Debeka Insurance AG, Koblenz	2.7	83 000	83 000	Mon: 4:30–19:00	Tue-Fri: 5:00–19:00	none	none	none

^a Air exchange rate as stated by the building operator given in ventilated building volumes per hour.

Moreover, H₂O and CO₂ are transported into the building via the ambient air feed \dot{V}_{feed} and via the recycling flow $\dot{V}_{recycling}$ expressed by the rates k_2^i and k_3^i , respectively:

$$k_2^i = \dot{V}_{feed} \cdot c_{i, ambient} \quad (2)$$

$$k_3^i = \frac{\dot{V}_{recycling}}{V_{building}} \quad (3)$$

$c_{i, ambient}$ represents the ambient H₂O- or CO₂-concentration. $V_{building}$ depicts the volume of the building.

In case of no dehumidification and no CO₂-separation, the exhaust flow $\dot{V}_{exhaust}$ leaving the building constitutes the only sink term for H₂O and CO₂ given by the rate k_4^i :

$$k_4^i = \frac{\dot{V}_{exhaust}}{V_{building}} \quad (4)$$

The overall mass balance of H₂O or CO₂ in buildings using HVAC/DAC-coupling in a recirculation mode is given by:

$$\frac{dm_i}{dt} = k_1^i + k_2^i + k_3^i \cdot m_i - k_4^i \cdot m_i - k_5^i \quad (5)$$

In equation (5)

m_i is the mass of either H₂O or CO₂ in g,

t is the time in h,

k_1^i is the occupancy-related emission rate for H₂O or CO₂ in g h⁻¹ resulting from respiration,

k_2^i is the input rate for H₂O or CO₂ in g h⁻¹ resulting from ambient air feed,

k_3^i is the recycling rate for H₂O or CO₂ in h⁻¹ determined by the ratio $\frac{\dot{V}_{recycling}}{V_{building}}$,

k_4^i is the air exchange rate in h⁻¹ determined by the ratio $\frac{\dot{V}_{exhaust}}{V_{building}}$, and

k_5^i is the required dehumidification rate/CO₂-separation rate in g h⁻¹ to avoid accumulation of H₂O or CO₂ in the building.

Equation (5) can be solved by inserting $m_i(t=0) = m_{i,0}$ and setting $k_5^i = 0$:

$$m_i = \left[m_{i,0} + \frac{(k_1^i + k_2^i)}{(k_3^i - k_4^i)} \right] \cdot e^{(k_3^i - k_4^i)t} - \frac{(k_1^i + k_2^i)}{(k_3^i - k_4^i)} \quad (6)$$

In this study, equation (6) is used to calculate steady-state concentrations of CO₂ in a recirculating ventilation setup assuming an average CO₂-separation rate of 60%. This value is assumed as an average performance over an adsorber lifetime based on findings by Kim et al. [28]. The CO₂-separation rate depends, i.e., on the DAC adsorber material, the actual load of the adsorber and the adsorption conditions. In the following steady-state-calculations, k_3^i is multiplied by a factor of ((1 - 0.6) · 0.8). This factor accounts for the assumed CO₂-separation rate of 60% and a recirculation rate of 80%. Further considerations resort to a steady-state CO₂-concentration in the feed of the HVAC/DAC-system calculated via equation (6).

2.3. Simulation of the energy saving potential in buildings using HVAC/DAC-coupling in a recirculation mode

Numerical simulations were carried out to determine the potential energy savings in the investigated buildings that can be realized by implementation of a HVAC/DAC-coupling in a recirculation mode. The main aspects are to determine the reduction of heating/cooling effort due to reduced volumetric feed rate of ambient air as well as altered dehumidification and dehumidification requirements in a mainly recirculating setup. Therefore, typical meteorological data (ambient temperature T , relative humidity φ and pressure p) were used to determine the amount of energy needed to either heat or cool ambient air. Historical meteorological data sets were evaluated over a period of six years on an

hourly basis. These reference data sets are supposed to represent typical meteorological conditions of the investigated region of the building locations and also allow to differentiate between hot and dry conditions as well as cool and moist ones. The hourly resolution is needed to properly display the actual schedule, in which the building is populated. This approach yields additional information on how a HVAC/DAC-coupling could perform in other climate zones. The meteorological input data is publicly available from the Website of the German Weather Service. The data was recorded near Cologne-Bonn Airport in southwest Germany and is available with an hourly time-resolution [44].

The model parameters for the numerical simulations of required humidification/dehumidification efforts as well as required heating/cooling efforts were chosen in accordance with the design criteria for the relative air humidity specified for the indoor environmental quality of category II specified in EN 16798-1. The relative air humidity design parameters for humidification and dehumidification are 25% and 60%, respectively. Numerical simulations were performed for an indoor air temperature of 21 °C since this represents a conservative modelling approach with respect to humidification/dehumidification requirements.

The time-resolved calculation of ambient air heat capacities using historical data sets of ambient air temperature, relative humidity and pressure facilitates the estimation of energy demand for air conditioning to meet the pre-defined requirements in accordance with indoor environmental quality of category II specified in EN 16798-1.

To determine the energy needed to either heat or cool ambient air to meet indoor environmental quality requirements, several physical parameters of ambient air entering the building need to be calculated. Firstly, the saturation vapour pressure of humid air needs to be calculated using equation (7). Secondly, the gas constant of humid air is calculated according to equation (8) [45,46].

$$e_{sat, H_2O} = 611.2 \text{ hPa} \cdot e^{\left(\frac{-17.67 - \vartheta}{243.12 + \vartheta}\right)} \quad (7)$$

In equation (7)

e_{sat, H_2O} is the saturation vapour pressure in hPa and
 ϑ is the temperature in °C.

$$R_{air, hum} = \frac{R_{air, dry}}{1 - \left(\frac{\varphi \cdot e_{sat, H_2O}}{p}\right) \cdot \left(1 - \frac{R_{air, dry}}{R_{H_2O, gas}}\right)} \quad (8)$$

In equation (8)

$R_{air, hum}$ is the gas constant of humid air in J (kg K)⁻¹,
 $R_{air, dry}$ is the gas constant of dry air in J (kg K)⁻¹ ($R_{air, dry} = 0.287$ kJ (kg K)⁻¹),
 $R_{H_2O, gas}$ is the gas constant of water in J (kg K)⁻¹ ($R_{H_2O, gas} = 0.461$ kJ (kg K)⁻¹),
 φ is the relative air humidity in %, and
 p is the air pressure in hPa.

Gas constants are derived by dividing the universal gas constant R by the molar mass M of air (28.96 g mol⁻¹ [47]) and water (18.02 g mol⁻¹ [48]).

With the values given by equations (7) and (8), the specific density of humid air $\rho_{air, hum}$ can be calculated following equation (9) [46].

$$\rho_{air, hum} = \frac{p}{R_{air, hum} \cdot T} \quad (9)$$

In equation (9)

$\rho_{air, hum}$ is the specific density of humid air in g m⁻³ and
 T is the absolute Temperature in K.

Finally, the absolute humidity of air ρ_{H_2O} (in g m⁻³) is derived from the given relative humidity (φ) via equation (10), which was fitted in the range from 273 K to 313 K [49].

$$\rho_{H_2O} = \left(0.0004 \frac{1}{K^3} \cdot T^3 - 0.2867 \frac{1}{K^2} \cdot T^2 + 77.212 \frac{1}{K} \cdot T - 6959.1\right) \cdot \varphi \cdot 1 \frac{g}{m^3} \quad (10)$$

With the given values for the specific density of humid air $\rho_{air, hum}$, the absolute humidity of air ρ_{H_2O} and the specific heat capacities of dry air ($c_{p, air}$) and gaseous water (c_{p, H_2O}), the heat capacity of ambient air $c_{p, amb}$ is calculated using equation (11). To facilitate this calculation, several assumptions are made. It is assumed, that heating and cooling of air does not result in pressure or volume changes. Furthermore, the temperature dependence of heat capacities of water and air is neglected. This is justified because in the observed range of air temperatures (-20 °C–35 °C), the corresponding heat capacities differed by less than 1%. Heat capacities are therefore regarded as independent from the air temperature in the observed temperature range. Thus, the actual heat capacity of ambient air depends solely on air pressure and humidity.

$$c_{p, amb} = \left(\frac{\rho_{air, hum} - \rho_{H_2O}}{\rho_{air, hum}} \cdot c_{p, air}\right) + \left(\frac{\rho_{H_2O}}{\rho_{air, hum}} \cdot c_{p, H_2O}\right) \quad (11)$$

In equation (11)

$c_{p, amb}$ is the heat capacity of ambient air for observed relative humidity and pressure in J (g K)⁻¹,

$c_{p, air}$ is the heat capacity of dry air in J (g K)⁻¹ ($c_{p, air} = 0.926$ kJ (kg K)⁻¹ at standard conditions [48]), and

c_{p, H_2O} is the heat capacity of gaseous water in J (g K)⁻¹ ($c_{p, H_2O} = 1.839$ kJ (kg K)⁻¹ at standard conditions [48]).

With the given heat capacity $c_{p, amb}$, the energy demand for air conditioning \dot{Q}_{AC} (comprising heating/cooling efforts and humidification/dehumidification efforts) of the ambient air feed entering the building can be calculated according to equation (12) in compliance with the specifications for the relative air humidity of category II given in EN 16798-1. To determine an energy demand for humidification/dehumidification, the enthalpy of vaporization Q_v of water at 21 °C (2450 kJ kg⁻¹ [50]) is multiplied with a factor of 1.2 to compensate energy losses in real systems. This results in an energy demand for humidity control processes of 2940 kJ kg⁻¹ (0.817 kWh kg⁻¹).

$$\dot{Q}_{AC} = \rho_{air, hum} \cdot \dot{V}_{feed} \cdot c_{p, amb} \cdot \Delta T + 1,2 \cdot Q_v \cdot \rho_{H_2O} \cdot \dot{V}_{feed} \quad (12)$$

In equation (12)

\dot{Q}_{AC} is the energy demand for air conditioning of the ambient air feed in J h⁻¹,

\dot{V}_{feed} is the ambient air feed rate in m³ h⁻¹,

Table 2

General input parameters for numerical simulations.

Parameter	Value
Target value for indoor air temperature [°C]	21
Observation period for meteorological data	2015–2020
Density of CO ₂ (at 20 °C, 1 bar) [g L ⁻¹]	1.815
Occupant-related emission rate for H ₂ O [g person ⁻¹ h ⁻¹]	80 ^a
Occupant-related emission rate for CO ₂ [g person ⁻¹ h ⁻¹]	32.4 ^b
Target value for relative indoor air humidity [%]	25–60 ^c
Energy demand for (de)humidification [kWh kg ⁻¹]	0.817
Ventilation schedule [Central European Summer Time]	6:00–18:00

^a Amount derived from Ref. [51] assuming light work for people, some indoor plants and wet surfaces (bathroom, kitchen).

^b Amount derived from Ref. [52] assuming a metabolic rate of 1.5 corresponding to office work. Office workers are considered to be 30–40 years old and of neutral gender (50% female, 50% male).

^c According to EN 16798-1, the relative humidity of indoor air in category II is required to range between 25 and 60% RH. The (de)humidification requirement in the buildings investigated in this study is simulated numerically to comply with the specifications of category II given in EN 16798-1. If the humidity exceeds the limits of acceptable humidity in any hour, the amount of energy is calculated to remove or add water to comply again with these limits.

ΔT is the temperature difference between ambient air temperature and indoor air temperature in K, and

Q_v is the enthalpy of vaporization of water at 21 °C in kJ kg⁻¹ ($Q_v = 2450$ kJ kg⁻¹ [50]).

In this numerical simulation, it is assumed that the investigated building possesses a heat exchanger and an air conditioning system. The simulation provides information on potential energy savings resulting from a HVAC-system operated in different recirculation modes. This virtual amount of energy would be available for CO₂ capturing instead. The full set of assumptions and parameters used for the simulations is provided in Table 2.

Energy production and losses inside the building, which are not directly related to HVAC such as diffusion, passive heating and cooling, are neglected since this would influence conventional ventilation concepts and a HVAC/DAC-coupling in a recirculation mode equally. Another assumption is that there is no heat loss in the ventilation system and no additional heat generation (e.g. due to waste heat from fan operation).

2.4. Model scenarios for the evaluation of the energy saving potential in hypothetical model buildings using HVAC/DAC-coupling in a recirculation mode

The enormous energetic effort to separate CO₂ from air is one of the main problems of DAC. Since the further development of the technology takes time for scale up and energetic optimization, it can be useful to partially compensate energy demands in another area. This study focuses on the research question how much energy can be saved, if DAC enables higher recirculation rates in the built environment and thereby reduces the energy demand for heating/cooling of ambient feed.

For this purpose, model scenarios were constructed to simulate the specific amount of energy needed to condition ambient air entering the respective building to meet the indoor requirements for indoor environmental quality of category II according to EN 16798-1. As outlined above, the simulation is based on historical meteorological data (ambient air temperature, pressure and relative air humidity). Each model scenario is limited in terms of the assumed ventilation time schedule (see Table 2), so that energy demands are only summed up for the assumed operating time of the ventilation system. The system is completely reset over night, assuming each day starts with a building filled with air of the desired temperature. Starting humidity is determined on the basis of historical meteorological data of the absolute ambient air humidity. The resulting absolute indoor air humidity at 21 °C is calculated according equation (10). The corresponding energy demand for air conditioning is calculated using equation (12). Additional heat generation and losses due to surface interactions, passive diffusion, additional devices are neglected, since these contributions to the overall energy demand are independent from the respective ventilation concept.

For the simulation of indoor air humidity it is assumed that all

occupants emit a constant amount of water of 80 g person⁻¹ h⁻¹, and no water is absorbed or released in the building or the ventilation system. As long as the relative humidity is within the given boundaries (category II specified in EN 16798-1), no (de)humidification is considered. Upon reaching one limit, the amount of energy is calculated according equation (12) to keep the relative indoor air humidity within the specified limits. The building occupancy is considered as an average of persons being present over the whole time when the ventilation system is in operation.

For the simulation of indoor air CO₂-concentration, it is assumed, that all occupants emit a constant amount of CO₂ of 32.4 g person⁻¹ h⁻¹. Furthermore, the CO₂ feed is set to the steady-state concentration calculated according equation (6) in the model scenarios. Since the application has not yet been practically tested, real diurnal CO₂-profiles in a building with HVAC/DAC-coupling operated in a recirculation mode are not available.

All model scenarios resort to the parameters and calculations mentioned above to simulate the energy demand for air conditioning without recirculation and DAC, with both technologies implemented, and the difference of both settings. Furthermore, the amount of CO₂ that is accessible for capturing is calculated. Finally, the energy saving potential is divided by the amount of accessible CO₂ to give an extrapolation of how much energy can be used to capture CO₂ without increasing the buildings energy demand.

The first scenario serves as reference and all parameters are summarized in Table 3. In scenario 1, the model building has an occupied area of 1000 m² and a height of 3.5 m, resulting in an indoor air volume of 3500 m³. 100 persons occupy this area. The air exchange rate is set to 2.7 h⁻¹. CO₂-concentrations of both indoor air and exhaust air flow are set to constant values of 398 ppm, respectively. These model scenario parameters are chosen to represent a single floor of the investigated real building D, for which HVAC and building parameters are well known (see Table 1).

Scenarios 2–4 are designed to assess how different building parameters influence the energy saving potential through implementation of a HVAC/DAC-coupling in recirculation mode. Scenario 2 simulates the same building as scenario 1, but the ventilation effort is doubled. This refers to a modern building, where the air exchange rate is increased to provide a better IAQ. Scenario 3 provides an example for highly occupied buildings such as schools, where humidity control plays a more important role. Here, the occupancy is doubled in comparison to reference scenario 1. Scenario 4 represents an old building with a less modern air conditioning system and no heat recovery. All scenario parameters are summarized in Table 4.

3. Results and discussion

3.1. CO₂-loads in real buildings

The buildings listed in Table 1 were investigated for CO₂-loads in the exhaust air flow of the ventilation system. The measured CO₂-concentration profiles were numerically integrated over the operating time of

Table 3
Model building parameters for scenario 1.

Parameter	Value
Volume of model building [m ³]	3500
Ventilation rate [m ³ h ⁻¹]	9450
Number of occupants [-]	100
AC efficiency factor [kWh kWh ⁻¹]	3 ^a
Heat recovery efficiency [%]	80 ^b
Assumed mean CO ₂ -load for DAC feed [ppm]	398 ^c
Recirculation rate [%]	80

^a Value chosen to be reasonable average of currently installed AC systems [53].

^b Value chosen as reasonable average of state-of-the-art heat exchangers [54].

^c Steady-state CO₂-concentration calculated using equation (6).

Table 4
Model building parameters for scenarios 2–4.

Parameter	Scenario 2	Scenario 3	Scenario 4
Volume of model building [m ³]	3500	3500	3500
Ventilation rate [m ³ h ⁻¹]	18900	9450	9450
Number of occupants [-]	100	200	100
AC efficiency factor [kWh kWh ⁻¹]	3	3	2 ^a
Heat recovery efficiency [%]	80	80	0
Assumed mean CO ₂ -load for DAC feed [ppm]	258 ^b	678 ^b	398 ^b
Recirculation rate [%]	80	80	80

^a Assumed older AC with an approximate energy efficiency factor of 2 [53].

^b Steady-state CO₂-concentration calculated using equation (6).

Table 5
Measured CO₂-loads in investigated buildings.

Measurement period	Building	Exhaust flow rate [m ³ h ⁻¹]	Average CO ₂ -loads [kg d ⁻¹]
04/09/21-04/17/21	A	15300	157.0
04/19/21-04/26/21	B	24000	118.4
04/27/21-05/04/21	C	19240	114.3
05/05/21-05/12/21	D	83000	530.2

the ventilation system. Results were averaged over the measurement period to report a mass of CO₂ per day (see Table 5).

It can be shown, that ventilation systems of public or commercial buildings transport substantial amounts of CO₂ in their daily operation. A building with a transported mass of 150 kg d⁻¹ would subsequently

lead to a yearly mass of 37.5 t transported CO₂ (assuming 250 working days). It is noteworthy that the results depicted in Table 5 were recorded in a measurement period characterized by low building occupancy (typically lower than 30% of regularly expected occupancy).

The typical diurnal profiles depicted in Fig. 2 show relatively

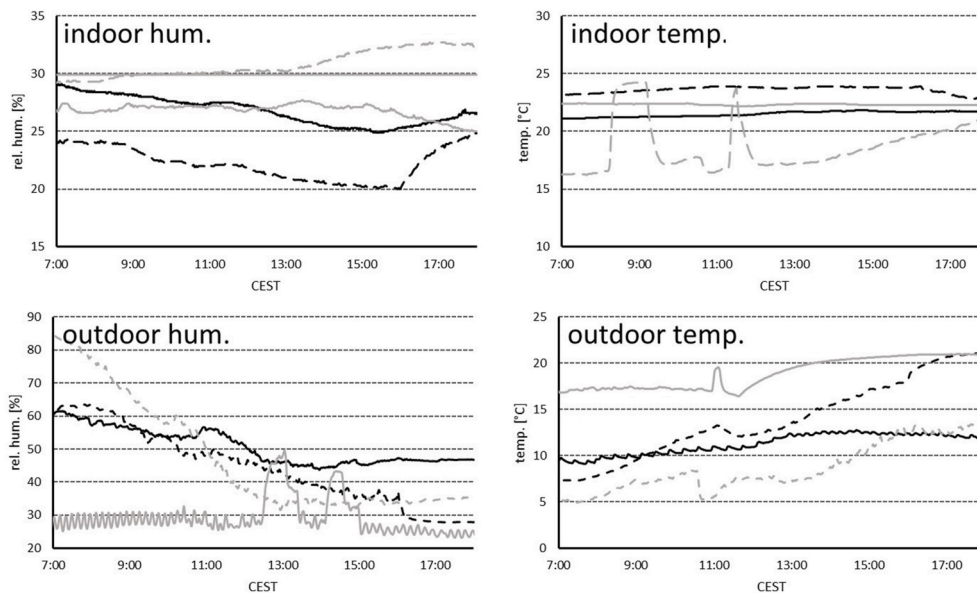


Fig. 2. Typical diurnal profiles of relative humidity and temperature measured in the exhaust (indoor) and inlet (outdoor) air flow of investigated model buildings A (solid black), B (dashed black), C (solid grey) and D (dashed grey).

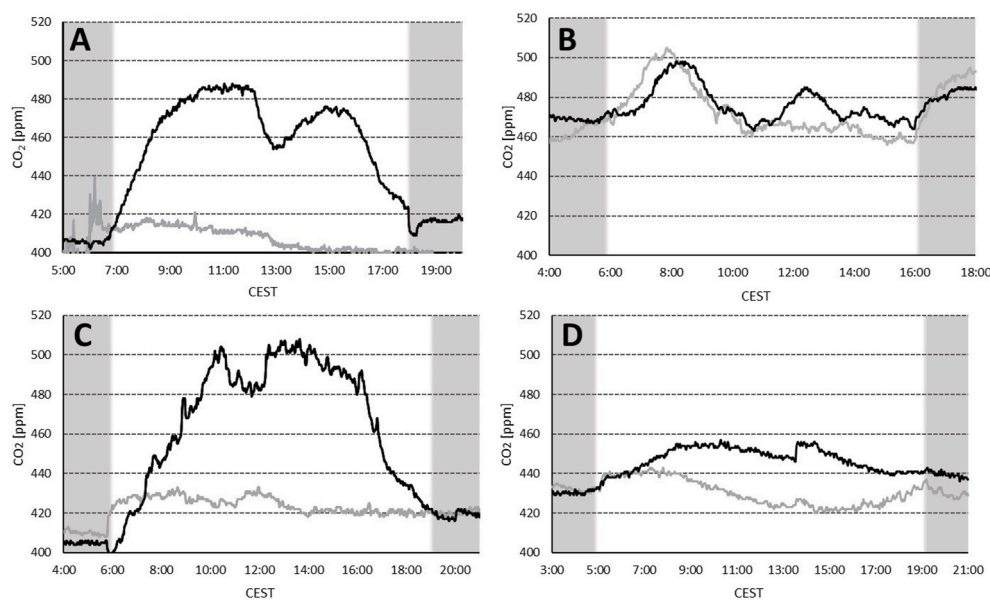


Fig. 3. Typical examples of diurnal CO₂-concentration profiles measured in the ambient air feed (grey) and the exhaust flow (black) of investigated real buildings A – D. Grey shaded areas indicate time periods where the ventilation system was out of operation. Please note that after the ventilation system is switched off in the evening, there is no forced convection in the ducts and thus no ideal mixing of the air.

Table 6

Averaged CO₂-loads ventilated and occupancy-related CO₂-emission rates resulting from respiration in the investigated buildings. Values are arithmetic means over the measurement time of five days restricted to time periods with the ventilation system being in operation.

Building	Average CO ₂ -load [kg d ⁻¹]	Occupancy-related CO ₂ -emission rate	
		[kg d ⁻¹]	[%]
A	157.0	15.5	9.9
B	118.4	–	–
C	114.3	7.7	6.7
D	530.2	20.5	3.9

constant relative humidity and temperature values inside the buildings (upper panels), although the outside conditions change remarkably over a whole day (lower panels). Indoor humidity is expectedly low, correspondent to the meteorological conditions in Germany for April and May 2021. Heating ambient air while it enters the building results in a significant decrease of relative humidity. Fluctuations in building D's exhaust temperature may be caused by the time-dependant ventilation scheme of different building areas with different temperatures such as canteens and server rooms. In building C, the sensor could only be placed downstream of the heat recovery and humidity management system due to technical accessibility. Therefore, the ambient air data of building C refers to partially processed air and does not represent real ambient conditions.

In addition to the absolute CO₂-loads in the exhaust flow, the differences between feed and exhaust flow were monitored to investigate the amount of CO₂ that is exhaled by the occupants.

Fig. 3 shows the differences of CO₂-loads in ambient air feed and exhaust air flow of investigated real buildings A - D. With the exception of building B, the measurements show typical diurnal profiles with an initial raise of the CO₂-concentration in the morning, followed by a rather constant concentration until afternoon followed by a steady decline around the time when the occupants leave the building in the evening. Building B is an inoperative cafeteria and therefore almost not charged with indoor generated CO₂. For buildings B and C, periods were observed where ambient air feed contains more CO₂ than the exhaust flow. This can be justified by increased levels of CO₂ due to traffic-related emission sources near the inlet of the building's ventilation system in the early morning hours. The area between grey and black measurements can be numerically integrated to yield the occupancy-

Table 7

Simulation results scenario 1.

parameter	unit	high	low	average
Energy demand no DAC, no recirculation flow	MWh year ⁻¹	23.26 (2016)	19.14 (2020)	21.33
Energy demand ^{a,b}	MWh year ⁻¹	14.70 (2016)	11.97 (2020)	13.48
Energy saving potential^b	MWh year⁻¹	8.56 (2016)	7.17 (2020)	7.85
CO ₂ -separation potential	t			20.59
Energy available per ton CO ₂ ^b	MWh t ⁻¹	0.42 (2016)	0.34 (2020)	0.38
Energy distribution averaged 2015-20		No DAC ^a	DAC ^a	difference ^a
Energy demand heating/cooling ^b	MWh year ⁻¹	15.76	3.15	-12.61
Water added/removed ^b	t year ⁻¹	0.38/6.44	0.18/12.46	-0.2/6.02
Energy demand humidity control ^b	MWh year ⁻¹	5.57	10.33	4.76
Dehumidification only ^b	MWh year ⁻¹	5.26	10.18	4.92

^a Differences between conventional ventilation and HVAC/DAC-coupling in recirculation mode, referred to as "No DAC" and "DAC", respectively.

^b With HVAC/DAC-coupling in recirculation mode.

related CO₂-emission rate resulting from respiration.

Table 6 depicts the averaged CO₂-loads in kilograms per day for each building. The exhaust CO₂-concentration was numerically integrated over all five monitored working days and arithmetically averaged to give an average CO₂-load per day. The occupancy related CO₂-emission rates are numerical integrals over the same time, calculated by the difference of inlet- and exhaust CO₂-concentration. As shown in Table 6, the occupancy-related CO₂-emission rate represents a minor contribution of 4%–10% of the average CO₂-loads transported by the ventilation system. This small contribution of occupancy-related CO₂-emissions to the overall CO₂-loads in the investigated buildings can be explained by the low occupancy of the buildings during the measurement period (typically lower than 30% of regularly expected occupancy). However, measurements of the CO₂-concentrations in building D performed in 2019 indicate that the contribution of occupancy-related CO₂-emissions to the overall CO₂-loads ranges between 12% and 17% when the building was regularly populated [55]. This shows that at least in building D the occupancy-related CO₂-emission rate tends to be approximately 4–5 times larger compared to the value reported in Table 6. It is questionable if the relatively large factor of 4–5 is applicable to the remaining investigated buildings. However, it represents a rough estimation of how much occupancy-related CO₂-emissions can be expected in public or commercial buildings under regular occupancy conditions.

The fraction of occupancy-related CO₂-emissions is a crucial parameter for the evaluation of the feasibility of a HVAC/DAC-coupling in recirculation mode. By the reduction of ambient air feed, the occupancy-related CO₂-emissions represent the main feed for the DAC modules. It is noteworthy, that the volume of the building and the passive diffusion rate also plays an important role in this regard, especially in the early morning during start-up of the ventilation system.

3.2. Energy saving potential in hypothetical model buildings using HVAC/DAC-coupling in a recirculation mode

The numerical simulation results for scenario 1 are depicted in Table 7. Scenario 1 represents a reference with respect to a single floor of the investigated real building D. The results for scenario 2 to 4 are depicted in Table 8. Scenario 2 and 3 represent the same model building as scenario 1 with either a higher air exchange rate (scenario 2) or a higher occupancy (scenario 3), respectively. Scenario 4 represents a building of the same structural parameters but without heat recovery and less efficient AC. Tables 7 and 8 show the annual energy demand for the respective model scenario without DAC and without recirculation flow. Furthermore, the energy demand for a HVAC/DAC-coupling in recirculation mode is shown. This allows for the calculation of a specific

Table 8

Simulation results for scenarios 2–4. All values as average per year over 6 years.

parameter	unit	Scenario 2	Scenario 3	Scenario 4
Energy demand no DAC, no recirculation flow	MWh year ⁻¹	36.59	23.46	77.74
Energy demand ^a	MWh year ⁻¹	13.31	32.03	24.76
Energy saving potential^a	MWh year⁻¹	23.28	none	52.97
CO ₂ -separation potential	t	26.69	35.07	20.59
Energy available per ton CO ₂ ^a	MWh t ⁻¹	0.87	none	2.57
Energy demand heating/cooling ^a	MWh year ⁻¹	6.30	3.15	14.43
Water added/removed ^a	t year ⁻¹	0.21/8.36	0.18/35.17	0.18/12.46
Energy demand humidity control ^a	MWh year ⁻¹	7.00	28.88	10.33

^a With HVAC/DAC-coupling in recirculation mode.

annual energy saving potential for each scenario. For scenario 1, the most and least energy demanding years are shown as “high” and “low” values, respectively, to give an impression of annual differences depending on meteorological conditions. Moreover, the annual CO₂-loads are summarized to give a CO₂-separation potential in tons of CO₂ per year. This allows for the calculation of spare energy that can be used to separate one ton of CO₂. Beside heating and cooling, the second major energy consumer in ventilation systems is humidity control. The absolute energy demands of heating/cooling processes and humidity control are given in the bottom part of Tables 7 and 8. Furthermore, the amount of energy exclusively needed for dehumidification is given in Table 7.

In scenario 1, the implementation of a HVAC/DAC-coupling in recirculation mode results in a lowered average annual energy consumption of the model building. The energy demand is decreased by 37% from 21.33 to 13.48 MWh per year. This effect is a combination of an energy saving for heating/cooling of 12.61 MWh per year, which overcompensates the increased energy demand for humidity control of 4.76 MWh per year. The main portion of this energy is needed to remove 12.46 t of water. Based on the simulated spare energy of 7.85 MWh per year and the simulated CO₂-separation potential of 20.59 tons per year, 0.38 MWh per ton of CO₂ can be invested to separate CO₂ using DAC. This spare energy can be invested without increasing the buildings energy costs in comparison to an approach without DAC.

The bottom half of Table 7 depicts the distribution of energy needed for HVAC purposes. The energy demand for heating and cooling is significantly lowered by approximately 80% when a HVAC/DAC-coupling in recirculation mode is implemented. However, the energy demand for humidity control is significantly higher for the recirculation setup. It is furthermore shown, that dehumidification requires a major portion (>95%) of the energy demand for humidity control. This is expected in a recirculating HVAC system, where occupant-related water release leads to higher air humidity.

It is noteworthy, that the most energy demanding year 2016 required approximately 20% more energy than the least energy demanding year 2020. This shows the significant influences of meteorological conditions on the energy demand of HVAC systems.

Table 8 depicts the simulation results for alternative scenarios. Scenario 2 refers to an equally populated building compared to scenario 1, where the air exchange rate is doubled. This obviously results in a higher energy demand, since more air has to be heated or chilled prior to entering the building. The occupancy is kept at 100 persons. However, the overall ventilated amount of CO₂ increases because of the larger volume of ambient air, which contains approximately 400 ppm CO₂. Additionally, the increased air exchange rate leads to a more effective removal of humidity with the exhaust airflow. Thereby, the necessary amount of extracted water is lowered by 4 tons in comparison to scenario 1 with half the air exchange rate. The simulated spare energy of 23.28 MWh per year and the simulated CO₂-separation potential of 26.69 tons per year result in 0.87 MWh per ton of CO₂ that can be invested to separate CO₂ using DAC. In this scenario, heating/cooling and humidity control have a comparable energy demand of each 6–7 MWh per year.

Scenario 3 refers to an equally ventilated building compared to scenario 1, where occupancy is doubled. As a result, the increased occupancy leads to a larger build-up of humidity and thereby results in a larger amount of water to be removed and therefore higher energy demand for dehumidification. The dehumidification energy demand of 28.88 MWh per year is even larger than the energy demand without a HVAC/DAC-coupling in recirculation mode of 23.46 MWh per year. DAC becomes unfeasible in this scenario.

Scenario 4 represents a less modern building without a heat recovery for exhaust air and an AC with an efficiency factor of only 2 instead of 3. As a result, the energy demand without a HVAC/DAC-coupling in recirculation mode is approximately 3 times larger compared to scenario 1. Considering a HVAC/DAC-coupling in recirculation mode, the energy demand is even roughly equal to scenario 1 without DAC.

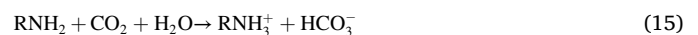
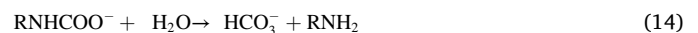
On the one hand, this shows how important heat exchangers and state-of-the-art air conditioners are. On the other hand, it results in the largest energy saving potential for the HVAC/DAC-coupling in recirculation mode. Taking into account the simulated spare energy of 52.97 MWh per year and the simulated CO₂-separation potential of 20.59 tons per year, 2.57 MWh per ton of CO₂ can be invested to separate CO₂ using DAC. Dehumidification accounts for about 40% of the energy demand in this scenario.

4. Conclusion

This mainly theoretical study shows that a HVAC/DAC-coupling in recirculation mode offers the unique potential to lower the energy demand of buildings in certain scenarios. Based on the simulated energy saving potentials and the simulated CO₂-separation potentials, energy available per ton of separated CO₂ through DAC-technology ranges between 0.38 MWh t⁻¹ (scenario 1) and 2.57 MWh t⁻¹ (scenario 4). Comparing these simulation results with actual energy demands of the DAC-technology per ton of separated CO₂ of 2–3 MWh t⁻¹ [25] clearly shows that – depending on the building operating conditions and the meteorological conditions – DAC represents a valuable contribution towards energy-efficient building ventilation and the simultaneous provision of hygienically harmless IAQ regarding the prevailing CO₂-concentration. In addition, the HVAC/DAC-coupling offers the possibility to utilize CO₂-loads in indoor air as a novel non-fossil carbon source. The assessment of the technical and economic feasibility of a HVAC/DAC-coupling strongly depends on (i) the DAC-technology itself and on (ii) the degree of systemic integration of the technology into the energy infrastructure of a real building.

4.1. Technical success factors for DAC in the built environment

A critical success factor for the use of the DAC technology in the built environment is the further development of sorbent materials allowing reversible and energy-efficient CO₂-sorption processes. Especially the regeneration of sorbents by applying heat [38], radiation [36], vacuum [39] or a combination of these methods [40,41] needs to be carefully studied with regard to the required energy input. Additionally, many commercially available CO₂-adsorbents also adsorb H₂O together with CO₂. Especially adsorbents with primary amines as active CO₂-binding position have this capability [56].



Equations (13) – (15) show the chemical mechanisms involved in the interaction of primary amines with CO₂ and H₂O as presented by Kim et al. [56]. In dry air, CO₂ occupies two amines (13). However, in moist air one H₂O and one CO₂ molecule occupy only one amine (equation (14) and (15)). This chemical mechanism shows the capabilities of amine-based adsorbents not only to work better in moist air, but also to capture water along with CO₂. This leads to the expectation, that the HVAC/DAC-coupling in recirculation mode actively lowers the air humidity and therefore further decreases the buildings energy demand as less effort is necessary to remove water from indoor air in the actual HVAC setup. This is especially relevant for highly occupied and poorly ventilated buildings, where the energy demand for dehumidification can exceed the energy demand for heating/cooling.

Another issue is the cost of CO₂ adsorbents and their long-term stability. Especially in temperature- and pressure-swing-applications, the sorbents have to withstand thermal and mechanical stress, respectively. Sorbents are also permanently exposed to chemically reactive molecules such as ozone, nitrogen oxides and organic compounds. Discontinuous operating conditions as well as chemical stress might shorten the

lifetime of the sorbents. Technical feasibility of deploying the DAC-technology in the built environment therefore strongly depends on affordable and long-lived sorbents.

The HVAC/DAC-coupling proposed in this study resorts to an air recirculation approach. This leads to the situation that – without further measures – certain trace substances might accumulate in the ventilation system. In the built environment, air quality parameters like the concentration of microbial constituents (mould, bacteria, viruses), the total amount of volatile organic compounds (TVOC), the concentration of particulate matter (PM), and the concentration of odorous substances need special attention. European Standards specify a minimum ambient air flow rate to avoid accumulation of the above-mentioned trace constituents in indoor air. This minimum ambient air flow rate is intended to cover occupancy-related emissions as well as material-related emissions and therefore varies with the number of room occupants and with the room area [57]. The German trade association for climate and ventilation recommends not to undershoot a minimum ambient air flow rate of about $20 \text{ m}^3 (\text{h} \cdot \text{person})^{-1}$, even when ambient air purification and filters are used [58]. A HVAC/DAC-coupling in recirculation mode must be designed in accordance with these minimum requirements to cover occupant-related and material-related emissions in the built environment. Cleaning the recycled air flow before it re-enters the building may result in higher costs due to additional filters and a higher ventilation effort. The numerical simulations performed in this study do not consider a potentially increased ventilation effort for the HVAC/DAC approach. The size of a DAC-plant may also be considered. Adsorbents are expected to be relatively large to achieve both, high capacity and a low pressure drop. Large installations may cause problems, especially in existing buildings.

Trace constituents (TVOC, PM, odorous substances) originate from indoor sources and also infiltrate the building via the ambient air flow. It needs to be investigated, if these air quality parameters tend to increase in a HVAC/DAC-coupling in recirculation mode. However, indoor air chemistry is at least partially driven by oxidizing species such as ozone which mainly enter the building through ambient air. Recirculating air flows may therefore even lower indoor air chemistry driven by ozonolysis and thereby suppress the formation of secondary pollutants via this pathway.

In conventional ventilation systems the measurement of CO_2 -concentrations is used to assess IAQ. It is assumed that by lowering the CO_2 -concentrations through ventilation measures, the concentration of other trace constituents is also lowered. CO_2 is therefore regarded as main IAQ-parameter. In a building equipped with a HVAC/DAC-coupling the CO_2 -concentration cannot serve as the main parameter to assess IAQ and other IAQ-parameters like, e.g. TVOC, need to be monitored.

4.2. Economic success factors for DAC in the built environment

The economic feasibility of a HVAC/DAC-coupling in recirculation mode can be quantified by considering the energy saving potential that can be realized by a HVAC-system in recirculation mode and the energy demand for the operation of the DAC module comprising adsorption, desorption and potentially compression of CO_2 . This study is focussed on the simulation of energy saving potentials of HVAC/DAC-couplings in recirculation mode for several model scenarios. The results of this study show that significant energy saving potentials can be realized by the implementation of a HVAC/DAC-coupling in recirculating mode, especially in renovation projects for older buildings.

To date, DAC-technology is mainly applied in ambient air [13–15]. These DAC-plants do not benefit from energy saving potentials that can be realized in a HVAC/DAC-coupling in recirculation mode in the built environment. CO_2 sorbent materials are still subject of current research and are only available in small scales. Nevertheless, the application of DAC in the built environment might offer an easier market entry for these materials.

The accessibility to non-fossil carbon is a co-benefit of the novel

building ventilation concept presented in this study. After separation using the DAC-technology, CO_2 must be either stored or converted into another chemical such as methane or methanol via Power-to-X (P2X) processes. While these technologies are subject of current research, the connected issues and efficiencies are uncertain [59]. The feasibility of such an integrated system strongly depends on technological developments. It is furthermore expected, that ongoing defossilization of industrial processes will lead to a demand for alternative carbon-sources in the near future. As a result, an increase in CO_2 prices can be expected which might help to make DAC commercially feasible.

In conclusion, it can be stated, that there are several opportunities to form synergies between HVAC and DAC. Though, the technical and economical evaluation of a complete HVAC/DAC-coupling in recirculation mode and operated with a P2X-plant depends on various factors that are subject to large uncertainties. Different technologies constitute promising approaches to be included into a holistic energy concept of a HVAC/DAC-coupling: heat or electricity sources that are available in urban areas, namely solar heat and waste heat or energy from photovoltaics or wind sources. DAC could be an opportunity to a more efficient use of local photovoltaic installations, as the amount of energy that is used in a specific building can be increased to avoid feeding energy into the public electricity network. DAC offers a vast amount of potential applications and synergies leading to circular economies. There is not only ambient air to take into consideration but also indoor air. In addition to public or commercial buildings, new technological approaches may lead to the usage of small-scale DAC installations in residential houses.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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