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Weather conditions severely impact optimal direct air capture siting

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ABSTRACT

Direct air capture (DAC) is rapidly gaining attention as a key technological approach to mitigating climate change. While techno-economic assessments increasingly incorporate DAC, they often overlook the influence of weather variability on both energy demand and plant productivity. In this study, we analyze how local weather patterns affect the two most promising DAC approaches: the solid sorbent and the liquid solvent processes. We reveal for a German case study, that the integration of DAC with renewable energy sources necessitates temporal and spatial considerations, as fluctuations in energy supply and demand can significantly impact operational feasibility. We demonstrate energy demand fluctuations of DAC exceeding 100 % over the course of a year and estimate future DAC costs in Germany in a range from 197 €/t_{CO2} to 1035 €/t_{CO2}, depending on the region and technology. These results emphasize the need for detailed, site-specific assessments to ensure future cost-optimal DAC deployment.

1. Introduction

Carbon dioxide removal (CDR) has gained significant attention in recent years due to its attributed role in mitigating climate change. In its 6th assessment report, the Intergovernmental Panel on Climate Change states that CDR fulfills an important role in reducing CO_2 emissions in the near term, offsetting residual emissions from ‘hard-to-abate’ sectors, and achieving negative emissions in the long term [1]. While conventional methods such as afforestation and reforestation currently account for the largest share of carbon dioxide removal, novel methods such as direct air capture (DAC) with storage are gaining significant attention in both research and policy making [2]. Two DAC processes have emerged as notable for their advanced technology readiness levels: the liquid solvent or high temperature (HT) process, with a stated technology readiness level of 7–8, and the solid sorbent or low temperature (LT) process, with a stated technology readiness level of 9, corresponding to a commercial-scale technology [3].

The future economic viability of these processes is, however, still the subject of extensive debates. Reported costs of CO_2 capture by DAC vary widely depending on the models and assumptions used. While current capture costs are estimated to be in the range of 450 to 1500 €/t_{CO2}, depending on the region [4], future projections range from costs as low as <100 €/t_{CO2} [5–7] to a more conservative 300 €/t_{CO2} [8] with strong uncertainties [9]. The influence of the prevailing weather conditions on the operation of DAC systems has received less attention so far, especially in energy system modelling and techno-economic assessments, despite its potential significant impact on the expected costs [4,10–17].

Several studies have analyzed the effect of air temperature and relative humidity variations on DAC performance [10–12,18–20], indicating a significant impact on the specific energy demand and productivity of the processes. These effects are explained by the influence of temperature and humidity on the thermodynamic and kinetic properties of the CO_2 uptake, which affects plant performance [11]. In LT-DAC systems, for instance, air temperature influences the working capacity of the sorbent, while relative humidity can facilitate CO_2 adsorption but simultaneously increases the energy required for water desorption [18]. Due to the substantial variability in temperature and relative humidity during DAC operation, dynamic operating strategies have been explored by various researchers [12,18–20]. These studies suggest that dynamic operation can slightly reduce energy consumption [18,19] and may also enhance overall plant productivity [19]. However, such strategies impose additional control challenges and require validation under real-world operating conditions. Additionally, recent research has investigated the effect of local varying CO_2 concentrations, suggesting an impact on the productivity of solid sorbent DAC [21,22]. Especially intraday variations of the CO_2 concentration, resulting from CO_2 flux

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into and out of plants, can influence DAC performance [21]. However, the influence is strongly correlated with relative humidity and temperature [21] and further research is needed to quantify the impact of the different input parameters.

To date, most research has focused on the technical aspects of these influences, with less emphasis on broader system-level implications, such as cost-optimal siting of DAC facilities and the interaction with the required energy system. While some studies analyze the DAC plants and their corresponding energy systems with high temporal resolution, they often lack detailed spatial resolution, or vice versa. Furthermore, only a few studies consider both LT- and HT-DAC systems. No study has yet compared both DAC systems, accounting for the influence of weather conditions and the energy system at high spatial and temporal resolution.

Since tackling this research gap is highly relevant for clarifying the role of DAC in future energy systems and enabling large scale DAC deployment, we conduct a detailed techno-economic assessment of renewable powered LT- and HT-DAC systems with high spatial and temporal resolution. Germany has been chosen for the case study, as its legal commitment to achieve greenhouse gas neutrality by 2045 [23] highlights the need for a rollout of DAC technologies. Multiple studies emphasize the anticipated importance of DAC in the German energy system [24–26], with recent research projecting a significant carbon dioxide removal demand of 57 Mt_{CO2} annually through DAC by 2045 [27]. Despite this significant demand, a comprehensive evaluation of potential DAC siting within Germany has not yet been performed, highlighting the need for our detailed site-specific analysis to find well-suited DAC locations. Our comprehensive analysis of DAC in Germany therefore addresses two key research questions: (1) What are the future expected costs of DAC deployment in Germany? and (2) What general insights can be derived regarding optimal DAC siting based on the German case study?

To answer these questions, we start by evaluating the influence of weather conditions (temperature and relative humidity) on the operation of LT- and HT-DAC systems in Germany. We consider an amine-functionalized adsorption process based on data from previous research [11] and an electrified liquid solvent process (see Methods). Building upon this, we develop a techno-economic optimization model for renewable powered DAC systems (see Fig. 1 and Methods) and perform mass optimization with hourly resolution to derive the levelized cost of DAC (LCOD) for 11,000 regions across Germany. The restriction to renewable-powered systems was applied to reflect the characteristics of future energy systems, particularly given that operation with fossil fuels significantly diminishes or even negates the net CO_2 capture potential [13,28,29]. Our study provides insights into potentially well-suited DAC locations as well as a detailed analysis of the relevant aspects for a cost-optimal operation of DAC systems.

2. Results

2.1. Influence of weather on DAC operation

Our results highlight that a high temporal resolution is essential to accurately capture the rapidly changing operation conditions driven by fluctuating weather patterns. For the case of Germany, temporal resolution proves particularly relevant compared to spatial resolution, as weather-induced variations in specific energy demand and productivity change more rapidly on a temporal than on a spatial scale. However, the findings also reveal that spatial resolution remains important, as conditions in neighboring regions can differ significantly (see Fig. 2A-C).

The specific energy demand of DAC plants is significantly affected by the site-specific air temperature and relative humidity. For LT-DAC systems, the heat demand is the main contributor to the overall energy demand, as it is an order of magnitude larger than the electricity demand. Generally, the heat demand of LT-DAC systems is primarily influenced by the relative humidity, with higher relative humidities resulting in higher heat demands. Thus, sites with lower relative humidity are typically more suitable for LT-DAC systems. For Germany, the average specific heat demand for the LT-DAC system exhibits a notable variation across different regions (see Fig. 2B). In the eastern part of the country, the average specific heat demand is observed to be 2.95 MWh/t_{CO2}, while in the northern part, it reaches 3.3 MWh/t_{CO2}. The lower average heat demand in the eastern part is explained by the lower average relative humidity (see Methods and SI Sections 1 and 2).

Conversely, the electricity demand of LT-DAC systems is predominately driven by the temperature, with higher temperatures resulting in higher electricity demands. The average specific electricity demand varies between 0.163 MWh/t_{CO2} in the southern part of Germany and 0.185 MWh/t_{CO2} in the eastern and southwestern parts and the variation is mainly explained by the prevailing temperature (see Fig. 2A and Fig. 7).

For HT-DAC systems, hot and humid regions are generally preferable. While such regions are not present in Germany, the high relative humidity in the northern part and the comparably high temperature in the western part result in the most favorable HT-DAC conditions in Germany (see Fig. 2C). The average specific electricity demand of the

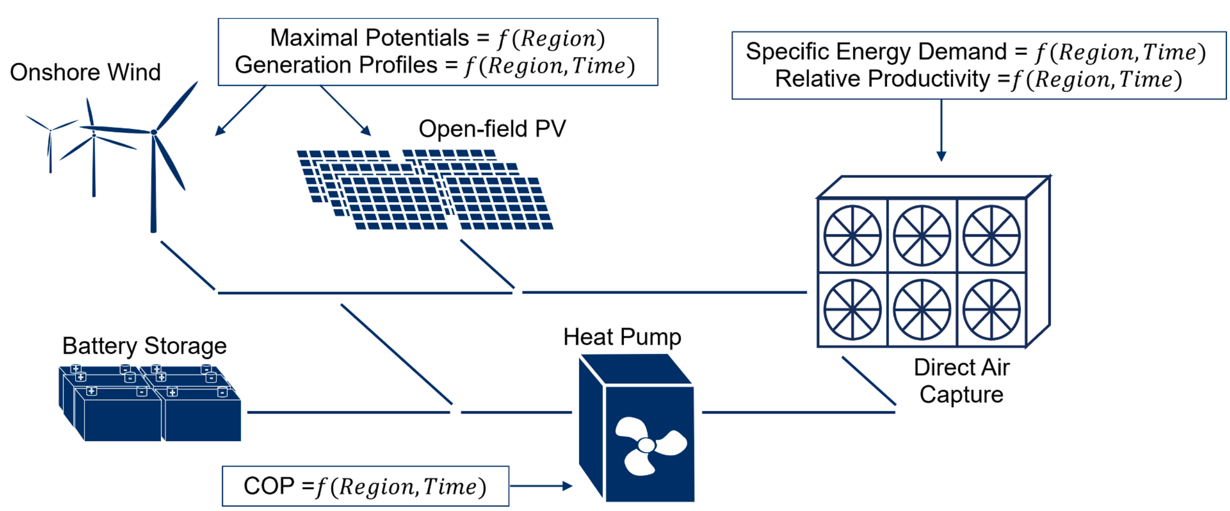

Fig. 1. Structure of the analyzed off-grid DAC system coupled to renewable energy supply, storage and conversion. The parameters which are variable dependent on the region and the time are indicated. For LT-DAC an illustrative amine-functionalized adsorption process is considered (see Methods). For HT-DAC an electrified system without a heat pump is modeled (see Methods).

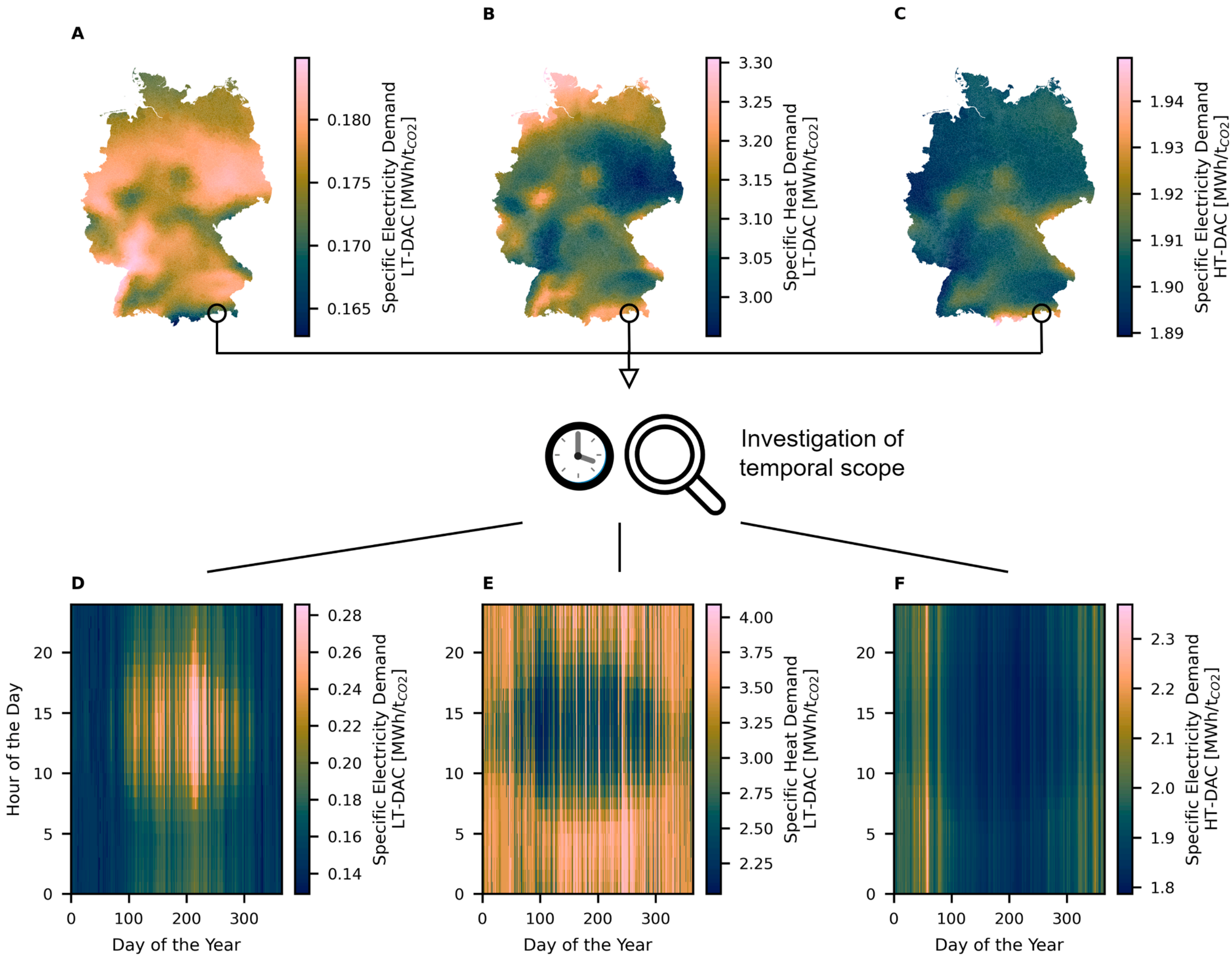

Fig. 2. Specific energy demand of LT- and electrified HT-DAC systems in Germany for the weather year 2018. The weather year 2018 was chosen as it is a representative weather year [30] and aligns with the renewable energy supply profiles used in this study [31] (see Methods). A-C. Spatial scope: location dependent average specific energy demand at constant DAC operation throughout the year. D-F. Temporal scope: hourly resolved specific energy demand for one exemplary region in southern Germany.

electrified HT-DAC system varies between 1.89 MWh/t$_{CO2}$ in the western and northern part of Germany and 1.95 MWh/t$_{CO2}$ in the southernmost part of Germany. The HT-DAC system is not that greatly affected by the environmental conditions, but generally low temperatures combined with low relative humidities result in high electricity demand (see Fig. 6C and SI Section 2). For the HT-DAC system, only a specific electricity demand is depicted, given that a fully electrified system is considered in this study.

A review of the yearly average data reveals notable but not overly significant differences across Germany. This perspective, however, neglects the effect of changing weather conditions throughout the year. While the average temperature in Germany is within the range of 6 °C to 13 °C and the average relative humidity is within the range of 69 % to 82 % for the weather year 2018, the temperature at a specific location can vary by >50 °C and the relative humidity can vary by >60 % throughout a year (see Fig. 7A, B and SI Section 1). Accordingly, a more significant effect of the weather conditions on the specific energy demand is observed on a temporal scale. This effect is of particular relevance to the operation of the energy system supplying the necessary energy to the DAC plant.

Fig. 2D-F illustrate the hourly resolved specific energy demand of both DAC plants for one exemplary region that is representative of the weather pattern in Germany. The specific electricity demand of LT-DAC ranges from 0.13 MWh/t$_{CO2}$ to 0.29 MWh/t$_{CO2}$ for the region under consideration. Notably, the highest specific electricity demand is present during daytime in summer. This is a consequence of the elevated temperature, which exceeded 30 °C during that period. Conversely, the lowest electricity demand is observed in winter, when temperatures are approximately −10 °C. The lowest specific LT-DAC heat demand of 2.1 MWh/t$_{CO2}$ is observed during daytime in summer, due to relatively low humidity levels, which range from 30 % to 50 % during that period. The highest specific heat demand of 4.1 MWh/t$_{CO2}$ is observed during night in summer, where the relative humidity exceeded 90 % (see SI Section 1). Generally, the specific heat demand can fluctuate by up to 100 % throughout the day.

The lowest specific electricity demand of the electrified HT-DAC plant is observed in summer months, with about 1.8 MWh/t$_{CO2}$, while the highest specific electricity demand is observed in winter months, with close to 2.4 MWh/t$_{CO2}$. As the HT-DAC system is most significantly influenced by temperature, operation during the summer months is generally preferable. In comparison to the LT-DAC system, the fluctuation of the specific energy demand is less significant. However, a variation of over 30 % is observed throughout the year.

While the specific energy demand of HT-DAC systems is less dependent on weather conditions, the relative productivity of such plants is more heavily affected by these conditions. Generally, for DAC

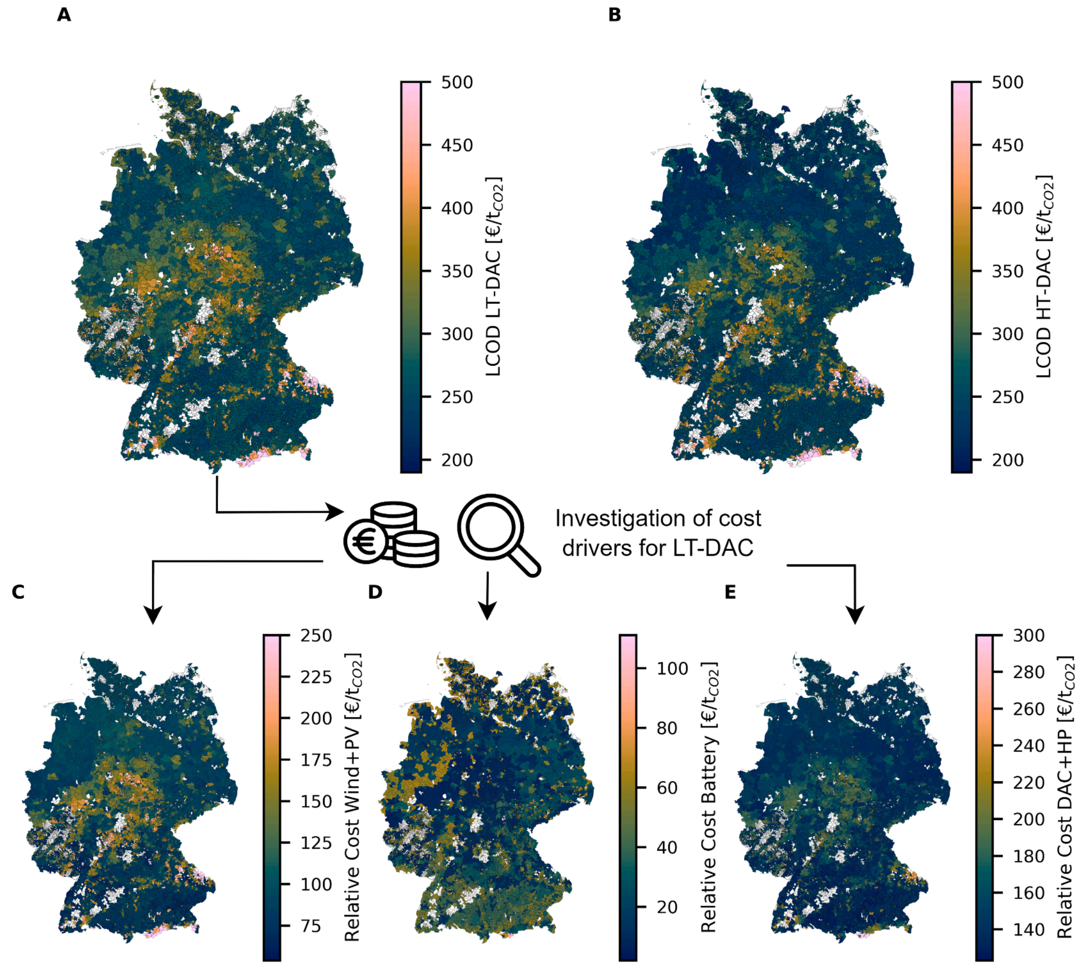

Fig. 3. A, B. Expected LCOD in Germany for LT- and HT-DAC systems in 2045 for the weather year 2018. Notably, some regions are omitted because there is no renewable energy potential available in these regions (see SI Section 4) [31]. Both cost axes are limited to the same range to enable comparison of the technologies. LCOD greater or equal to 500 €/t_{CO2} are only found in a few regions which are all depicted in the same color. C-E. Cost contributions of the different system components to the total LCOD of LT-DAC systems.

systems, the productivity of the plant varies with the prevailing environmental conditions [10,11]. In this context, relative productivity is defined as the ratio of the actual productivity under specific operating conditions to the productivity under design conditions, analogue to the capacity factor used for systems such as wind turbines. This approach enables a standardized comparison of productivity variations due to environmental conditions across different systems, independent of their installed capacities. The relative productivity does only change slightly on a spatial scale, with a location-dependent yearly average of 1.01 to 1.04 for LT-DAC systems and 0.83 to 0.91 for HT-DAC systems (see SI Figure S2). This indicates that, on average, a LT-DAC system with a nominal capacity of 1000 t_{CO2}/a could remove 1010 t_{CO2}/a to 1040 t_{CO2}/a in Germany when operated at maximum capacity throughout the year, whereas a HT-DAC system with the same nominal capacity would only remove 830 t_{CO2}/a to 910 t_{CO2}/a. At temporal scale, a more significant variation is observed, particularly for HT-DAC systems, with a change in relative productivity ranging from 0.45 to 1.1 in the region under consideration (see SI Figure S3). More information on the relative productivity of both DAC systems in Germany can be found in the SI (Section 3).

2.2. Cost drivers for optimal DAC siting

Our analysis reveals that total costs are predominantly influenced by the cost of the DAC plant itself. However, site-specific cost differences are primarily driven by the cost of the energy supply system, which depends on two key factors: the site-specific energy demand of the DAC plant and the cost of energy supply. Our previous analysis of DAC energy demand demonstrated site-specific variations of approximately 10–15 % (see Fig. 2A-C). While this variation contributes to cost differences, it does not account for the significant differences observed in energy supply system costs (see Fig. 3C). Consequently, site-specific costs of island DAC systems can be heavily influenced by the availability of favorable wind or solar resources, which reduce energy costs and make certain locations more suitable for DAC deployment.

For both DAC technologies, the lowest LCOD are found in northern Germany, while the highest LCOD are found in southern Germany (see Fig. 3A, B). The LCOD of a renewable energy system connected to an LT-DAC plant varies considerably from 223 €/t_{CO2} to 848 €/t_{CO2} depending on the chosen location, with an average of 285 €/t_{CO2}. The LCOD for the corresponding HT-DAC system is within the range of 197 €/t_{CO2} to 1035 €/t_{CO2} with an average of 265 €/t_{CO2}. The results indicate that HT-DAC systems are slightly more cost-effective in north-western Germany, where the relative humidity is comparably high and LT-DAC systems require a considerable amount of heat for the operation. Nevertheless, given that the ranges and average values are comparable for both DAC types, a clear preference for one technology can only be derived for individual regions but not for Germany as a whole. This emphasizes the importance of considering both technologies in techno-economic assessments and highlights the need for detailed site-specific analyses.

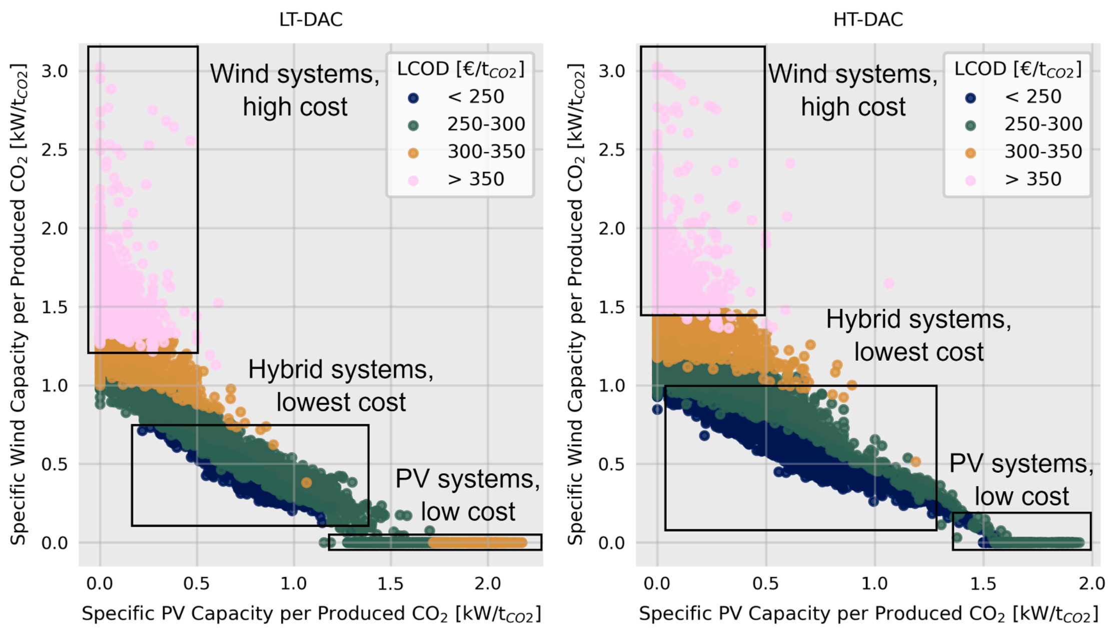

Fig. 4. Specific installed capacities of OFPV and wind plants per produced CO_2 by LT- and HT-DAC and the resulting LCOD for all modeled regions in Germany.

An analysis of cost drivers for LT-DAC systems in Germany reveals that while the contribution of the DAC plant and the heat pump are the highest on average with 152 €/t_{CO2}, the contribution of the energy supply system varies significantly depending on the location (see Fig. 3C). The highest specific contribution of the energy supply system for an LT-DAC system is 348 €/t_{CO2}, while the lowest is 54 €/t_{CO2}, with an average of 101 €/t_{CO2}. The battery is found to have the lowest relative LCOD contribution with an average of 32 €/t_{CO2}. Qualitatively similar results are also observed for the HT-DAC system (see SI Figure S5).

Our techno-economic optimization of DAC systems integrated with renewable energy supply demonstrates a close competition between LT- and HT-DAC systems, even in the context of Germany. This underscores the necessity of considering both technologies and performing site-specific analyses. Our results indicate that flexible system design and operation can overcome geographical constraints, such as limited wind potential, and result in comparable capacity factors in most regions (see SI Figure S8). However, hybrid systems combining OFPV and wind power are generally preferred, as they achieve higher capacity factors for DAC plants and result in the lowest LCOD (see Fig. 4). Systems powered exclusively by OFPV could be combined with large-scale battery storage and result in comparable cost. Contrarily, a lack of OFPV potential results in the highest costs. Therefore, sufficient free space for OFPV modules should be considered in DAC siting decisions. More information on the system design in different regions can be found in the SI (see SI Section 5). Finally, our results challenge the common assumption of constant operation of DAC plants by showing that cost-optimal renewable powered systems achieve capacity factors between 60 and 70 %, significantly lower than the widely used assumption of 8000 full load hours or capacity factors around 90 % [4,8,13].

To assess the influence of individual parameters on the resulting LCOD, a sensitivity analysis was conducted for both LT- and HT-DAC systems in two distinct regions. Hourly resolved weather data, along with the corresponding optimized system designs and operation, are provided in the SI (see SI Figure S1 and Section 5). The selected regions - Bad Aibling and Fehmarn - are characterized by favorable conditions for PV and wind energy, respectively.

The analysis reveals that the weather-dependent specific energy demand of the DAC unit has the most pronounced impact on LCOD. A ± 10 % change in this time-dependent parameter results in LCOD variations ranging from 9 to 15 €/t_{CO2}, depending on the region and DAC technology (see Fig. 5). Since all other parameters were held constant, the differences observed between the two regions can be directly attributed to local weather patterns, emphasizing their critical role in DAC system operation. Changes in the capital expenditure (capex) of the DAC plant show a similar effect on LCOD across both regions, given that comparable capacity factors are reached by the systems in both regions (see SI Table S1). Variations in wind turbine capex affect LCOD only in Fehmarn, where wind power is a significant component of the system. Contrarily, in Bad Aibling, wind capacity is minimal or absent. In both regions PV power is incorporated in the system, but the system in Bad Aibling is more sensitive to changes in PV capex, given that it is exclusively powered by PV. This dependency also explains the greater impact of battery capex variations in Bad Aibling, due to the higher installed battery capacity required in PV-dominated regions.

3. Discussion

In the following, we start by discussing the general implications of our study and afterwards outline the limitations and provide an outlook for future research.

3.1. General implications

Several general implications for cost-optimal DAC siting can be derived. We find a pronounced importance of the temporal resolution for DAC modeling, given that rapidly changing weather conditions significantly impact both the specific energy demand and the productivity of DAC systems. For instance, in Germany, we observe annual variations in the specific energy demand exceeding 100 % for LT-DAC and >30 % for HT-DAC, despite the country's relatively stable weather conditions. For countries with a more pronounced seasonal variability the importance of temporal resolution is expected to be even greater. On a spatial scale, our analysis reveals notable differences in energy demand across regions in Germany, with average heat demand of LT-DAC plants varying by over 10 %. Notably, Germany is only located in one climate zone and a comparably small country. Considering larger

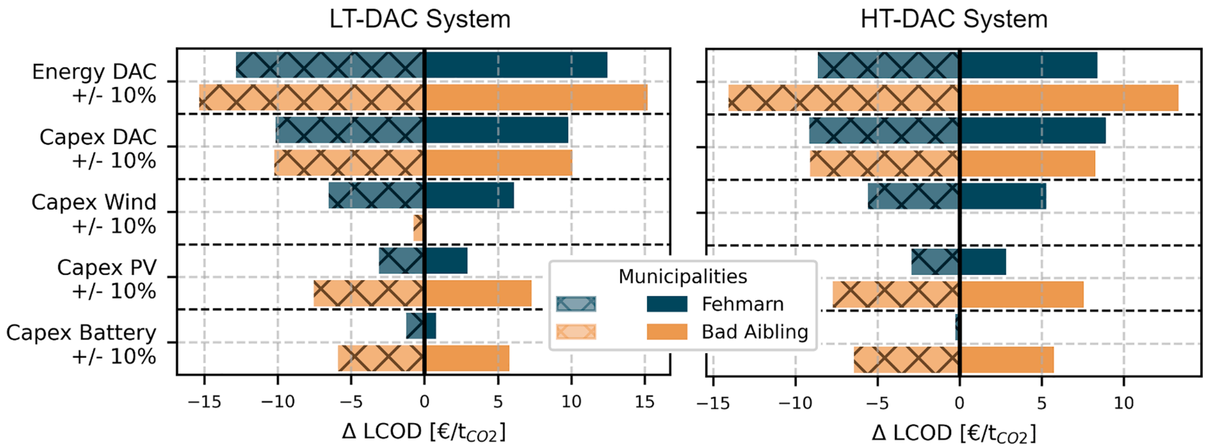

Fig. 5. Impact of the variation of input parameters on the resulting LCOD for two illustrative regions. Bad Aibling is located in southern Germany and experiences favorable PV conditions, while Fehmarn is located in northern Germany with favorable wind resources.

countries located in various climate zones, such as China or the US, spatial resolution is expected to play an even more significant role.

The integration of direct air capture into energy system models highlights the critical importance of high-resolution modeling, particularly when DAC plants are powered by renewable energy systems. Temporal mismatches between energy supply and demand could arise due to the volatility of renewable energy supply. Similarly, spatial mismatches can occur between favorable locations for DAC and ideal sites for renewable energy supply. Our analysis of DAC system cost contributions reveals that capture costs are predominantly driven by the capital costs of the DAC plant itself. However, variations in site-specific costs are primarily influenced by the energy supply system, with energy costs being the decisive factor. Although location-specific DAC energy demand plays a role, the availability and cost of renewable energy dominate the siting decision. These findings reinforce our core statement: Weather does matter. In this context, the significance of weather extends beyond DAC performance to encompass the costs of renewable energy supply, which are heavily influenced by weather-dependent factors such as wind speed and solar radiation. Weather independent renewable energy supply systems, such as geothermal plants [32], could potentially enable favorable DAC operation during times of low energy demand and should be analyzed in future research.

By 2045, we estimate average LCOD of 285 €/t_{CO2} and 265 €/t_{CO2} in Germany for LT- and HT-DAC systems, respectively. While this is in close proximity to a recent study that proposed 341 \$/t_{CO2} for HT- and 374 \$/t_{CO2} for LT-DAC systems at 1 Gt_{CO2}/a removal scale [8], it is a more conservative estimate compared to several other studies which often overlook the variability of renewable energy supply and the influence of weather on DAC performance. The relevance of temporal considerations is further supported by the observation that DAC operation generally closely resembles energy supply, with cost-optimal capacity factors for DAC plants ranging between 60 % and 70 %. These results demonstrate that constant operation at high load is not ideal for DAC systems powered by renewable energy, despite the high capital cost of the DAC plant itself. A grid connection could potentially reduce the cost of DAC by enabling higher capacity factors. However, carbon intensity of the electricity must be considered as it may drastically reduce or even negate the net CO_2 capture potential [13]. Nevertheless, future research should investigate grid-connected DAC systems in detail, given that the main location-specific cost differences observed in this study are attributable to the strongly varying cost of the off-grid energy system.

3.2. Limitations and outlook

While we performed a detailed techno-economic assessment of the combined DAC and renewable energy system, we relied on literature data for the DAC models utilized. Therefore, certain factors must be considered when evaluating the assessment. Firstly, the lower TRL of the HT-DAC process implies a greater degree of uncertainty regarding future cost developments [3]. Additionally, the uncertainty of the LCOD estimate for the HT-DAC process is increased by the usage of an electrified process [33]. This requires the utilization of an electrified calciner, which is not yet commercially available on a large scale. We do not consider future reductions in the energy demand of the DAC process, as there are no sophisticated models available which include both the influence of environmental conditions and future energy demand reductions due to technological developments. However, future research should address the uncertainties surrounding DAC development by conducting further sensitivity analyses and incorporating potential future reductions in energy demand into techno-economic assessments.

Since the scope of our study is the investigation of LT- and HT-DAC plants coupled with renewable energy systems, transport and storage of the captured CO_2 is not considered in this analysis. While we acknowledge the importance of considering transport and storage, we decided to not include this in the analysis as the exact location of future storage sites is highly uncertain and the transport costs depend strongly on the chosen mode of transport [34] (e.g. pipeline or truck).

Furthermore, we investigated off-grid DAC systems solely powered by renewable energy supply and did not model a possible grid connection. This choice was made to highlight the location-dependent characteristics of the systems and emphasize the relevance of site-specific analyses to find cost optimal placements. While future DAC systems might be connected to the grid, we believe that the choice of off-grid systems reflects the characteristics of future energy systems rather well.

Finally, we chose the weather year 2018 for our analysis as it is an average year from a global perspective and often used in assessments [30,31]. However, the choice of the weather year can heavily influence the design of energy systems [35] and robust design by using multiple weather years should be investigated.

4. Conclusion

In this study, we present the first system level comparison of LT-DAC and HT-DAC plants, conducted with high spatial and temporal resolution. Our findings underscore a key conclusion: Weather does matter. To improve accuracy and reliability of DAC assessments, it is crucial to

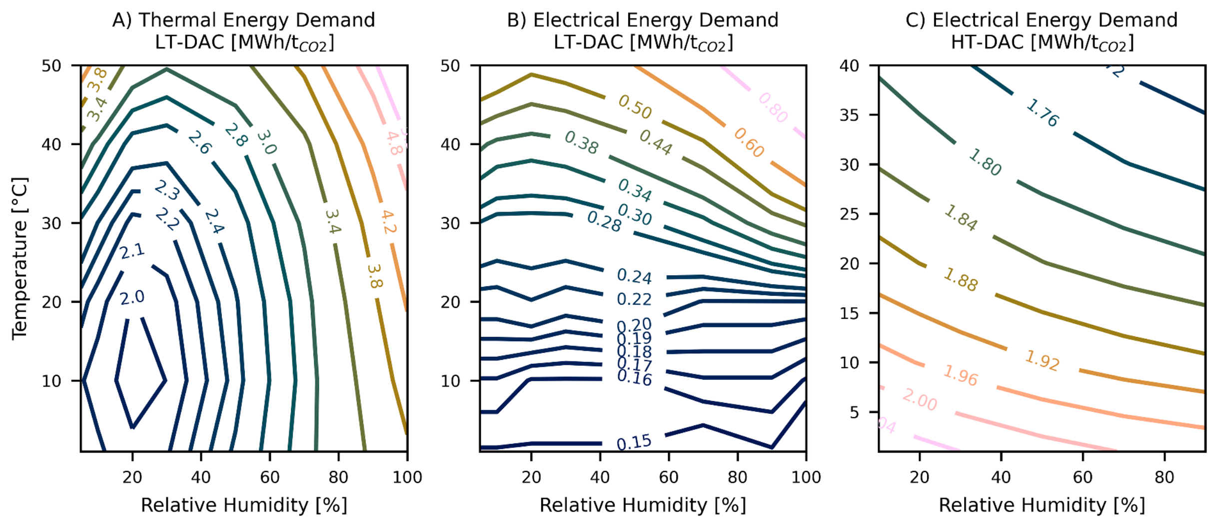

Fig. 6. Specific energy demand of DAC plants dependent on the weather conditions derived from own adaptations based on existing literature [10,11,33]. A, B. Thermal and electrical energy demand of the LT-DAC system. C. Electrical energy demand of the electrified HT-DAC system.

account for the temporal and spatial variability of weather conditions, rather than relying solely on average energy demand and productivity data, as seen frequently in scientific literature. While spatial resolution is relevant, we find a pronounced importance of the temporal resolution for DAC modeling, given that weather conditions change more rapidly on a temporal than on a spatial scale.

Beyond the direct influence on DAC operation, we highlight the relevance of weather conditions for the connected energy system by showing that neighboring regions achieve significantly different capture cost due to varying eligibility and conditions for renewable energy plants. The relevance of temporal resolution is additionally emphasized due to the volatility of renewable energy supply which needs to be considered.

While our key findings apply to regions worldwide, specific characteristics of other countries and their weather conditions must be considered with high temporal and spatial resolution for final recommendations on DAC siting. Therefore, location-specific assessments are necessary to support cost-optimal DAC deployment.

5. Methods

The key models deployed in this study are the LT- and HT-DAC models and the techno-economic optimization model. To quantify the influence of weather conditions at different locations in Germany, we used the ERA5 [36] data set to obtain hourly resolved temperature and relative humidity profiles for all 11,003 German municipalities. Renewable energy potentials and energy supply profiles serve as a crucial input to the optimization model. The deployed models and the utilized data are presented in the following.

5.1. LT-DAC

To incorporate the influence of weather conditions on LT-DAC, data from an existing model of a previous study serves as a basis [11]. The underlying model reflects the cyclic steam-assisted vacuum-pressure temperature swing adsorption technology and utilizes an amine-functionalized sorbent for CO_2 capture. Co-adsorption is considered by utilizing binary CO_2—H_2O isotherms and the different cycles of the process are modeled by either 2D (for all cycles with heating and cooling) or 1D (for all other cycles) adsorption models. For the exact characteristic of the model and the original data refer to the work of Sendi et al. [11] who have simulated the model for various weather conditions and derived the specific energy demand as well as the productivity. In this work, the given data is adapted to reflect the actual system under investigation and then combined with hourly resolved weather data to generate timeseries data of LT-DAC energy demand and relative productivity for each considered region. As in this analysis only DAC without subsequent storage is considered, the electricity needed for compression is assumed to be 0.4 GJ/t_{CO2} [37] and subtracted from the stated electricity demand, which includes compression for CO_2 storage [11]. Additionally, the needed heat for preheating of water to 100 °C prior to steam generation is not included in the stated heat demand and thus calculated by assuming a constant heat capacity of 4.18 kJ/(kg*K) and an ambient temperature of 20 °C. The mass flow is derived from the stated energy requirement for steam generation and the evaporation enthalpy of water at 100 °C. By applying these two steps to the given data [11], the needed specific energy demand of the DAC process without subsequent storage can be derived. The influence of the weather data on the specific energy demand of adsorption-based DAC is visualized in Fig. 6A, B.

5.2. HT-DAC

For HT-DAC the influence of weather conditions is modeled based on a previous study [10] and adapted to reflect a fully electrified system. Therefore, the weather dependency of the CO_2 capture rate of a natural gas powered HT-DAC system was derived and the dependency of the energy demand on the capture rate was modeled [10] (see SI Section 2). The model consists of an air contactor in which an aqueous KOH solution is employed to absorb CO_2. The resulting K_2CO_3 is regenerated by forming calcium carbonate which is then fed into a calciner and decomposed. For the exact plant design and further process specifications refer to the work of An et al. [10] who have evaluated the CO_2 capture rate under varying temperature and relative humidity conditions. Since the derived model and the stated data is only valid for a natural gas powered system it was adapted to reflect the energy demand of an electrified system [33] (see SI Section 2). Accordingly, the influence of the weather conditions on the capture rate of an electrified system and a function describing the relationship of the electricity demand dependent on the capture rate are derived. By combining the derived equations for the influence of the weather on the capture rate and the influence of the capture rate on the electricity demand with the hourly resolved weather data for each considered region, timeseries data for the specific electricity demand in each municipality can be derived. The influence of the weather data on the specific energy demand of electrified HT-DAC is illustrated in Fig. 6C.

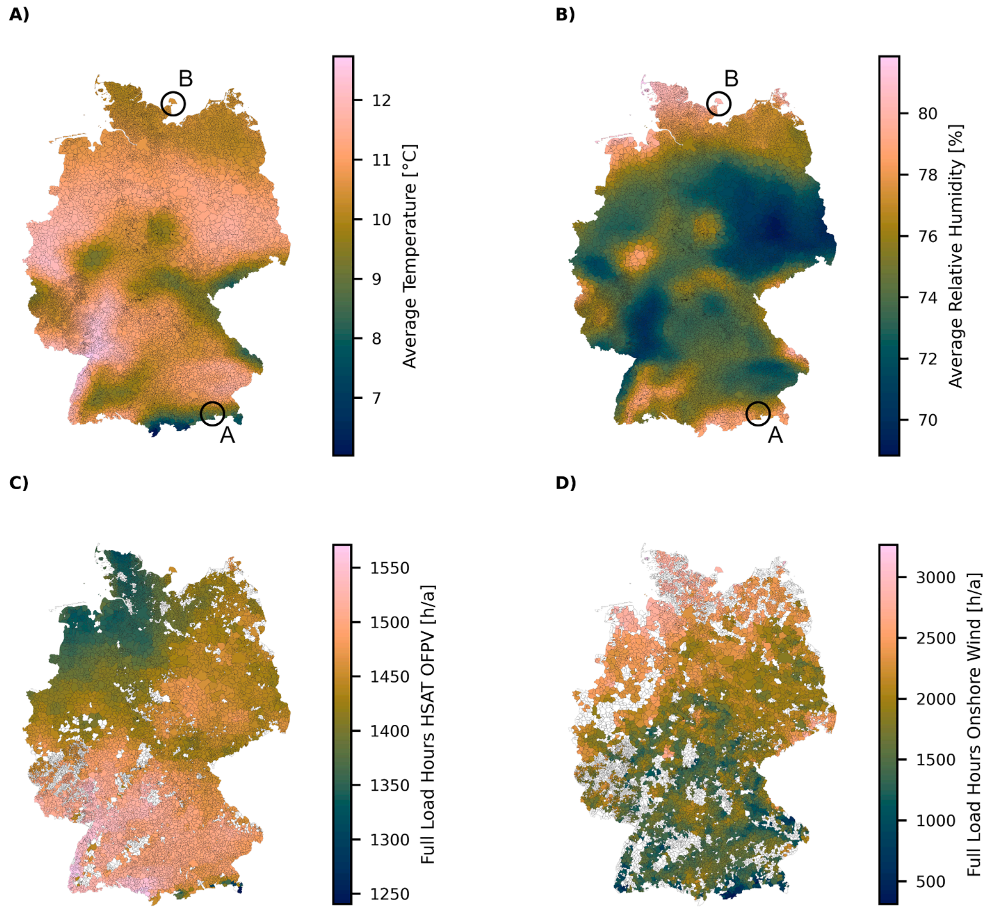

Fig. 7. A, B. Average weather in Germany for the weather year 2018 [36]. Hourly resolved temperature and relative humidity profiles for the two marked regions, A and B, can be found in the SI. C, D. Annual full load hours for HSAT OFPV and onshore wind turbines in Germany for the weather year 2018 [31].

5.3. Weather data

The utilized weather data from ERA5 [36] has been interpolated between the grid points (0.25° x 0.25°) to receive values for regions in between. The relative humidity was then calculated based on the given dewpoint and air temperature by the Sonntag formula [38]. For each of the 11,003 considered regions, hourly resolved timeseries of temperature and relative humidity are combined with the derived DAC energy demand and productivity data. The average weather in all considered regions is shown in Fig. 7A, B. Timeseries data for the marked regions can be found in the SI (see SI Section 1).

5.4. Renewable energy potential in Germany

In this study, we investigate off-grid or island DAC systems that are powered exclusively by renewable energy resources located close to the DAC plant, e.g. in the same municipality. We consider onshore wind turbines and horizontal single-axis tracking open-field photovoltaic (HSAT OFPV) systems to power the DAC plant. The potentials as well as the hourly resolved supply profiles are based on analyses carried out in cooperation with the International Energy Agency for their Global Hydrogen Review 2024 [31,39] (for specifics, see SI Section 4). The wind turbines and PV systems were simulated with exact placements and then aggregated for each region considered. The used potentials and the annual full load hours (FLH) for onshore wind as well as for HSAT OFPV are presented in Fig. 7C, D and in the SI (see SI Section 4) on a municipality level. The FLH for HSAT OFPV vary between 1550 h/a in southern Germany and 1300 h/a in northern Germany. In contrast, the FLH of onshore wind turbines are slightly above 3000 h/a in the northern part of Germany near the North and Baltic Sea and below 500 h/a in the southern part near the Alps (see Fig. 7C, D).

5.5. Techno-economic optimization model

For each German municipality, an off-grid energy system consisting of onshore wind, HSAT OFPV, battery storage, a heat pump in the case of LT-DAC, and a DAC plant is modeled to evaluate the site-specific influence of the DAC operation as well as the influence of renewable energy availability. For the LT-DAC system heat at 110 °C, needed for the desorption phase of the DAC plant [11], is externally supplied by a heat pump. The heat pump is modeled by calculating the coefficient of performance based on the prevailing temperature in each hour and region, as well as a second law efficiency of 50 % [11]. For the HT-DAC system a fully electrified plant is considered, eliminating the necessity of an external high temperature heat source. Fig. 1 illustrates the model's components and their interconnections as well as the spatial and temporal dependency of the components. The demand of 57 Mt_{CO2}/a for DAC in Germany in 2045 [27] is distributed evenly among the 11,003 municipalities based on the available renewable energy potentials. For each municipality, a maximum utilization of 40 % of the available potential is allowed to ensure the availability of renewable energy for other applications, such as electrification. We performed mass optimization to derive the levelized cost of DAC (LCOD) in each of the 11,003 German municipalities for both technologies, LT- and HT-DAC. The techno-economic optimization model is based on the ETHOS.FINE [40,41] framework and employs an hourly resolution to combine the derived DAC data with the available renewable energy supply profiles. For each time step, mass and energy conservation are enforced and the specific

Table 1
Techno-economic parameters used in the present study.

Component	Capital cost	Fixed operational cost [% of capital cost]	Economic lifetime	Further aspects	Based on
HSAT OFPV	450 €/kW	1.7 %	20		[27, 42]
Onshore Wind	1025 €/kW	2.5 %	20		[27]
Battery	140 €/kWh	2.5 %	15	94 % charge / discharge efficiency	[27]
Heat pump	760 €/kW	0.85 %	20	50 % 2nd law efficiency, 110 °C sink temperature	[11, 27]
LT-DAC	790 €/(t/a)	–	20	20 €/t variable operational cost	[27]
HT-DAC	575 €/(t/a)	–	20	30 €/t variable operational cost	[27]

energy demand and productivity of the DAC plant serve as a constraint. The intermittency of the renewable energy plants is considered by restricting the maximum possible energy supply in each time step by the corresponding hourly resolved capacity factors and the maximum technical potential in each region. During optimization, the capacity of each component as well as the corresponding operation in each hour of a year are optimized to minimize the total annual system cost (TAC). To obtain the TAC, the capital costs of all components are discounted by the capital recovery factor and the operating costs are added. The LCOD for each municipality are derived by dividing the total annual system cost by the produced CO_2 mass in each hour of the year $op_{CO2,t}$:

$$LCOD = \frac{TAC}{\sum_{t=0}^{T} op_{CO2,t}} \quad (1)$$

The techno-economic parameters are presented in Table 1. All currency values are expressed in 2020 €. The considered year for the analysis is 2045, which is the target year for achieving greenhouse gas neutrality in Germany. A discount rate of 6 % is used for all components [27].

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT and DeepL in order to improve the language of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

CRediT authorship contribution statement

Henrik Wenzel: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Freia Harzendorf:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Kenneth Okosun:** Writing – original draft, Methodology. **Thomas Schöb:** Writing – review & editing, Supervision, Conceptualization. **Jann Michael Weinand:** Writing – review & editing, Supervision. **Detlef Stolten:** Supervision, Funding acquisition.

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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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.adapen.2025.100229.

Data availability

Data will be made available on request.

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